UNIVERSITE DE LILLE
École doctorale Sciences de l'Homme et de la Société
U.F.R. de Psychologie
Laboratoire de Sciences Cognitives et Affectives (SCALab) - UMR CNRS 9193

THESE

EN VUE DE L'OBTENTION DU GRADE DE DOCTEUR
DISCIPLINE : PSYCHOLOGIE

MODIFICATIONS DEVELOPPEMENTALES ET CONTEXTUELLES DES REPRESENTATIONS MOTRICES IMPLIQUEES DANS LA PERCEPTION DES OBJETS MANIPULABLES

DEVELOPMENTAL AND CONTEXTUAL MODIFICATIONS OF THE MOTOR REPRESENTATIONS INVOLVED IN MANIPULABLE OBJECT PERCEPTION

Présentée et soutenue publiquement par

Marc GODARD

Sous la direction de la Dr. Solène KALENINE et du Dr. Yannick WAMAIN

Le mercredi 26 Mai 2021

Composition du jury :

Dr. Tatjana NAZIR, DR CNRS, Université de Lille (Présidente du jury)

Dr. Christine ASSAIANTE, DR CNRS, Université d'Aix-Marseille (Rapporteure)

Dr. Lionel BRUNEL, MCF-HDR, Université Montpellier 3 (Rapporteur)

Dr. Richard PALLUEL-GERMAIN, MCF, Université Grenoble Alpes (Examinateur)

Dr. Solène KALENINE, CR CNRS-HDR, Université de Lille (Directrice de thèse)

Dr. Yannick WAMAIN, MCF, Université de Lille (Co-encadrant de thèse)

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L'université n'entend donner aucune approbation ni improbation aux opinions émises dans les thèses. Ces opinions doivent être considérées comme propres à leurs auteurs.

Je dédie cette thèse à tous ceux dont j'ai endossé le costume[1]. Je me reconnais en chacun d'eux. Ce sont eux qui m'ont façonné tel que je suis. Grands-parents et parents de mon exceptionnelle[2] enfance, frères et sœur dans la folie, amis dans les joies et les peines, amant dans la plus grande intimité, professeurs experts et novices étudiants sur les bancs de la connaissance, collègues dans le travail d'équipe et la rivalité, fous et sages dans la confrontation à la réalité. Tous ces individus ont contribué de près ou de loin à mon parcours, par leur soutien inconditionnel comme conditionnel, ou à l'inverse en créant des difficultés, qui lorsque surmontées, ont forgé mon caractère.

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Dédicace inspirée du livre[3] « Le banquet des affamés » de Didier DAENINCKX

[1] Entendre, par le « costume », l'ego. La/les représentation(s) que tous ces individus se sont faite(s) de moi.
[2] Le terme « exceptionnel » est un terme démocratique utilisé pour éviter les étiquettes, il peut signifier tout et son contraire (Charlie Gordon dans « Des fleurs pour Algernon »).
[3] Détail personnel : Lecteur passionné, je n'ai jamais dépassé la 10ème page de ce livre, même après 3 tentatives.

“Permettez-moi de vous présenter mon ennemi intime…”

MICHEL STROGOFF ***; Jules Verne, 1876***

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HIGHLIGHTS

- Perception and action are closely interconnected at the cerebral and representational levels
- Manipulable object perception is assumed to evoke motor information (i.e., affordances) as a function of the relation between the observer, the object and the surrounding environment
- Co-evocation of affordances causes competition and is detrimental for manipulable object perception
- Among paradigms designed to investigate affordance evocation, the action priming paradigm raises fewer theoretical and/or methodological issues and provide reliable results
- Affordance sensitivity varies across age periods, reducing behavioral consequences, of affordance evocation and affordance competition, on perceptual processing of manipulable objects
- Verbal contexts modulate affordance evocation and reduce neural consequences of affordance competition during perceptual processing of manipulable objects.
- Inter-individual and intra-individual factors modulate the mechanisms at play during affordance competition, but it remains to clarify how and when these factors get involved
- Neuro-computational modeling might be one solution to explore these questions

RESUME

La perception et l'action sont deux processus dynamiques et interconnectés. Ils partagent de nombreux corrélats cérébraux et font partie intégrante des représentations cognitives. Dans ce projet de thèse, nous nous sommes concentrés sur les conceptions représentationnelles des liens perception-action pour les objets manipulables. Les conceptions les plus récentes s'accordent pour dire que la perception d'objets manipulables induit une réactivation de leurs informations motrices, ce qui est habituellement appelé « affordances ». Bien qu'un nombre important de preuves expérimentales suggèrent que l'évocation d'affordances lors de la perception d'objets soit automatique, plusieurs arguments expérimentaux montrent une variabilité inter-individuelle et intra-individuelle notable. L'expérience motrice individuelle et le contexte, tout particulièrement, module l'activation des affordances d'objet. Enfin, l'évocation d'affordances peut parfois être préjudiciable. Quand un unique objet évoque plusieurs affordances distinctes (objet « conflictuel »), ces affordances entrent en compétition. Cette compétition induit un coût de traitement, ralentissant les jugements perceptifs et supprimant la résonance motrice neurale (désynchronisation du rythme Mu). L'objectif de la thèse est d'évaluer comment le coût de la compétition peut être affecté par des facteurs individuels et contextuels. Dans une première série d'expériences, nous avons cherché à préciser les propriétés motrices d'objets évaluées avec les paradigmes classiquement utilisés pour mettre en lumière les effets d'affordance. Les résultats suggèrent qu'il est possible d'évaluer l'activation d'affordances fonctionnelles d'objets manipulables à l'aide d'un paradigme d'amorçage par l'action, en s'affranchissant de l'influence de la compatibilité spatiale dans l'évaluation des effets d'affordance. Dans une seconde étude, nous avons réalisé une vaste expérimentation sur le développement du coût de la compétition entre affordances auprès de participants âgés de 8 ans à l'âge adulte. Les résultats démontrent que le développement du coût de la compétition entre affordances et celui de l'évocation d'affordances lors de la catégorisation d'objets suivent des trajectoires non linéaires semblables. Dans une troisième étude, nous avons évalué l'influence du contexte visuel sur le coût de la compétition entre affordances à l'aide de l'électroencéphalographie. Les objets conflictuels étaient amorcés par des verbes écrits. Nous avons observé une réduction de la désynchronisation du rythme Mu quand les objets atteignables étaient précédés par un contexte verbal évoquant une action congruente avec l'utilisation fonctionnelle de l'objet. Cela suggère que le contexte verbal a biaisé le traitement de l'objet vers une affordance spécifique, réduisant le coût de la compétition. Dans l'ensemble, les données rapportées ici sont en accord avec les propositions récentes concernant le rôle du contexte et des caractéristiques individuelles dans l'activation des affordances d'objets. Ces résultats aideront à affiner et étendre les modèles neurobiologiques de la sélection d'action.

ABSTRACT

Perception and action are dynamically interconnected. They share several brain correlates and are constitutive parts of cognitive representations. In the present thesis, we emphasized on representational views that focus on perception-action interplay during manipulable object perception. Recent views agree on the idea that perceiving manipulable objects induces a revocation of their motor information, what is usually referred as “affordances”. Even though important experimental evidence suggests automatic evocation of affordances when perceiving manipulable objects, empirical arguments indicate noticeable inter-individual and intra-individual variabilities. Individual action abilities and context, in particular, modulate the activation of object affordances. Finally, affordance evocation may be sometimes detrimental for manipulable object perception. When distinct affordances are co-activated from a single visual object (“conflictual” objects), they compete between each other. This competition has a cost on manipulable object processing, slowing down perceptual judgements and suppressing neural motor resonance (Mu rhythm desynchronization). The objective of the thesis was to investigate how the cost of the competition between affordances may be affected by individual and contextual factors. In a first series of experiments, we aimed at specifying the object properties that are evaluated with classical paradigms assessing object-based affordances. Findings suggest that the activation of object functional affordances during visual processing of manufactured manipulable objects may be evaluated through action priming effects, bypassing the issue of the spatial compatibility confound in the evaluation of affordance effects. In a second study, a large investigation of the development of the affordance competition cost was conducted on participants from 8-year-olds to young adults. Findings demonstrate that the development of affordance competition cost follows a non-linear trajectory and parallels age-related changes in affordance evocation. In a third study, the influence of visual context on the competition cost between affordances during object perception was evaluated using electrophysiological measures. Conflictual objects were primed by written verbs. We found a release of Mu rhythm desynchronization when reachable objects were preceded by a contextual verb denoted an action congruent with the object use. This suggests that the verbal context may bias object processing toward one specific affordance, hence reducing the cost of affordance competition on manipulable object processing. Together, the findings reported are consistent with recent accounts concerning the role of the context and individual characteristics in the activation of object affordances and will help refining and extending recent neurobiological models of action selection.

PUBLICATIONS, COMMUNICATIONS & MOBILITY

Publications

Godard, M., Wamain, Y., & Kalénine, S. (2019). Do manufactured and natural objects evoke similar motor information? The case of action priming. Quarterly Journal of Experimental Psychology, 1747021819862210.

Godard, M., Delepoulle, S., Wamain, Y., & Kalénine, S. (submitted). How competition between action representations affects object perception during development.

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Communication (oral & poster)

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Godard, M., Wamain, Y., Delepoulle, S., & Kalénine, S. (7-9 March 2019). Predicting object visual processing from motor affordance sensitivity and conflict monitoring abilities: a developmental study. *International Convention of Psychological Science*, Paris, France. **Poster**.

Godard, M., Wamain, Y., & Kalénine, S. (2018). Distinguer les effets d'affordances de l'effet Simon lors de la perception d'objet. *Congrès de la Société Française de Psychologie*, Reims, France. **Talk**.

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Mobility

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CONTENTS

FIGURES

TABLES

BOXES

ABBREVIATIONS

2AS : Two Action System (theory)
2D : Two dimensions
3D : Three dimensions
AIP : Anterior intraparietal cortex
aSMG : Anterior supramarginal gyrus
BOI : Body-object interaction
CI : Confidence interval
cm : Centimeter
dPMC : Dorsal premotor cortex
EEG : Electroencephalography
ERP : Event related potential
FARS : Fagg-Arbib-Rizzolatti-Sakata (model)
FDR : False discovery rate
fMRI : Functional magnetic resonance imagery
Hz : Hertz
ICA : Independent component analysis
IFG : Inferior frontal gyrus
IPL : Inferior parietal lobule
ITI : Inter-stimuli intervals
LL : Log-likelihood ratio
LOC : Lateral occipital cortex
M : Mean
MAD : Median absolute deviation
MEG : Magnetoencephalography
MEP : Motor evoked potentials
ms : Millisecond
n : Number of participants
NAC : Number of action codes
NEF : Neural Engineering Framework
PET : Positron emission tomography
PFC : Prefrontal cortex
phAIP : Putative human homolog of anterior intraparietal
PMC : Premotor cortex
pMTG : Posterior middle temporal gyrus
PSS : Perceptual Symbol System
RT : Response time
SD : Standard deviation
SMA : Supplementary motor area
SMG : Superior marginal gyrus
SOA : Stimulus onset asynchrony
SPA : Semantic pointer architecture
SPAUN : Semantic pointer architecture unified network
SPL : Superior parietal lobule
TMS : Transcranial magnetic stimulation
TRoPICALS : Two-route, prefrontal instruction, competition of affordances, language simulation (model)
V : Volt
vPMC : ventral premotor cortex

Other abbreviations

e.g. : *Exempli gratia*
i.e., : *Id est*
vs. : *Versus*
cf. : *Confer*
etc. : *Etcetera*

INTRODUCTION

CHAPTER 1. PERCEPTION IS FOR ACTION

Recent conceptions of perception discussed its functional contribution in guiding action in the environment. There is indeed a considerable consensus for saying that perception is an adaptative function that enables one to pick up information from the environment to act and survive. Researchers have investigated perception for its contribution in discriminating object properties necessary for identification and for action, for representing others' actions and representing object-associated actions. They have also investigated the integration of covariations between action and perceptual properties of the environment in cognitive representations. For instance, researchers have investigated the integration of action constraints in space perception and the integration of sensorimotor information in long-term conceptual knowledge. Interconnections between perception and action are supported by many theoretical accounts and empirical evidence. Among them, multiple debates exist, some of which will be discussed in the present chapter, but none of them will really question the interrelation between perception and action. In this first chapter, we will attempt to convince the reader that perception and action are dynamically interconnected. As most of the literature on the domain, we will mainly focus on visual perception. The aim is to provide the reader with a relevant background about the relationship between visual perception and action suitable for discussing the perception of manipulable objects in Chapters 2 and 3. We will first depict the precursor approaches that assumed that perception could not be conceptualized without considering its fundamental role in action: the ecological approach of visual perception (Gibson, 1986). We will pursue by discussing neurophysiological discoveries of the end of the last century that have highlighted similar brain correlates for perception and action. Finally, we will discuss recent cognitive approaches that assume close interconnections between perception, action and their cognitive representations. The present thesis falls into these cognitive conceptions.

I. The ecological approach of visual perception

In the second half of the 20th century, Gibson proposed an ecological approach to visual perception (Gibson, 1979, 1986) that today, constitutes the roots of enactive approaches of perception. His conception has inspired a substantial number of works. To cite some examples, one may consider works on human interaction with machines (Flach & Hancock, 1992; Gaver, 1991), on conception design (Dhami et al., 2004) and his approach has even been extended to auditory perception (Gaver, 1993). Without going into details, the main contribution of ecological approaches is to consider the interplay between organisms – especially humans – and the environment (Bronfenbrenner, 1979; Gibson, 1986).

The ecological approach of visual perception differs from its contemporaries by refuting the inference principle. The inference principle postulates that stimulations (*e.g.*, light, wave) are passively received by sensory channels (e.g., eyes, ears) and undergo computational processes by the cognitive system to bring out percepts (i.e., perception as we experience it). In opposition to this conception, the ecological approach to visual perception postulates a direct perception of environmental information (Gibson, 1986), meaning that information is contained in the environment, fully present in the stimulation pattern (also called invariant properties) of sensory input and thus refuting the concept of mental representation (Baggs & Chemero, 2018). Furthermore, Gibson (1986) emphasized on the adaptative role of the action-perception relationship. Action-perception relationship is thought to be an adaptative function for the survival of the individual according to environmental constraints (Ho, 1991). For example, space and time dimensions are considered to be perceived at the individual scale, depending on individual own action capabilities (for space perception) and life events (for time perception). In this regard, perception is considered to be unique to each individual and inseparable from action, perception guiding action in the environment and action leading to modulation in what it is perceived. Gibson (1986) goes even further by suggesting that perception is not only serving action but is an active phenomenon that emerges from action and from exploration of the environment.

The core element of Gibson's approach (Gibson, 1979, 1986) is the term "affordance" that he coined to define information given by the environment to an organism. Affordances refer to action possibilities of an individual in the environment according to its own action capabilities. Along with perception, affordances are unique to each individual (Mark, 1987; Warren, 1984; Warren & Whang, 1987). They belong to objectivity and subjectivity, because they exist independently of perception but depend on individual's action capabilities. For example, Warren (1984) showed that not all individuals perceive stairs of different heights as climbable, taller individuals judging higher stairs to be more climbable than smaller individuals. However, they found that the maximum stair height to be climbable was not higher than 88% of the leg length of each individual, suggesting that affordances depend on each individual but follow consistent rules across them. According to Gibson, affordances are therefore potential actions evoked by the environment – existing without being perceived – but their perception depends on the characteristics of the individual who perceives them.

To conclude, even though the ecological approach to visual perception is a contentious theory (Baggs & Chemero, 2018) - the absence of any cognitive/brain processing of sensorial information is largely debated – the theory has mainly contributed in focusing the conception of perception at the interplay between human beings and their environment, considering its strong interconnection with action. Furthermore, since Gibson has proposed the term "affordance" (1979, 1986), the term has been used in many different ways, especially for studying the perception of manipulable objects (Osiurak et al., 2017). The different conceptions of the term "affordance" will be discussed in chapter 2.

II. Neurophysiological approaches

From a neurophysiological point of view, it has been recently emphasized that perception and action are two systems that show no clear distinction, that is visual and action processing share several brain correlates. Most evidence comes from studies in monkeys, including ablation studies and single-cell recording. Discoveries were then extended to humans through direct and indirect evidence.

1. The two visual pathways

At the beginning of the 80's, the discovery of two distinct cortical visual pathways in the monkey brain has provided substantive evidence for the existence of specific perceptual processing serving actions (Mishkin et al., 1983). The discovery was then extended to humans and refined through direct and indirect evidence. We will first discuss the discovery of the two visual pathways in monkeys and then, we will discuss evidence that extended the discovery to humans.

a. Discovery in monkeys

The visual system of the monkey was scrutinized by a researcher team who highlighted two separate visual pathways serving object and spatial vision respectively (Mishkin et al., 1983). Both pathways were shown to be functionally and neuroanatomically distinct (Mishkin & Ungerleider, 1982; Van Essen et al., 1992; Young, 1992). The first one is known as the ventral visual pathway and connects occipital to temporal cortices. The second one is known as the dorsal visual pathway and connects occipital to parietal cortices. Using ablation of monkey brain areas, the researchers established the functional mapping of both pathways (Cowey & Gross, 1970; Mishkin et al., 1982; Pohl, 1973). Monkeys initially learned to discriminate objects or spatial locations (**Figure 1**). Then, scientists performed brain surgery on monkeys, removing the bilateral inferior temporal cortex or the bilateral posterior parietal cortex. Results showed that lesion of the temporal cortex impaired specifically the performance in object discrimination task while lesion of the parietal cortex impaired specifically the performance in the spatial location discrimination task. In accordance with these results, the ventral visual pathway is claimed to subtend the processing of object physical characteristics (Cowey & Gross, 1970), with for example, the processing of object colors and shapes (Desimone et al., 1985) while the dorsal visual pathway is claimed to subtend the processing of spatial relations (Mishkin et al., 1982), with for example, the processing of the allocentric frame of reference (Pohl, 1973). The ventral and dorsal pathways are called the “what” and “where” systems respectively (Ungerleider & Haxby, 1994), as they are assumed to process object identity and object location in space (Goodale et al., 1992).

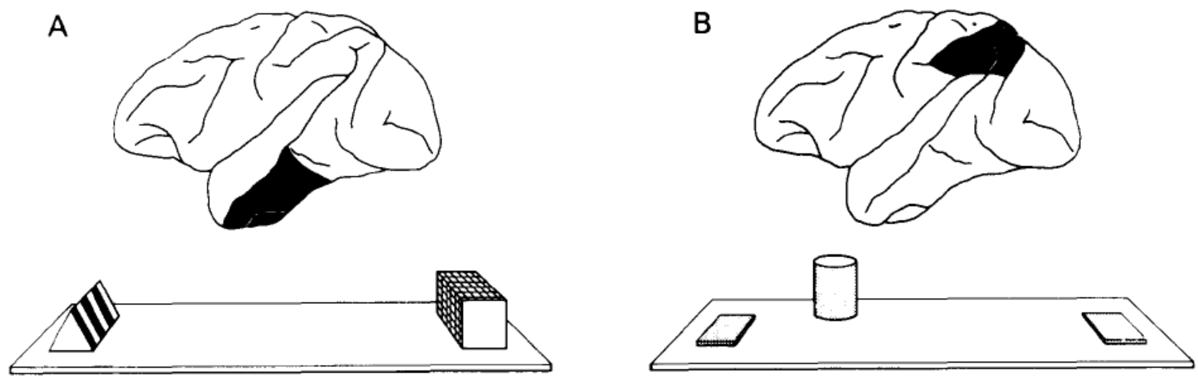

Figure 1. (A) Object discrimination task. Monkeys are trained to recognize an object and are rewarded if they choose the unfamiliar object in the subsequent task. **(B) Spatial location discrimination task**. Monkeys are trained to recognize distances and are rewarded if they choose the shorter distance between a cylinder and the rectangular ‘landmark’ in the subsequent task. Darkened brain parts represent lesioned brain areas that affect performances in the task presented below it: the equivalent of (A) the inferior temporal cortex and (B) the posterior parietal cortex in monkeys. *Figure from Mishkin, Ungerleider and Macko (1983).*

b. Generalization in humans

Lately, the dorsal visual pathway was associated with the processing of every kinds of visuomotor activities (Goodale et al., 1991, 1992; Goodale, 1993; Milner & Goodale, 1993) and therefore, inherited the name of the "How" system. Milner and Goodale (2006) dressed a significant description of all the functions attributed to the "How" system since then, that is for example the coding of object properties and space for action. The final point of Milner & Goodale (2006) regarding the dorsal visual pathway draws a clear recap of its functioning, that is the dorsal visual pathway is a *"system dedicated to the sensorimotor transformations underlying the visual control of action"* (p. 53).

In humans, the functional mapping of the ventral and dorsal visual pathways has been highlighted by several sources of evidence, in particular coming from neuropsychology (Goodale et al., 1991, 1992; Goodale, 1993; Jeannerod et al., 1994; Milner & Goodale, 1993), neuroimaging (Culham et al., 2003; Gallivan et al., 2009; Malach et al., 1995, 2002) and behavioral studies (Aglioti et al., 1995; Króliczak et al., 2006). Neuropsychological studies on lesioned patients constitute the best analogy with ablation studies in monkeys, but also the more direct evidence for the existence of two separate visual pathways in humans.

Neuropsychological evidence came from the observation of distinct impairments following dorsal or ventral brain lesions in patients (Goodale et al., 1991; Jeannerod et al., 1994). For instance, Goodale et al. (1991) reported the case of patient DF, who suffered from visual form agnosia following lesion in the ventral visual pathway (i.e., in the lateral occipital cortex, LOC). DF was unable to assess visual characteristics of objects, such as orientation or shape. However, she demonstrated preserved ability when using the same object visual characteristics for orienting (Goodale et al., 1991) and correctly positioning her hand to grasp it (Goodale, 1993). In contrast, Jeannerod et al. (1994) reported the case of patient AT, who suffered from optic ataxia[4] following lesion in the dorsal visual pathway (i.e., in the parieto-occipital areas). AT was unable to grasp correctly unfamiliar 3D shapes, but demonstrated preserved ability when familiar objects with the same shape were presented. AT also showed preserved perceptual and representational processing of objects. Additional evidence in patients highlighted the functional role of the dorsal visual pathway for object-directed actions (Jakobson et al., 1991; Perenin & Vighetto, 1988). Both studies reported cases of patients with unilateral or bilateral lesions of the dorsal regions (i.e., posterior parietal lobe) resulting in optic ataxia. Both studies described persistent deficits (i.e., up to 17 months after brain lesions) in the components of goal-directed hand actions, including mis-reaching, hand orientation errors, lack of accuracy in grip aperture. Together these findings suggest a double dissociation between the functional role of the dorsal and ventral visual pathways. The dorsal visual pathway would be necessary for object-directed actions whereas the ventral visual pathway would be necessary for object recognition.

Neuroimaging studies in healthy participants (Culham et al., 2003; Gallivan et al., 2009) constitute indirect evidence that contributes to broaden the knowledge around the distinction between the dorsal and ventral visual regions. Using fMRI recordings (see **Figure 2**), Culham et al. (2003) demonstrated that grasping, compared to reaching movements, induced specific activation of the dorsal visual regions, especially the anterior intraparietal cortex (AIP). In contrast, their analyses revealed that the visual perception of intact objects compared to scrambled version of the same objects induced specific activation of the ventral visual regions, especially in the lateral occipital cortex (LOC).

Additional behavioral studies (Aglioti et al., 1995; Króliczak et al., 2006) support the functional dissociation between the dorsal and ventral visual regions. Using illusions, such as

[4] Optic ataxia is defined as *"a disorder of visually-guided hand movements not related to motor, somatosensory, visual field or visual acuity deficits"* (p.1, Jakobson et al., 1991).

the Ebbinghaus (Aglioti et al., 1995) or the Hollow-face illusion (Króliczak et al., 2006), it has been demonstrated that the processing of visual control of actions is not always affected by the conscious perception of the environment. In other words, when the processing of visual characteristics (i.e., ventral regions) is sensitive to illusion, the processing of those characteristics for action (i.e., dorsal regions) is not. Together these findings strongly support the functional dissociation between dorsal and ventral visual regions, which process independently object properties for action and object properties for identification.

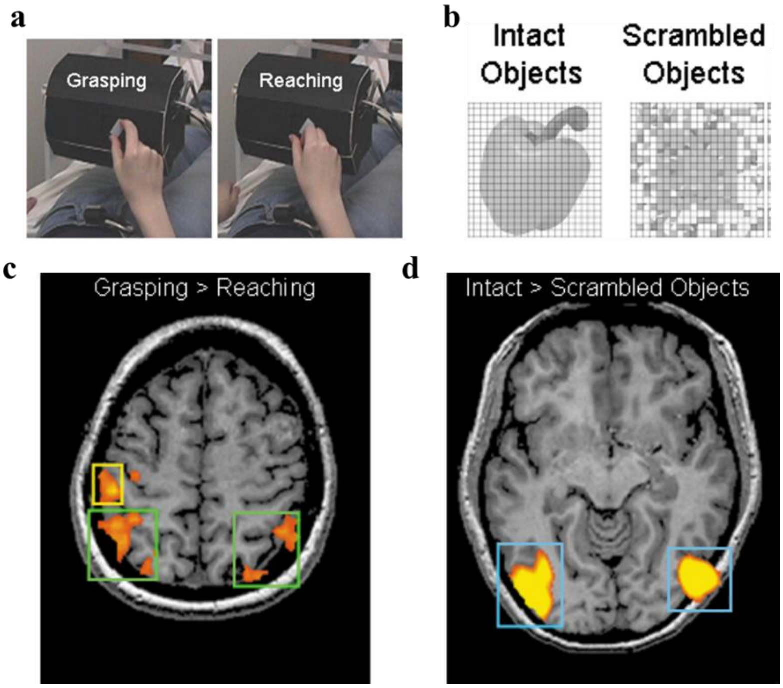

Figure 2. Experimental setting of Culham et al. (2003). **(a) Tasks.** Participants performed grasping (left) or reaching (right) movements toward the rectangular target. **(b) Example of stimuli.** Pictures of objects were either intact (left) or scrambled (right). **(c) Grasping vs. reaching brain activation.** Grasping compared to reaching condition induces specific activation of three parietal regions: postcentral sulcus of the left hemisphere, and two regions in the intraparietal cortex. **(d) Intact vs. scrambled brain activation.** Intact compared to scrambled objects induce specific activation of the bilateral lateral occipital cortex. *Figures from Culham et al. (2003).*

Intermediate synthesis

Facing such an accumulation of evidence, it is well-accepted that the visual processing of objects, in primates, is achieved by at least two separate visual pathways (Milner & Goodale, 2006) : one pathway subtending the processing of visual characteristics for assessing object identity (i.e., the “what” system) and one pathway subtending the processing of object associated actions (i.e., the “how” system”). It is important to note that the visual system of primates seems to possess specific perceptual processing serving actions (i.e., the dorsal pathway). It strongly supports the idea that perception and action are two systems intimately interconnected. Therefore, depending on the level of object processing under interest, one must consider the subtending visual pathway. In the present thesis, we will focus on the action properties associated with manipulable objects and therefore, the phenomena of interest will mainly involve the dorsal visual pathway.

2. Visuomotor neurons (canonical and mirror neurons)

On top of discoveries of two brain visual pathways in monkeys and humans, neurophysiologists, working at the cell level, identified the presence of neurons in monkeys' premotor cortex coding for both visual and motor information. These neurons were discovered using single-cell recording method, which remains the best method to prove the presence of such neurons. However, this technique, which is relatively invasive, is only rarely used in humans. Therefore, the presence of such neurons in the human brain remains unclear and stands mostly on indirect evidence. As done in the previous section, we will first discuss the discovery of visuomotor neurons in monkeys and then, we will discuss evidence that suggests the existence of such visuomotor neurons in humans.

a. Discovery in monkeys

Few years after the discovery of the two visual pathways (Mishkin et al., 1983), the premotor cortex of monkeys was shown to host multiple motor and cognitive functions (Rizzolatti et al., 2002), including action execution and understanding but also visuomotor transformations (Rizzolatti & Luppino, 2001). Using single-cell recording methods, researchers highlighted the presence of neurons in area F5 of monkeys' brain, corresponding to the ventral premotor cortex in humans, that fired when performing object-directed actions (Rizzolatti et al., 1988). Moreover, around 20% of the recorded neurons fired also when visual stimuli were presented to monkeys. These results assume the presence of visuomotor neurons in the equivalent in monkeys' brain area equivalent to the ventral premotor cortex in humans. Lately, the same researchers' team emphasized two classes of visuomotor neurons, which they named mirror and canonical neurons (Rizzolatti & Fadiga, 1998), according to the visual stimuli they fired to.

Mirror neurons were shown to fire when monkeys performed an object-directed action and when they observed another monkey or the experimenter performing the same object-directed action. Canonical neurons were shown to fire when monkeys performed an object-directed action and when they observed the same object without any subsequent action (Murata et al., 1997; Raos et al., 2006). See **Figure 3** for an example of single cell recording of canonical neurons. Consistent with these discoveries, it was suggested that mirror neurons coded the understanding of others' actions (Rizzolatti & Sinigaglia, 2010; Umilta et al., 2001) and canonical neurons coded the transformation of object visual characteristics into motor commands (Jeannerod et al., 1995). More globally, Rizzolatti and Fadiga (Rizzolatti & Fadiga, 1998) suggested that both classes of neurons are involved in representing actions, or what they called *"ideas on how to act"* (p. 89).

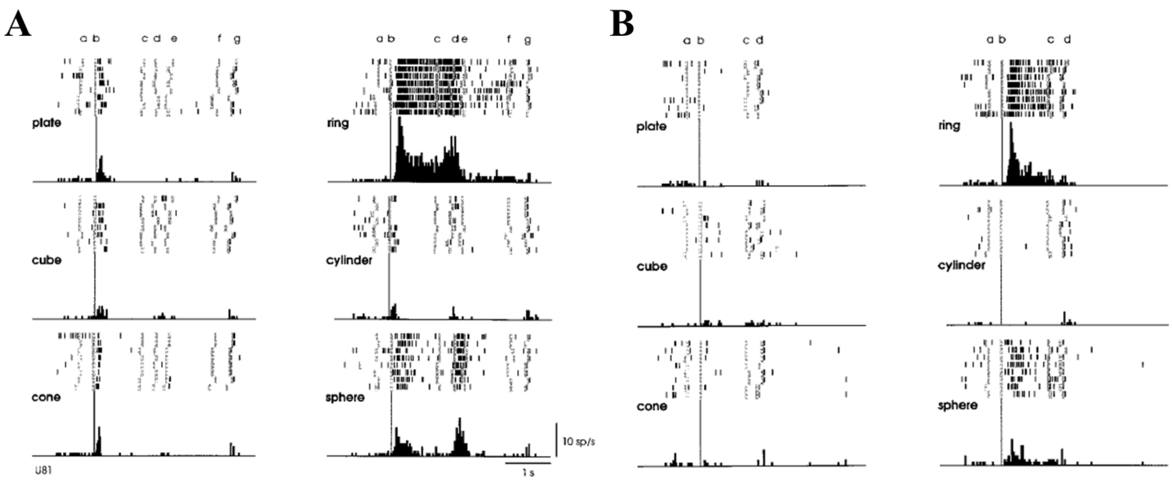

Figure 3. Neural activity (rasters and histograms) during single cell recording of canonical neurons discharging during **(A)** object-directed action (grasping) and **(B)** passive fixation of the same object without any subsequent action. The objects could be a plate, a ring, a cube, a cylinder, a cone or a sphere. Y-axis indicates the (approximate) onset of trials. *Figure from Murata et al. (1997).*

Most findings emphasize the presence of mirror and canonical neurons in the equivalent of the ventral premotor cortex in monkeys. Although it has been first highlighted that mirror and canonical neurons are present in different subdivisions of the premotor cortex of monkeys (i.e., in F5ab and F5c, Rizzolatti et al., 2002), a recent study suggested that they can be found intermixed in this area (Bonini et al., 2014). Furthermore, Bonini et al. (2014) highlighted a new category of visuomotor neurons: canonical-mirror neurons that fire to action execution, to the observation of others' actions and to the simple observation of graspable objects. They also provided evidence that visuomotor neurons respond differently depending on the location of objects in space. When responding to the simple observation of graspable objects, canonical-mirror as well as canonical neurons were sensitive to location of objects, showing higher firing rate for objects presented close to the monkeys when compared to objects presented far from them. In contrast, when responding to the observation of others' actions, canonical-mirror as well as mirror neurons were not sensitive to objects' location. The present findings suggest that while being sensitive to others' actions (i.e., *"ideas on how to act"*) regardless of the distance from the observer, visuomotor neurons represent graspable objects in a space-sensitive manner and fire only when objects are presented at short distance from the observer.

Mirror and canonical neurons have also been discovered in other brain regions, such as parietal, premotor and primary motor areas (Kilner & Lemon, 2013; Murata et al., 2000; Rizzolatti & Fadiga, 1998). In the case of canonical neurons, it has been thus suggested that they must be part of the dorsal visual pathway, transforming visual information into motor representation (Jeannerod et al., 1995). For instance, reversible inactivation of the equivalent of the premotor cortex (Fogassi et al., 2001) and the anterior intraparietal cortex (AIP, Gallese et al., 1994) in monkeys leads to similar deficits in correctly reaching and grasping objects. These results suggest that canonical neurons in both regions subserved the visual guidance of motor acts. Despite a few interesting recent refinements on the diversity of visuomotor neurons and their different properties, their role in action representation has received less interest over the past few years due to the challenge of studying them in humans. We below make a review of some evidence supporting the presence of mirror and canonical neurons in humans.

b. Generalization in humans

Studying the mirror neuron system in humans is more challenging, as the single-cell recording method raises important ethical issues. Therefore, the existence of visuomotor neurons in humans comes mostly from indirect evidence using techniques that assess the functioning of a population of neurons (i.e., EEG, MEG, fMRI, PET) instead of single neuron activity (Fogassi & Simone, 2013). Furthermore, as mirror and canonical neurons have been shown to fire according to distinct visual stimuli (Rizzolatti & Fadiga, 1998), the evidence in humans is associated with distinct literatures focusing on perception of others' actions on the one hand and perception of objects on the other hand. We will therefore discuss both literatures separately. Then, we will discuss the only direct evidence in humans that demonstrates the existence of mirror (not canonical) neurons, although not in the typical "*mirror neuron regions*" described in monkeys (Keysers & Gazzola, 2010; Mukamel et al., 2010). Finally, we will mention recent critics recommending to be cautious when interpreting studies on visuomotor neurons, especially when considering their functional mappings.

Generalization of mirror neurons in humans

The mirror neuron literature is richer than the literature on canonical neurons. The fact is that mirror neuron discovery has led to a great enthusiasm in the researcher community, which has straightly investigated this topic after this discovery. One possible reason is that the existence of such neurons was thought to subtend many human social abilities, such as imitation, learning and empathy (Fabbri-destro & Rizzolatti, 2008) and therefore, having important clinical implications, such as in autistic spectrum syndrome (Cattaneo & Rizzolatti, 2009).

Investigations of mirror neurons were thus conducted using many different brain imaging techniques, such as positron emission tomography or functional magnetic resonance imagery (Molenberghs et al., 2012, for a meta-analysis on more than 100 fMRI studies). Most imaging studies have highlighted that mirror neurons in humans would be localized in two main brain areas: the inferior frontal gyrus (IFG) and the inferior parietal lobule (IPL). The mirror neuron system in humans was shown to respond when observing for understanding others' actions (Grafton et al., 1996; Rizzolatti et al., 1996) or for imitation of others' actions (Decety et al., 1997). More specific investigations of the ventral premotor cortex of humans highlighted a somatotopic organization of the brain responses to the observation of others' actions (Gazzola et al., 2007; Pelphrey et al., 2005; Sakreida et al., 2005; Wheaton et al., 2004). In parallel, it has been suggested that human mirror neuron regions were involved in the execution of a specific internal simulation to improve the understanding of others' actions (Calvo-merino et al., 2005, 2006). Together, these results are generally taken as a proof that human brain areas equivalent to those who host mirror neurons in monkeys subtend similar functions.

Generalization of canonical neurons in humans

The literature regarding canonical neuron is sparser than the literature on mirror neurons. Therefore, the existence of canonical neurons in humans has not been addressed directly. The involvement of the frontal lobe while retrieving information about objects originates mostly from another field of literature: the semantic categorization of visual stimuli (Gainotti et al., 1995). To understand how researchers came to ask which brain areas are activated when observing graspable objects, we will briefly touch this field of the literature (*see also section III. 2. b. Illustration n°2: The conceptual knowledge, for another theoretical use of the following evidence*).

After the observation of many patient studies with deficits in knowledge of specific object categories, often opposing living and non-living things (Shallice, 1988; Warrington & McCarthy, 1987; Warrington & Shallice, 1984), it has been suggested that perceptual and functional properties have different weights in the representation of object categories. Moreover, it is assumed that these properties were subtended by specific brain areas (De Renzi & Lucchelli, 1994). Therefore, deficits in knowledge of specific object categories would be associated with brain lesions that subtend the most significant properties of the category (e.g., motor attributes for tools). Indeed, Gainotti et al. (1995) showed that deficits in manufactured object categorization were nearly always associated with lesions in the fronto-parietal areas, which subtend the processing of somatosensory and motor functions. Similar to the inactivation consequences of the parietal cortex in monkeys (Murata et al., 2000), patients with lesions of the posterior parietal cortex demonstrate difficulty in correctly grasping and using tools (De Renzi & Lucchelli, 1988). Together, these findings highlight that the premotor and parietal cortices, corresponding to the canonical neuron regions in monkeys, process properties associated with manufactured objects (i.e., sensorimotor attributes).

The mapping of premotor and parietal regions with manufactured object categorization in humans was at the initiative of several neuroimaging studies investigating the brain correlates of the processing of manufactured objects and tools (Chao & Martin, 2000; Grafton et al., 1997; Grèzes et al., 2003; Grèzes & Decety, 2002; Martin et al., 1996; Perani et al., 1995). These studies highlighted that the observation and recognition of manufactured objects compared to other categories (e.g., animals, face, house) induced specific activations of the left dorsal premotor cortex (Perani et al., 1995), the left ventral premotor cortex (Grafton et al., 1997), the inferior frontal gyrus (Grèzes & Decety, 2002), and the inferior and intraparietal cortices (Grèzes et al., 2003; Grèzes & Decety, 2002). A recent meta-analysis on 70 studies (Ishibashi et al., 2016) supports the involvement of the left premotor and parietal cortices for tool recognition, tool naming and tool action-retrieval. Together, these results are all empirical arguments in favor of the idea that human brain areas equivalent to those who host canonical neurons in monkeys subtend similar functions.

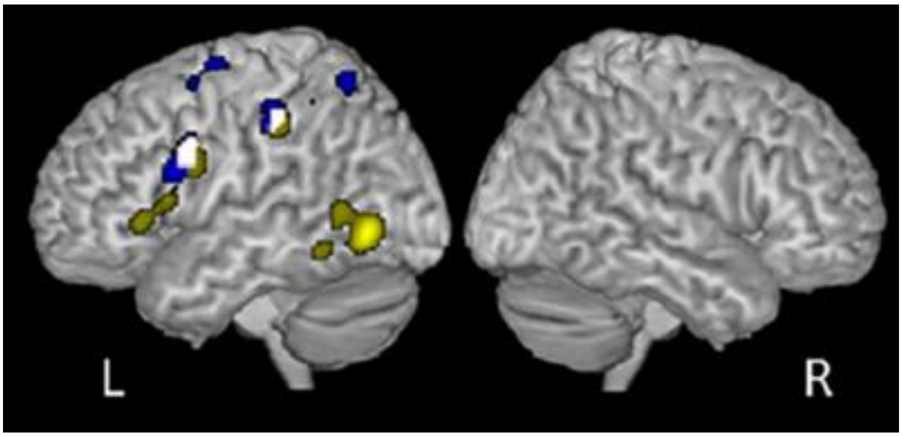

Figure 4. In yellow, significant activated regions for tool identification (recognition and naming). In blue, significant activated regions for tool action-retrieval. In white, overlapping activated regions. *Figure from Ishibashi et al. (2016).*

The only proof of mirror neurons in humans and some critics

The accumulation of neuroimaging evidence showing that the activity of human brain areas - equivalent to those who host visuomotor neurons in monkeys - correlates with tasks involving the understanding of others' actions or the processing of object motor properties had led more than one to claim the existence of visuomotor neurons in humans. Nonetheless, as mentioned at first, neuroimaging techniques can only assess the activity of a population of neurons and not the activity of single neurons (Fogassi & Simone, 2013). Therefore, recordings in the mentioned studies could result from the activity of other categories of neurons (Dinstein et al., 2008). It is only recently that a single-cell recording study in humans (i.e., patients with pharmacologically intractable epilepsy) has demonstrated the existence of mirror neurons (not canonical neurons), though not in the typical '*mirror neuron regions*' (Mukamel et al., 2010), but in the supplementary motor area (SMA) and the hippocampus. These last results clarify two aspects about mirror neurons in humans: (1) humans do possess mirror neurons and (2) mirror neurons are certainly not confined to the well-known *‘mirror neuron regions’* (Keysers & Gazzola, 2010).

The functional mapping of visuomotor neurons in monkeys and in humans is, however, subject to multiple critics (Hickok, 2010; Steinhorst & Funke, 2014). For example, using visuomotor neuron responses as a measure of the processing of others’ actions or object motor attributes in monkeys is considered as a reductionist approach (Steinhorst & Funke, 2014). In humans, it is clear that some brain responses are associated with the understanding of other’s actions and the processing of object motor properties. It has also been demonstrated that humans do possess at least mirror neurons. However, mapping those two discoveries together is speculative (Hickok, 2010). Therefore, the current debate in the literature is not related to the existence of mirror neurons in humans *per se*, but rather to the functional properties that the researcher community gave to them.

Intermediate synthesis

Despite the recent critics on the functional mapping of visuomotor neurons, this discovery has served to broaden the knowledge around the neural correlates associated with the understanding of others’ actions and the processing of object motor attributes. If the functional mapping of canonical and mirror neurons is being confirmed, this will suggest that depending on the function of interest, one will need to consider the corresponding visuomotor neurons. In the case of the present thesis, we will focus on the action properties associated with manipulable objects and therefore, the phenomena of interest should be associated with canonical neuron activity.

Synthesis on neurophysiological approaches

Overall, the neurophysiological approaches suggest that both perception and action processing at the brain level are sometimes difficult to distinguish. Evidence from the literature on the two visual pathways and visuomotor neurons emphasized that perception and action share several brain correlates. In a sense, evidence in monkeys and generalization to humans suggest that we are phylogenetically and biologically organized for processing perception and action in a similar way. Additionally, we can consider both neurophysiological approaches as complementary aspects. The two-visual pathway framework describes the brain functioning for transforming visual to motor information at the level of neuron networks and the visuomotor neuron framework describing similar functions at the single-neuron level. Furthermore, when one approach emphasized the role of the parietal cortex in transforming object visual characteristics to motor properties (i.e., the two visual pathways), the other stressed the role of the premotor cortex in representing motor properties. Therefore, according to these discoveries, when one perceives graspable objects, it is natural to assume that its visual properties for action will be processed by the dorsal visual pathway (the "How" system), especially in the parietal cortex (i.e., anterior intraparietal cortex) and that, when specified, these properties will be transmitted to the premotor cortex. It is also legitimate to assume that in the premotor cortex, canonical neurons should be in charge of representing the selected action properties of the object. As an example, perceiving a mug will induce transformation of its visual features into action properties in the parietal cortex (e.g., matching of the mug size with the appropriate grasp aperture), and the specified action properties will be sent to the premotor cortex, allowing the perceiver to represent the typical actions associated with the mug.

III. Grounded cognition approaches

Grounded approaches assume that perception and action are closely interconnected with cognition. Grounded approaches include a considerable number of accounts that are partially diverging, often because they focus on describing a specific cognitive function. Therefore, we will discuss below grounded approaches in two separate sections. In the first section, we will present an existing classification of grounded approaches, although without being exhaustive. This section aims to provide the reader with a short background about grounded approaches without entering too deeply into the actual debates that are beyond the scope of the present thesis. The second section will be used to illustrate two representational approaches that are highly related to the present thesis work. First, we will discuss an approach that focuses on a specific perceptual function: ***space perception***. Second, we will discuss an approach that focuses on the role of simulation in global perceptual and cognitive processing, and more specifically in the organization of ***conceptual knowledge***.

1. The multiple grounded accounts

Embodied, embedded, and situated accounts of cognition have different names because they emphasize on different aspects of the interconnection between perception, action and cognition, such as the role of the body or the internal cognitive simulation (Barsalou, 2008). Barsalou (2008) brought together all these representational approaches under the larger expression: "Grounded Cognition" and draw a clear picture (see **Figure 5**) of the different aspects that are under this appellation (Barsalou, 2020). Barsalou (2020) summarized the common view of cognition from a grounded perspective, that is cognition emerges from the *"interactions between multiple cognitive processes and the sensory modalities, the body, and the physical and social environments"* (p.2, Barsalou, 2020). Each grounded cognition approach would focus on the role of one or multiple of these aspects in cognition. We will therefore use the term "grounded cognition" as defined by Barsalou (2008, 2020) to refer to all these representational approaches.

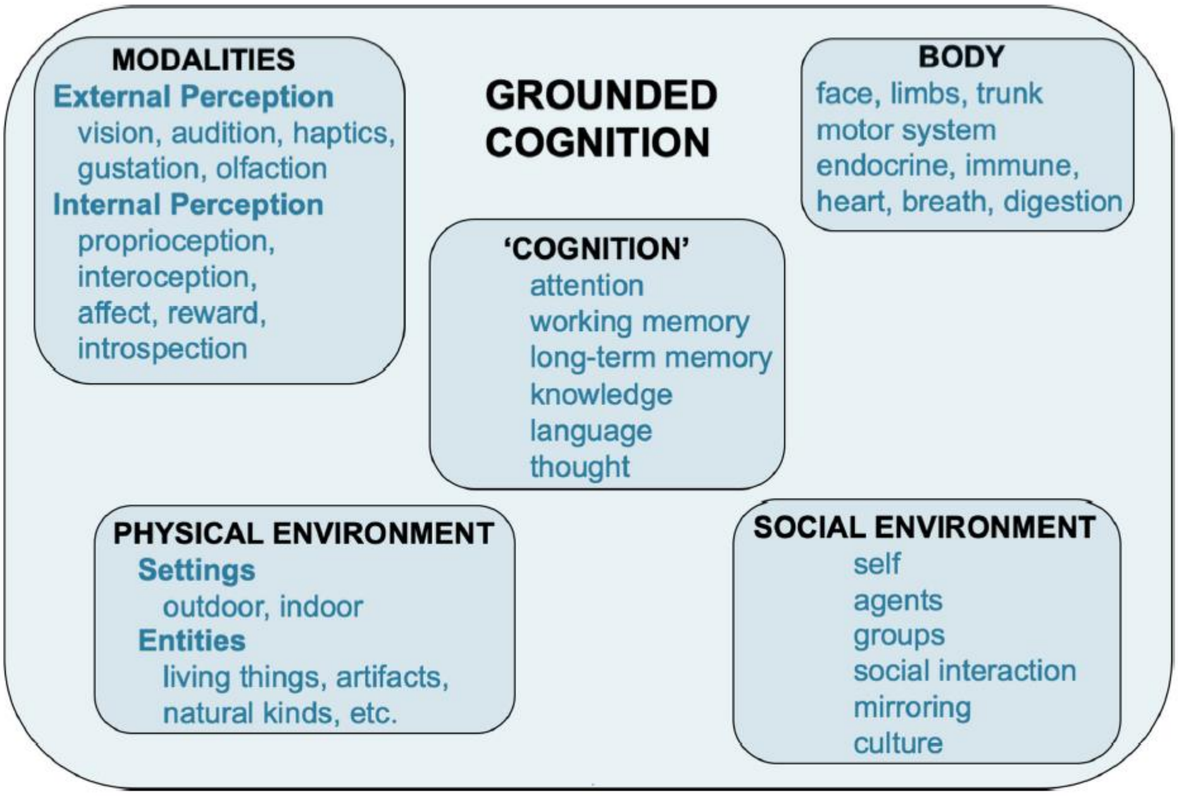

Figure 5. Domains of grounded cognition. Cognition emerges from grounding classic cognitive mechanisms in the perceptual modalities, body, physical environment, and social environment. *Figure and description from Barsalou (2020).*

Hence, grounded cognition theorists often assume that there are systematic connections between perception, action and cognition (Barsalou, 2020; Gentsch et al., 2016). According to the grounded cognition approach, cognition is therefore conceptualized as being rooted in action and perception experiences. It means that internal cognitive representations draw on sensorimotor processes occurring during life experiences. Since perception and action have been integrated in the conceptualization of cognition, many accounts have emerged (Gentsch et al., 2016). These accounts are partially diverging, often because they focus on describing a specific cognitive function (Barsalou, 2008, 2020; Gentsch et al., 2016; Wilson, 2002).

Therefore, when looking for the understanding of the key concepts of grounded cognition, one might feel a little confused. The huge number of concepts addressed by grounded theorists indeed leads to important misunderstandings (Barsalou, 2008; Wilson, 2002). Some authors even argued for a need for improvements in empirical evidence or a coherent theoretical framework (Ostarek & Huettig, 2019) and more seriously, important skepticism flies around grounded cognition (Goldinger et al., 2016).

To clarify the grounded cognition accounts, Gentsch et al. (2016) proposed a relevant framework for dealing with the multiple approaches. They suggested to classify approaches depending on the function (i.e., motor control, conceptual abilities, perception) the theories were primarily developed for, and by regarding how these theories conceived ability acquisition and constitution (Weber & Vosgerau, 2016). When considering the question of acquisition and constitution of abilities, the critical question is not to ask whether action and perception are related but how. Considering A and B as two abilities, the term "acquisition" applied to grounded cognition relates to the necessity of having ability A for acquiring ability B. The classical experience that illustrates an acquisition of ability came from Held and Hein (1963) who highlighted that self-generated movements (A) are necessary for developing depth perception (B). They harnessed two groups of kittens to a carousel. The first group actively moved around the carousel, while the other was driven by the first and thus passively moving. Both groups had the same amount of visual experiences and the same amount of movements, but a different amount of action-perception coupling. Results showed that passively moving kittens were not able to integrate visual experiences with movements causing deficits in visual perception, and especially depth perception. In summary, the ability to actively move (A) is necessary to acquire the ability to perceive depth (B). Thus, the term "acquisition" relates to the way action and perception become interconnected. In contrast, the term "constitution" applied to grounded cognition relates to the necessity of having ability A for acquiring ability B, and on how important is to maintain A for maintaining B. With regard to the study of Held and Hein (1963), it could be viewed as asking whether depth perception remains after losing self-movements. Every grounded theory has a similar view when considering ability acquisition but describes different constitutive relationships between action and perception. According to Weber and Vosgerau (2016), three types of relations are associated with the existing grounded cognition accounts, the fully constitutive relations (if A is lost, B is lost as well), the partially constitutive relations (if A is lost, B is partially impaired) and the non-constitutive relations (if A is lost, B is conserved).

Thereby, Gentsch et al. (2016) identified three main grounded action theories: (1) the common coding theories, (2) the internal models' theories and (3) the simulation theories. The common coding theories were primarily developed with a focus on motor control abilities and they usually claim for non-constitutive relation between action and perception (i.e., kitten lose the ability to move, but preserved depth perception). The internal model theories were primarily developed with a focus on either motor control abilities or visual perception and they claim respectively for non-constitutive or partially constitutive relation between action and perception (i.e., kitten lose the ability to move, and also partially the ability to perceive depth). The simulation theories were more heterogenous when considering their primarily focus (i.e., perception of others' actions or others' mental states, motor imagery, conceptual abilities, etc.) but all claim for a fully constitutive relation between action and perception (i.e., kitten lose the ability to move, and the ability to perceive depth). Although this lack of consistency in grounded cognition leads to important critics of the theory (Goldinger et al., 2016; Ostarek & Huettig, 2019), it is not often discussed. One reason might be related to the fact that researchers studied specific aspects of grounding that did not directly address the question, but instead they addressed more specific questions about aspects they were investigating.

In the present thesis, we will focus on a specific aspect of grounding (i.e., action representation in manipulable object perception). We will thus not directly address how constitutive the relationship between action and perception is. However, we will use concepts coming from multiple grounded accounts, and particularly from accounts that were primarily developed for investigating perception. Particularly, the present thesis will focus on the influence of space on the activation of motor properties associated with objects. The next section will illustrate grounded approaches that emphasize on the role of sensorimotor representations in (1) **space perception** (Previc, 1990, 1998) and the role of (2) **simulation mechanisms** in conceptual knowledge (Barsalou, 1999, 2008).

2. Two illustrations of grounded cognition approaches

In the context of the present thesis, we will use concepts from grounded accounts that were primarily developed for investigating perception. Particularly, the present thesis will take roots in grounded conceptualization of space perception and simulation of properties about objects. In this sense, we felt it was important to illustrate this section with grounded approaches that emphasize the role of sensorimotor representations in (1) **space perception** (Previc, 1990, 1998) and the role of (2) **simulation mechanisms** in conceptual knowledge (Barsalou, 1999, 2008).

a. Grounding space perception

Within grounded cognition approaches, researchers gave particular interest in the way we perceive the space around us. It is why space perception has been widely investigated over these past years with studies ranging from neurophysiological investigations in monkeys to behavioral, neuropsychological and neuroimaging investigations in humans. The accumulated evidence on space perception have led to claim for the perception of two functionally distinct parts of space: peripersonal (i.e., near the body) and extrapersonal (i.e., far from the body) spaces (Previc, 1990, 1998). Previc (1998) even argued for the existence of three functional distinct extrapersonal spaces (i.e., focal, action and ambient extrapersonal), but all were described to be outside observers' action possibilities. In contrast, peripersonal space was described to contain the space around the observer, that includes direct action possibilities. We will conserve the distinction between peripersonal and extrapersonal spaces. The following discussion will specifically emphasize on the functional aspects of peripersonal space, but by comparison it is possible to infer the functional aspects of extrapersonal space.

The functional distinction between peripersonal and extrapersonal spaces was first supported by neurophysiological evidence coming from monkeys (Rizzolatti et al., 1981). For example, the study demonstrated the existence of different categories of neurons, in the frontal lobe of monkeys, firing differently according to the distance between the monkey and the stimuli (Maravita & Iriki, 2004). The distinction was further extended to humans by means of neuropsychological observations made on lesioned patients (Cowey et al., 1994; Halligan & Marshall, 1991). Lesioned patient studies showed either stronger left neglect symptoms[5] in peripersonal compared to extrapersonal space (Halligan & Marshall, 1991) or the reversed pattern (Cowey et al., 1994), supporting the functional distinction between both spaces. Recent grounded accounts of space perception still claim for this functional distinction and further assume that people experience the world as a function of their action constraints (Morgado & Palluel-Germain, 2015; Proffitt & Linkenauger, 2013). Morgado and Palluel-Germain (2015) defined action constraints as all the characteristics of the organism, the task or the environment influencing the processing of space properties. Barsalou (2008) made a similar description, suggesting that *"space is shaped by the body, the body's relation to the environment, and the*

[5] *"Neglect is behaviorally defined as a deficit in processing or responding to sensory stimuli in the contralateral hemispace, a part of the own body, the part of an imagined scene, or may include the failure to act with the contralesional limbs despite intact motor functions"* (p.1, Kerkhoff, 2001)

body's potential for action" (p. 625). We below argue about how space perception is shaped according to the three aspects mentioned by Barsalou (2008).

Space perception is shaped by the body

First, it is argued that space perception is shaped by the body's characteristics, such as its morphology (e.g., size), physiology (e.g., resources) or behavioral skills (e.g., locomotion), (see Morgado & Palluel-Germain, 2015, for a review on Action Constraints Theories). For an example of morphology constraints, it has been shown that peripersonal space representation shares a systematic relation with the arm length of participants (Longo & Lourenco, 2007), longer arm lengths being associated with larger peripersonal spaces. It suggests distinct space perception for each individual according to their morphology. Recent advances showed flexibility in the representation of the peripersonal space – the use of a tool with a long handle extending its representation (Bourgeois et al., 2014; Canzoneri et al., 2013; Quesque et al., 2016). Additionally, an extension of neglect symptoms has been reported in the extrapersonal space of patients neglecting the left portion of the peripersonal space when using tools (Berti & Frassinetti, 2000). These results are interpreted as an integration of the tool to the body's representation (also referred as body schema[6]) of individuals (see Martel et al., 2016, for an extended review on tool-use and body schema association). Therefore, authors assume that the body schema constitutes the architecture of peripersonal space (Cardinali et al., 2009).

[6] Body Schema is defined as *"the body representation used by the brain to control our movements"* (Martel et al., 2016).

Space perception is shaped by the body's relation to the environment

Second, it is argued that space perception is shaped by the body's relation to the environment and constraints. For example, space representation would be influenced by the presence of obstacles or by environmental structures (e.g., topography), but especially by the relation of these constraints with the potential displacements of the body in space (Morgado & Palluel-Germain, 2015). It has been shown that when participants had to estimate the distance of an object in front of them, their estimations were influenced by the width of a transparent obstacle placed between them and the object (Morgado et al., 2013), larger widths producing greater distance estimations. These results showed that external sensorimotor representations are involved in the representation of space. Other advances showed that information related to internal sensorimotor representations is also involved when representing space, such as weight (Lourenco & Longo, 2009) or energy consumption (White et al., 2013). Together, these results are interpreted as an integration of external and internal sensorimotor information in the representation of peripersonal space. Such information would help the individual to integrate the external (i.e., the environment) and internal (i.e., energy) constraints to evaluate the action efforts and risks (Morgado & Palluel-Germain, 2015).

Space perception is shaped by the body's potential for action

Third, it is argued that space perception is shaped by the body's potential for action. For example, it is suggested that space representation is influenced by the possibility to perform an action or by tool properties (Morgado & Palluel-Germain, 2015). For example, it has been shown that when participants intend to reach a target with a real tool (extending its reaching abilities), targets beyond reach were estimated closer than when intend to reach the target without a tool (Witt et al., 2005). Similar effect was found when participants intended to reach the target with an imaginary tool (Witt & Proffitt, 2008). Authors suggested that the representation of space is influenced by means of action simulation. Instead of simulating the actual possibilities to reach the target, individuals would simulate the further action with the tool, increasing their reaching abilities. Recent advances in the literature support the role of the body's potential for action in space representation by showing that the actual possibility to move is, somehow, necessary to trigger action information in peripersonal space (Iachini et al., 2014; Toussaint et al., 2020, 2021). Together, these results suggest that the simulation of the sensorimotor consequences of an action actively participates in the representation of peripersonal space, and thus in space perception. Such results have led researchers to argue for a functional representation of peripersonal space in terms of action possibilities. Peripersonal space would thus be a "*multisensory interface for body-object interaction*" (Brozzoli et al., 2012).

Conclusion

To conclude, peripersonal and extrapersonal spaces correspond to two functionally distinct regions of the space around an individual. Peripersonal space representation is specified by the representation people have of their body; the representation of constraints to which the organism must pay attention and the representation of simulated actions that individuals can perform on objects that are within reach. Recent investigations have also stressed the implication of peripersonal space in the regulation of our social interactions (Gigliotti et al., 2019). In contrast, the representation of extrapersonal space would be less influenced by all these constraints.

Grounding mechanisms underlying space perception are still widely investigated in the literature. Experimental investigations mainly revolve around two paradigms: (1) the multimodal integration and (2) the reachability estimation paradigms. The multimodal integration paradigm is mainly used to study the integration of multiple sensory inputs in peripersonal space, such as visuo-tactile integration (Làdavas et al., 1998) or audio-tactile integration (Maister et al., 2015). While participants receive a sensorial stimulation (e.g., visual), researchers deliver a tactile stimulation on participants' hand, either in synchrony or asynchrony with the first stimulation. Participants are then asked to inform researchers when they spot the tactile stimulation. Usually, cross-modal integration occurs in peripersonal space under the synchrony condition and emphasizes the grounding integration mechanisms of the cognitive system in peripersonal space. In contrast, the reachability estimation paradigm takes advantage of the functional distinction between peripersonal and extrapersonal spaces for evaluating the involvement of action representations in the processing of several categories of stimuli. For example, researchers studied the involvement of action representations during manipulable object perception (Costantini et al., 2010, 2011; Ferri et al., 2011), by comparing the processing of those stimuli when presented in peripersonal vs. extrapersonal spaces (see **Figure 6**).

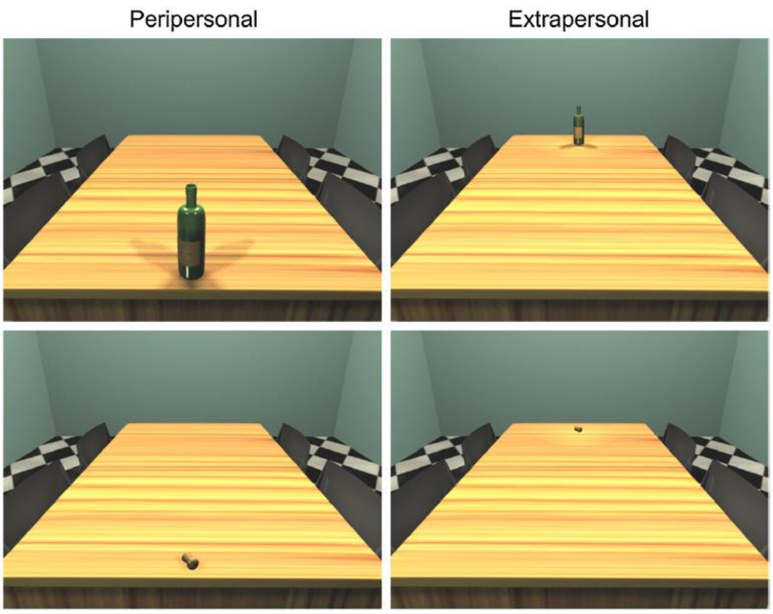

Figure 6. Example of an experimental paradigm that takes advantage of the functional distinction between peripersonal space and extrapersonal space for assessing object associated motor information (i.e., clench vs. pinch gestures). *Figure from Ferri et al.* (2011).

In the case of the present thesis, we will focus on the action properties associated with manipulable objects and therefore, we will take advantage of the functional dissociation between both spaces by using a reachability estimation paradigm (*see* **Figure 6**. *for an example of task taking advantage of the functional dissociation*). According to the functional aspects attributed to both spaces, perceiving manipulable objects in the peripersonal space should trigger motor information representative of the interrelation between the body and the object-associated actions. For example, perceiving a mug would induce activation of the representation of potential actions that we can have with it (e.g., simulation of the grasping gestures) but only when presented in peripersonal space.

b. Grounding conceptual knowledge

At the end of the 90's, Barsalou (1999) proposed a novel approach for the storage of conceptual knowledge in the brain in opposition to the traditional amodal accounts. Barsalou developed his theory to account for conceptual representations in long-term knowledge and called it "The Perceptual Symbol System" (PSS). PSS assumed that conceptual knowledge is grounded in our perceptual and motor experiences (i.e., perceptual symbols). Thus, the theory supports a modal conceptualization of cognition which emphasizes on the role of sensorimotor information in representations (see **Figure 7**). Accordingly, perception, action and cognition would share the same representational system.

For Barsalou (1999), perceptual symbols are (1) sensorimotor neural representations, (2) partial representations of life experiences, (3) multimodal and, (4) interconnected and organized in a simulator. Perceptual symbols would be in charge of representing actual experiences and later, long-term knowledge acquired through these experiences. Barsalou (1999) postulated that the neural representations of perceptual symbols would be constituted by the recordings of sensorimotor information collected during life experiences. Recent grounded accounts still claim for the involvement of sensorimotor information in neural representations of conceptual knowledge (Barsalou, 2015; Brunel et al., 2015; Moseley et al., 2015). Such proposals are rooted in two kinds of empirical supports.

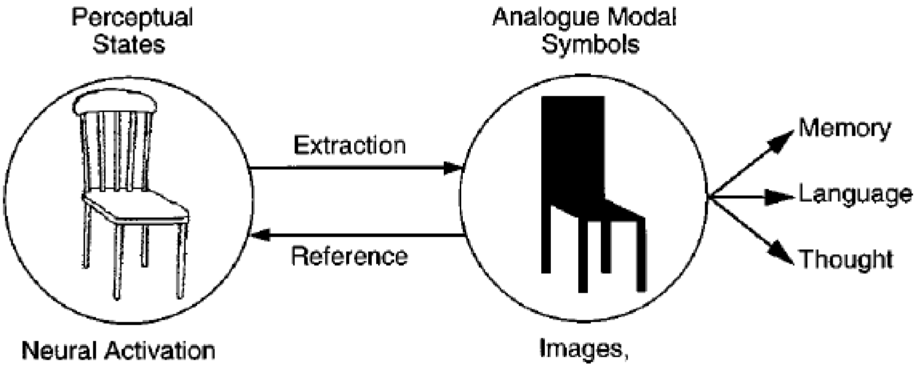

Figure 7. Basic assumption underlying perceptual symbol systems. Subsets of perceptual states in sensorimotor systems are extracted and stored in long-term knowledge to function as symbols in support of cognitive functions (e.g., memory, language, thought). As a result, the internal structure of these symbols is modal, and they are analogically related to the perceptual states that produced them. *Figure and description from Barsalou* (1999).

Sensorimotor information is involved in conceptual processing

Some empirical supports concern the involvement of sensorimotor brain regions while processing conceptual knowledge (Moseley et al., 2015). There is indeed a widely documented literature on the involvement of brain regions subtending the processing of sensory and motor information while dealing with concepts (Fernandino et al., 2015; Goldberg et al., 2006). Additionally, a somatotopic organization of the motor brain responses (i.e., in the premotor cortex) while assessing action properties of concepts has been highlighted, using words and sentences (Hauk et al., 2004; Pulvermüller et al., 2005; Shtyrov et al., 2014). For example, the words “lick”, “pick”, “kick” activate the premotor regions associated with facial, hand and foot movements, respectively. Together, these results support the idea that sensorimotor brain regions, activated when experiencing (i.e., perceiving, touching, etc.) elements of the world, are re-activated when one processes the concept associated with these experiences.

Functional contribution of sensorimotor information to conceptual processing

Other empirical supports focus on the necessity of assessing sensorimotor information while processing conceptual knowledge. Namely, it questions the functional contribution of sensorimotor information to conceptual processing. Moseley et al. (2015) suggested the existence of at least three types of empirical arguments in support of the functional role of sensorimotor information in conceptual knowledge. First, they emphasized on studies evaluating the velocity of sensorimotor activations while processing concepts (Pulvermüller et al., 2005; Shtyrov et al., 2014). For example, Shtyrov et al. (2014) reported somatotopic activations of motor brain areas while processing action verbs, as early as 80 ms after the beginning of the oral presentation of the verbs. Authors interpreted the results as an automatic implication of sensorimotor information in the conceptual processing of the verbs (Moseley et al., 2015; Shtyrov et al., 2014) – the velocity of the activation suggesting that no additional processing (e.g., conscious representation or epiphenomenon activation) could have occurred (Moseley et al., 2015). Together, these results suggest that sensorimotor information is an integral part of conceptual representations, and might not reflect other processes. Second, they focused on studies evaluating the mutual influences of sensorimotor and conceptual processing (Gentilucci & Gangitano, 1998; Glenberg & Kaschak, 2002; Pulvermüller et al., 2005). For example, Pulvermüller et al. (2005) reported that Transcranial Magnetic Stimulation (TMS) applied over motor areas facilitated lexical decision judgments on words in a somatotopic manner. Arm words (e.g., pick), but not leg words (e.g., kick), were categorized faster when TMS was applied on arm related motor regions compared to pseudowords. The same pattern was observed for leg words when TMS was applied over leg related motor regions. The reverse influence pattern was observed by showing that conceptual knowledge, evoked by words, modulated kinematics of reaching movements (Gentilucci & Gangitano, 1998). These results suggest that sensorimotor and conceptual processing interact with each other. Finally, they focused on studies evaluating the influence of impaired sensorimotor processing on conceptual knowledge. There are effectively, multiple patient studies highlighting that deficits in knowledge of specific concept categories are associated with brain lesions that subtend the relevant sensorimotor properties of the category (Gainotti et al., 1995; Warrington & Shallice, 1984). These final arguments are the least questionable and constitute the stronger argument supporting the functional contribution of sensorimotor information in conceptual knowledge.

Multimodal, interconnected and organized sensorimotor representations

As an explanation of the integration of sensorimotor information in conceptual knowledge (and neural representation), Barsalou (1999) postulated that selective attention acts as a filter choosing relevant sensorimotor information in the environment that produces the actual perceptual state and further storing this information in long-term knowledge. Partial information coming from different sources of information (e.g., visual, auditory, tactile, proprioceptive and introspection) would therefore be selected and integrated for producing internal representations (i.e., perceptual symbols). The actual perception of the world and the resulting long-term knowledge would correspond to these partial representations.

To account for the integration of the distinct sources of information into a unified perception and representation of the world, it has been suggested that these representations would be associated in a joint neural representation by means of Hebbian learning[7] (Moseley et al., 2015; Pulvermüller, 1999) or associative brain areas (Barsalou, 1999). The

[7] Hebbian' law: *« Cells that fire together, wire together"* (p.95, Moseley et al., 2015).

representations of coexistent and successive events (i.e., perceptual symbol) would be organized in a simulator, according to their spatial and temporal relationships, in order to form a continuous and dynamic representation of the world. As an example, when one is drinking coffee, the warmth of the coffee mug, the coffee smell, the room around the actor, the way the actor is holding the mug, etc., are all constituted of multiple pieces of sensorimotor information that are partially processed. The integration of all these pieces of information constitutes the conscious perceptual event of “drinking a coffee” and will be further integrated in the long-term representation of drinking coffee. Each time one drinks a coffee, a new perceptual event and representation is integrated with previous representations of the category “drink a coffee”. This description refers to what is called *“situated simulations”* (Barsalou, 1999, 2015). The term *“situated”* refers to the fact that each simulation occurs in a specific context and has for consequence to adjust the weight – or importance – that is given to each context element in representing the underlying category. The collection of representations is the core of simulation, the most fundamental mechanism for cognition according to Barsalou (2015). Simulation would re-enact specific knowledge that is likely to happen in the current context, what is called the *“pattern completion inference”* (Barsalou, 2015). Accordingly, next time one will take a coffee – at the sight of the mug – simulation mechanisms would re-enact the warmth of the mug, the smell of the coffee and how the mug should be held for drinking.

Grounding mechanisms underlying conceptual knowledge are still widely investigated in the literature. Even though the involvement of sensorimotor information in the representations of actions and manipulable objects makes consensus in the literature (Borghi & Riggio, 2015; Buxbaum & Kalénine, 2010; Ellis & Tucker, 2000), such involvement in the representation of abstract concepts remains under debates (Brunel et al., 2015; Moseley et al., 2015).

Conclusion

To conclude, the involvement and the functional role of sensorimotor information in the emergence of perceptual states and in the representation of conceptual knowledge is well-accepted. Conceptual knowledge must be represented by the perceptual and motor experiences that occurred during the interaction with the elements the concepts refer to. When the elements are re-encountered, simulation mechanisms will make inference about the properties associated with these elements based on their representation. The re-enactment of sensorimotor properties associated with concepts has been usually studied using verbal context. Nevertheless, several studies have shown that perceptual stimuli, such as objects or tools, re-activated the brain regions associated with their sensorimotor properties (Chao & Martin, 2000; Grafton et al., 1997; Grèzes et al., 2003; Grèzes & Decety, 2002; Ishibashi et al., 2016; Martin et al., 1996; Perani et al., 1995), suggesting that inference also occurs in non-verbal contexts. In the case of the present thesis, we will focus on the action properties associated with manipulable objects. According to the grounded theories of conceptual knowledge, the perception of manipulable objects should trigger sensorimotor information encountered when we have interacted with them. For example, perceiving a mug should re-activate representations of the way we typically interact with mugs (i.e., the way we grasp and use them).

Synthesis on grounded cognition approaches

In the first part of the present section, we draw a non-exhaustive picture of the multiple grounded approaches of cognition. The existence of multiple grounded approaches is mostly due to the diversity of functions they focus on (e.g., space perception, conceptual knowledge). Their diversity is also due to the function (i.e., motor control, conceptual abilities, perception) the theories were primarily developed for. The multiple approaches are often inconsistent while considering the constitution of the relation between action and perception but overall, they assume that both are intimately connected and are constitutive parts of cognitive representations. Thus, they support a modal conceptualization of cognition which emphasizes on the role of sensorimotor information in representations, including *"the perceptual modalities, the body, the physical and social environments"* (p.2, Barsalou, 2020).

In the second part of the present section, we have illustrated grounded approaches that focus on the role of sensorimotor representations in (1) **space perception** and (2) the role of **simulation mechanisms** in conceptual knowledge. We emphasized that space perception is subdivided into two functionally distinct regions of the space around an individual according to action constraints – the peripersonal and extrapersonal spaces – the peripersonal space being shaped by the body, the body's relation to the environment and the body's potential for actions. These discoveries strongly support interconnections between perception, action and cognition. We finally argued that the functional distinction between both spaces constitutes a great opportunity, that one can take advantage of, for studying the interconnections between perception and action, by comparing the processing of classes of stimuli in peripersonal and extrapersonal spaces.

From a more theoretical point of view, we discussed how conceptual knowledge is grounded in perceptual and motor experiences. We argued that representations of long-term conceptual knowledge are shaped by the sensorimotor information that occurred during the perceptual states which have produced them. We further explained that when one re-encounters previous situation, simulation mechanisms will re-enact the stored sensorimotor information, making inference about the sensorimotor properties that should be encountered in this situation. Therefore, according to these grounded approaches, when people perceive manipulable objects, it is natural to assume that the system will process them and re-enact the way people typically interact with them. It is also legitimate to assume that this information should be triggered according to the body's potential for actions, that is in the peripersonal space.

Global synthesis

Overall, the most recent approaches of perception assume that perception is closely interconnected with action. Perception is seen as an active phenomenon that guides actions and that is modulated by actions in the environment. Organisms would perceive their environment according to the potential actions it offers (i.e., affordances). Perception and action are also shown to share several brain correlates and are therefore, two neurophysiological systems that show no clear distinctions. It suggests that we are phylogenetically and biologically organized for processing perception and action in a similar way. Grounded theorists usually account for such neurophysiological evidence by suggesting that perception and action would be constitutive parts of cognitive representations. Thus, grounded theories support a modal conceptualization of cognition which emphasizes on the role of sensorimotor information in representations. Accordingly, perception, action and cognition would share the same representational system. For instance, it is assumed that space and conceptual knowledge representations are grounded in sensorimotor information. Space perception would be subdivided into two functionally distinct regions of the space around an individual – peripersonal and extrapersonal spaces – peripersonal space being shaped by action constraints and triggering sensorimotor processing. Conceptual knowledge would be shaped by the sensorimotor information that occurs during the perceptual states that produce them. It has then been suggested that when one re-encounters previous situations, simulation mechanisms of conceptual knowledge re-enacts stored information about these situations. Simulation mechanisms would make inference about the sensorimotor properties that should be encountered in the situation. The present thesis falls in these conceptions of perception-action coupling, and mostly within grounded approaches of cognition, assuming that perception and action are closely interconnected and take a significant part in cognition. In the following chapters, we will discuss the role of motor information while perceiving manipulable objects.

CHAPTER 2. ACTIVATION OF MOTOR INFORMATION DURING MANIPULABLE OBJECT PERCEPTION

In the first chapter, we emphasized that perception and action are closely interconnected. In line with an important aspect of Gibson (1986)'s work, we assumed that perception plays a fundamental role in action and that perception is an active phenomenon that emerges from action and from the exploration of the environment. We further postulated that perception and action processing share several brain correlates in monkeys and humans, suggesting similar phylogenetical and biological organizations for perceptual and action processing. Several empirical evidence observed specific brain processing for different action properties associated with manipulable objects (e.g., Culham et al., 2003; Mishkin et al., 1983; Perenin & Vighetto, 1988). Further evidence highlights similar coding at the single-neuron level for both the perception of manipulable objects and the production of actions on these same objects (Ishibashi et al., 2016; Rizzolatti & Fadiga, 1998). Taken on the whole, such observations have led researchers to consider the existence of close interconnections between perception and action at the brain level. Along with grounded approaches of cognition (Barsalou, 2008, 2020), we went further, suggesting that perception and action are intimately connected and are constitutive parts of cognitive representations. Thus, we support a modal conceptualization of cognition, emphasizing on the role of sensorimotor information in representations. Still in the domain of grounded cognition, authors have borrowed the term "affordance" from Gibson (1979), changing its initial definition to include brain and cognitive representational aspects. In this chapter, we will review this literature.

I. Automaticity, representation and brain processing

According to Gibson (1979), affordances are potential actions provided to an organism by its surrounding environment. They are therefore considered as environmental properties. However, since Gibson defined the term “affordance”, it has been used in many different ways. For instance, more restrictive conceptions have focused on affordance evocation during perception of manipulable objects instead of considering all the elements in the environment. These conception are usually in line with the grounded approaches of cognition (Barsalou, 2008) and consider that affordances are not environmental properties. Instead, affordances would consist in mental representations of sensorimotor and/or semantic properties of motor information associated with manipulable objects. Furthermore, it is assumed that they possess specific brain correlates. In this sense, authors refute the Gibson’s view of affordances, proposing a more representational point of view. The actual representational approaches of affordances constitute the background of the present thesis work.

In the context of the present thesis work, we will limit our interest to the cognitive and neuroscientific approaches that focused their conceptions on manipulable objects (Borghi & Riggio, 2015; Buxbaum & Kalénine, 2010; Ellis & Tucker, 2000; Osiurak et al., 2017). Before going into more details, one important question to ask is “what is a manipulable object?”. To avoid any confusion, the term “manipulable object” will be used to refer to both natural (e.g., fruits, vegetables) and manufactured objects (e.g., tools, utensils) that are graspable with one hand. The term “non-manipulable object” will therefore be used for any other kind of objects (e.g., trees, buildings, scrambled objects). When required for comprehension, we will remove the ambiguity by using the specific names of the mentioned categories (see **Figure 8** for examples).

Figure 8. Examples of manipulable and non-manipulable objects. Research on affordance evocation during objects perception are interested in manipulable object categories. In some case, authors compare the processing of manipulable objects with the processing of non-manipulable objects to assess the specific motor properties associated with manipulable objects.

Among representational approaches of affordance, various theoretical positions have emerged to account for the properties of motor information associated with manipulable objects (see Osiurak et al., 2017, for a recent literature review). The different theories have mainly organized affordance debates around three aspects: the automaticity of affordance evocation, the nature of the representation of the affordances and the cortical network involved in affordance perception. The automaticity of affordance evocation is discussed in **Box 1. Automaticity**. The representation of affordances and the cerebral networks involved in their perception are discussed below within the description of the recent representational conceptions of affordances.

Finally, Osiurak et al. (2017) spotted an ultimate debate in affordance perception which they called: “the frame of reference”, but we will not address this aspect in detail. To briefly mention it, the frame of reference concerns the part of the hand-tool interaction the affordance refers to: (1) the hand, (2) the tool, or (3) both the hand and the tool. We will skip this aspect because we are interested in affordances associated with manipulable objects in general while this aspect is specific to tool affordances. Hence, it refers to a more restrictive approach of affordances that does not easily apply to the present work. Nonetheless, Osiurak et al. (2017)’s review is interesting to mention as it draws a good picture of the several shapes that representational conceptions of affordances have taken these last past years in the literature (see. **Figure 9**).

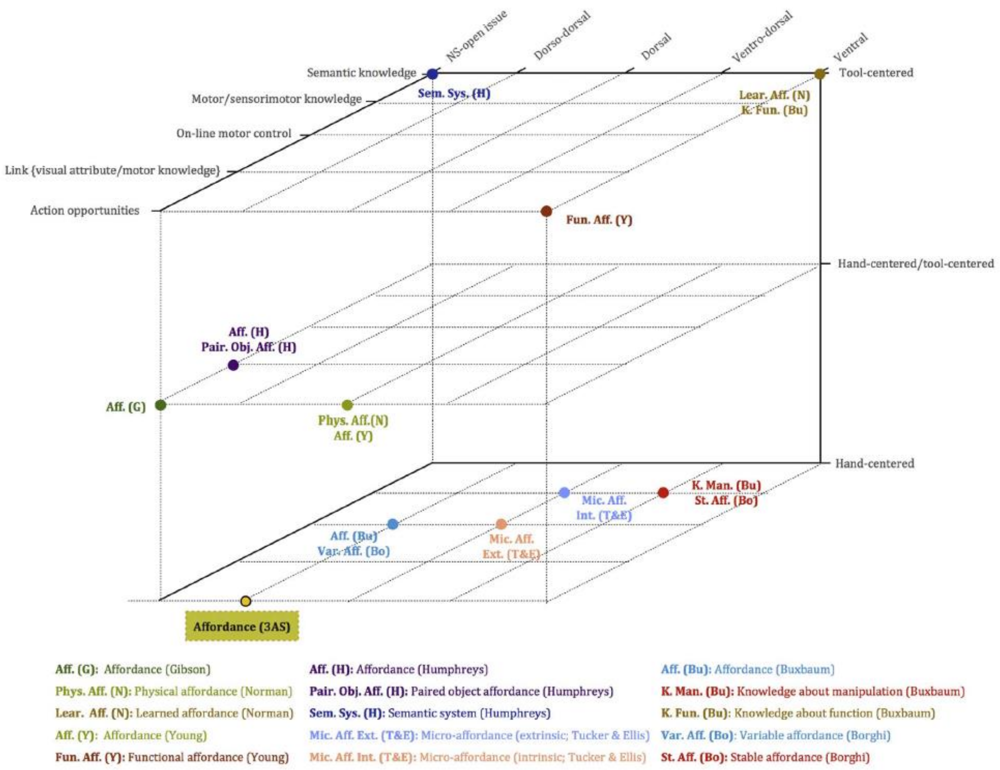

Figure 9. The main affordance conceptions distributed on a 3-dimensional graphic from Osiurak et al. (2017). The x-axis represents the cerebral system involved in affordance perception. The y-axis represents the frame of reference. The z-axis represents the nature of the representation of affordance.

Note that most conceptions assume that there exist multiple types of affordances with various properties along the three axes. Globally, most representational approaches consider perception of affordances as an evocation of the representation of action components when perceiving manipulable objects (such as reaching gesture, grasping gesture or typical interactions associated with objects). In the next section, we will discuss the most relevant conception for object processing: the micro-affordance account (Ellis & Tucker, 2000; Tucker & Ellis, 1998), the distinction between structural and functional affordances (Buxbaum & Kalénine, 2010), and the distinction between variable and stable affordances (Borghi & Riggio, 2009, 2015).

Box 1. Automaticity

Among the properties of affordances discussed in the literature, the automaticity of affordance evocation during manipulable object perception is not easy to address. Some authors will claim that affordances are automatically activated (Ellis & Tucker, 2000), some authors will claim that they are not (Borghi & Riggio, 2015; Buxbaum & Kalénine, 2010).

The main problem with defining automaticity of affordance evocation is not that there are disagreements in the literature, but rather that authors use different arguments against automaticity. The main arguments are usually the influence of contextual modulations (Borghi & Riggio, 2015) and modulations induced by the intention of the observers (Buxbaum & Kalénine, 2010).

In the literature as in Borghi & Riggio (2015), contextual modulations – including space, verbal context, visual context, etc. – are often presented in contrast to evidence toward automatic evocation of affordances. It will also be the case of the present thesis (see next sections of Chapter 2). Based on these observations, authors usually suggest that affordances are not always activated and thus they refute the automaticity of affordance evocation.

In the literature as in Buxbaum & Kalénine (2010), modulations by observers' intention – including task demands, action production, action training, etc. - are used as an argument against the automatic evocation of affordances. Intention will not be addressed in details in the present thesis work, except by considering task demands. On the basis of these observations, authors usually suggest that affordances are activated depending on the intention to act and thus refute the automaticity of affordance evocation.

In the present thesis we will consider that neither contextual modulation nor observers' intention constitute clear arguments for refuting the automaticity of affordance evocation. Instead, they both constitute evidence toward modulations of affordance evocation depending on circumstances. In our opinion, confusion lies in the use of the term automaticity. The term should be used to refer to the *consequences of* affordance evocation not to the evocation itself. Aforementioned arguments clearly demonstrate that consequences are not automatic.

In fact, Borghi & Riggio (2015) and Buxbaum & Kalénine (Buxbaum & Kalénine, 2010; see also, Kalénine & Buxbaum, 2015) provide views that are consistent with this opinion, suggesting that top-down biasing signals influence the automatic evocation of affordances.

"… result is not necessarily incompatible with an initial automatic activation of affordances followed by the selection of the affordances relevant to their current task" **(p.8, Borghi & Riggio, 2015).**

"… intention and motor preparation are likely to exert a 'top-down' biasing signal that serves to orient attention to goal-relevant features of the sensory input" **(p. 130, Kalénine & Buxbaum, 2015)**

Therefore, even if we below discuss in two contrastive sections (1) the initial claim about the automaticity of affordance evocation and (2) the contextual modulations of affordance evocation, we will not take a clear-cut conclusion against the automaticity of affordance evocation.

1. Micro-affordance account

In the beginning of the 90's, a group of cognitive psychologists were interest in the involvement of action components in the representation of manipulable objects (Tucker & Ellis, 1998). They redefined the concept of affordance and proposed the term of "micro-affordances" (Ellis & Tucker, 2000). Their account differs from the ecological approach of Gibson (1986) by suggesting that micro-affordances are potential actions that are intrinsic to object representation. Consequently, they do not consider affordances as environmental properties *per se* (Ellis et al., 2007; Tucker & Ellis, 1998). Moreover, the micro-affordance account is more specific than the Gibsonian's view of affordances and proposes that they are specific action parameters activated in response to specific visual features of objects. For example, location, orientation and size of a perceived object may potentiate specific grasping aperture or wrist orientation parameters according to the typical way to interact with the object (Ellis & Tucker, 2000). They described micro-affordances as motor information that are automatically and temporarily activated when perceiving a manipulable object (Ellis & Tucker, 2000; Tucker & Ellis, 2001). Tucker & Ellis (1998) emphasized that, the visuomotor on-line processing associated with the dorsal pathway (Milner & Goodale, 1993) was likely to be the system in charge of the processing of micro-affordances. However, recent advances in their works make them adapt their initial description of micro-affordances (Derbyshire et al., 2006; Tucker & Ellis, 2004). They observed that action components could be potentiated either by objects or by their names (Tucker & Ellis, 2004) and for some cases, instead of decaying, the potentiation of some action components enhances with time (Derbyshire et al., 2006). Consistent with these findings, they finally questioned the role of the dorsal stream (Milner & Goodale, 2006) in the processing of micro-affordances and they introduced a distinction between extrinsic and intrinsic micro-affordances (Derbyshire et al., 2006; Tucker & Ellis, 2004). The extrinsic micro-affordances would refer to potential action components activated by object visual characteristics that must be processed online because of some unpredictable aspects (e.g., location or orientation of the object in space). Extrinsic micro-affordances are suggested to be processed by the dorsal visual stream. The intrinsic micro-affordances would refer to potentiated action components that depends on represented object visual characteristics (e.g., size, shape) acquired through previous visuomotor interactions with the object. Concerning the nature of the representation of micro-affordances, they excluded the involvement of semantic representations as highlighted by the use of the term “pure physical affordances” in Symes et al. (2007). Extrinsic micro-affordances would rely on online processing and therefore, they would not be represented at all, while intrinsic micro-affordances would rely on sensorimotor representations.

2. Structural and functional affordances: Two Action Systems (2AS)

The studies of brain injured patients have contributed to a better understanding of cognitive functions. In the context of object-directed actions, studies on brain injured patients with apraxia - a neuropsychological disease usually characterized by deficits in skilled use action (Buxbaum, 2001) – concluded in the existence of two routes for action processing (Rothi et al., 1991). A “direct” route that operates direct transformation of visual information into action production (e.g., grasping a ball based on its spherical shape) and an “indirect” route that needs an access to semantic representations of actions (e.g., produce the specific gesture associated with the functional-use of an object by accessing its functional meaning). In line with this model, Buxbaum & Kalénine (2010) proposed the Two Action System (2AS) theory. The 2AS theory suggests that motor information assessed from visual objects are processed by two neuroanatomical and functional distinct systems. The two systems are supposed to process distinct motor information associated with objects: sensorimotor information and semantic motor information. Accordingly, Buxbaum & Kalénine (2010) used the term structural affordances to refer to sensorimotor information and the term functional affordances to refer to semantic action information associated with objects.

Structural affordances would refer to the evocation of gestures associated with the typical grasp of the object based on its volumetric characteristics, such as when grasping a glass with a specific hand aperture based on its size. Structural affordances would be automatically and temporarily activated. In contrast, functional affordances would correspond to the evocation of gestures associated with the typical use of objects based on conceptual representations, such as when poking the keys of a calculator according to its typical function. Functional affordances would need a specific context to be activated and would be more persistent through time. Note that a similar account can also be found in Bub and colleagues.(2008)'s work, where they suggested to distinguish between volumetric and functional affordances.

Advances in the model of the two-visual pathways (see Chapter 1 for a detailed description, Goodale et al., 1992), have proposed to subdivide the dorsal visual pathway into two neural streams in monkeys (Rizzolatti & Matelli, 2003). The first stream has been called the “dorso-dorsal” stream, as it would mainly include the superior parietal lobule (SPL) and the dorsal premotor cortex (dPMC). The second stream has been called the “ventro-dorsal” stream, as it would mainly include the inferior parietal lobule (IPL) and the ventral premotor cortex (vPMC). In monkeys, the dorso-dorsal stream would be involved in the “online” control of object-directed actions based on physical characteristics of objects, while the ventro-dorsal stream would be involved in action understanding (Rizzolatti & Matelli, 2003). In humans, the dorso-dorsal stream would be involved in action execution (e.g., grasping, reaching) based on current visual information (e.g., shape, size) while the ventro-dorsal stream would be involved in representing long term skilled actions (e.g., functional use actions). Accordingly, Buxbaum & Kalénine (2010) have assumed that structural affordances would be processed by the dorso-dorsal visual stream and functional affordances by the ventro-dorsal visual stream. To conclude, structural and functional affordances are described to account for the distinction between grasp and use gestures associated with objects. They are distinct action properties associated with distinct level of representations, structural affordances would be represented at the sensorimotor level, while functional affordances would be represented at the semantic level. Both affordances would be processed by distinct neuroanatomical substrates (i.e., dorso-dorsal and ventro-dorsal visual streams).

3. Stable and variable affordances

The idea that objects may afford components of potential actions of various origins has also been suggested by Borghi and Riggio (2009, 2015). They suggested that action components evoked by objects might derive either from current characteristics of the visual scene or from long-term associations of typical object-action interactions. Therefore, they proposed to distinguish variable from stable affordances (Borghi & Riggio, 2015). Initially called "temporary affordances" (Borghi & Riggio, 2009), variable affordances were defined by authors as action components activated from unpredictable visual characteristics of objects (e.g., orientation). Variable affordances were described to be dependent on the visual context, requiring an online processing of the object. On the contrary, stable affordances were defined as action components activated from invariant visual characteristics of objects that are not context-dependent. Stable affordances would be processed by means of the representation formed through the repetitive associations of the visual characteristics of objects and the typical actions performed on them. For example, while the handle-orientation of mugs is likely to vary following the different types of interactions we previously had with them, the size of all mugs we have encountered is mostly the same. In this context, the orientation of the handle constitutes the variable affordance while the typical size of the mugs constitutes the stable affordance.

Recent studies in line with visuomotor neuron discoveries in monkeys (Raos et al., 2006; Rizzolatti et al., 1988; Rizzolatti & Fadiga, 1998) have pointed toward the existence of two neural circuits processing distinct action parameters, one for object grasping in general and the other for tool use in humans (see for extanded explanation, Orban & Caruana, 2014). Both circuits would be part of the ventro-dorsal visual stream (Rizzolatti & Matelli, 2003). Transposed to humans, the first neural circuit - called phAIP (i.e., putative human homolog of anterior intraparietal) circuit in monkeys - would connect the anterior intraparietal (AIP) cortex to the dorsal and ventral premotor cortices (dPMC and vPMC). The second neural circuit would connect the anterior supramarginal gyrus (aSMG) to the ventral premotor cortex (vPMC) and would work in parallel with the phAIP circuit. Accordingly, Borghi & Riggio (2015) have assumed that variable affordances would be processed by the first circuit and stable affordances by the second.

To conclude, variable and stable affordances are described to account respectively for the distinction between unpredictable grasping actions (e.g., response to handle orientation of objects) and predictable grasping and using actions (e.g., grip aperture associated with typical mug size, and poking gesture associated with the typical use of a calculator). They are distinct action properties associated with distinct level of representations. Variable affordances would not be represented but they would need for a visuomotor control of actions. Stable affordances would be represented at the sensorimotor level. Finally, both affordances would be processed by distinct neuroanatomical substrates.

Intermediate synthesis

The main conceptualizations of affordance perception strongly support the idea that they emerge from the relation between the observer and the environment. Even though most of the actual conceptualizations of affordances focus on manipulable objects, they agree with some of the claims of the Gibsonian's ecological approach, by considering that affordance perception is flexible and can be updated through novel motor experiences. On the contrary, they disagree with the Gibsonian's approach by considering the involvement of neural representations of affordances. Some affordances would be considered as an evocation of sensorimotor representations of action components while perceiving visual characteristics of objects (i.e., extrinsic micro-affordances, structural and variable affordances), while other affordances would depend on deeper semantic representations of learned associations between typical visual characteristics of objects and specific action components (i.e., functional affordances). One common assumption of these three approaches is that one object might evoke distinct affordances, such as the typical associated grasping and using gestures. These multiple types of affordances are described with different properties that might account for the discrepancies in results observed in the literature on affordance perception.

II. Affordance evocation during manipulable object perception

Affordance evocation during manipulable object perception has been widely investigated in the literature. Initial behavioral and neurophysiological studies have highlighted fast and automatic involvement of motor information in object perceptual and conceptual processing. However, recent advances have provided important nuances to the initial claim about the automaticity of affordance evocation during object perception. The literature has instead pointed toward significant contextual modulations of affordance evocation. Researchers have also questioned which action properties of visual objects are actually activated and when. We will first discuss the initial claim about the automaticity of affordance evocation. Then, we will discuss recent evidence toward significant contextual modulations of affordance evocation. Finally, we will discuss about the flexible evocation of distinct affordances depending on the context.

1. Initial claim about the automaticity of affordance evocation

a. Behavioral evidence of affordance evocation during object perception

At the behavioral level, the phenomenon of affordance evocation has been classically demonstrated by showing that judgements about object general characteristics are facilitated when object visual properties, such as object size (Borghi et al., 2007; Ellis et al., 2007; Ellis & Tucker, 2000) or spatial orientation (Dekker & Mareschal, 2014; Fischer & Dahl, 2007; Pavese & Laurel, 2002; Pellicano et al., 2010; Tucker & Ellis, 1998), are compatible with some action components irrelevant for the judgement task. Among the princeps paradigms evaluating affordance effects, two versions of the stimulus-response compatibility paradigm have been designed. The first is the well-known handle-response compatibility paradigm[8] (Fischer & Dahl, 2007; Pellicano et al., 2010; Tucker & Ellis, 1998). In this paradigm, visual handled-

[8] See Azaad et al. (2019) for a recent meta-analysis on 38 handle compatibility paradigms.

objects are presented with handle oriented toward the left or the right (cf. **Figure 10**) while participants are asked to perform categorization judgements on the object (e.g. color change for Fisher & Dahl 2007; vertical orientation for Tucker & Ellis 1998; Riggio et al, 2008 or semantic judgements for Symes et al. 2005) by pressing left or right response buttons. Response times (RTs) for categorizing objects are typically faster when the handle is oriented toward the button to press, compared to when it is oriented toward the opposite direction.

The second object compatibility paradigm was first proposed by Tucker and Ellis (2001). Real objects that could be small (i.e., grasped with a precision grip) or large (i.e., grasped with a power grip) are presented to the participants. They are asked to determine whether presented objects were natural or manufactured by grasping a specific device with either a precision or a power grip (cf. **Figure 10**). Response times were faster when the response grip was compatible with the grip evoked by object real size. In both cases, the compatibility effects were interpreted as an automatic activation of the specific grasping gestures associated with the object when accessing the object concept (i.e., affordance effect).

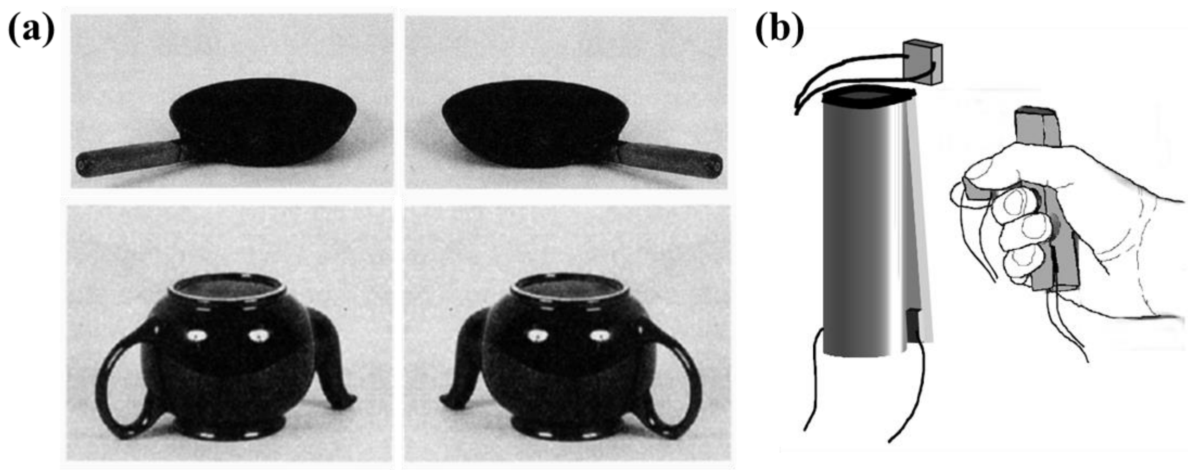

Figure 10. Examples of stimuli and apparatus used in compatibility paradigms. (a) Typical handled-objects used in the handle-compatibility paradigm. *Stimuli from Tucker & Ellis (1998)*. (b) Specific device *from Tucker & Ellis (2001).*

However, it has been suggested that these interpretations face multiple challenges (Borghi et al., 2007; Buxbaum & Kalénine, 2010; Riggio et al., 2008; Symes et al., 2005; Yang & Beilock, 2011). First, the affordance effects measured by handle-response compatibility paradigms could be tainted by the spatial compatibility between the side of the response hand and the side of the object handle. Hence, facilitation of handle-compatible responses could have occurred without evoking the specific grasping gestures of the objects and may merely be due to a spatial compatibility effect. Second, the affordance effects measured by the stimulus-response compatibility paradigm using the specific device (Tucker & Ellis, 2001) may not reflect the activation of the grip evoked by object real size (Heurley et al., 2020). Indeed, real object perception provides direct visual information about object size. Thus, affordance effects could occur without motor information being a part of the object conceptual representation and could merely be due to a visuomotor matching. Third, the presence of a specific motor response questions the automaticity of affordance evocation. These three challenges will be addressed in more details in the first chapter of the “experimental contribution” of this manuscript.

Another alternative to measure affordance evocation comes from visuomotor priming paradigms. In such paradigms, researchers evaluate the effect of a prime on object recognition or categorization (Borghi et al., 2007; Collette et al., 2016), and also on object-directed actions (Craighero et al., 1996). Among these paradigms evaluating affordance effects, two types of primes have been used. They could consist either in objects sharing - or not - similar visual or action properties with the object serving as targets (Collette et al., 2016; Craighero et al., 1996, 1998; Helbig et al., 2006), or in hand postures compatible - or not - with the typical gestures associated with the object serving as targets (Borghi et al., 2007; Bub et al., 2013; Godard et al., 2019; Helbig et al., 2010; Ni et al., 2018; Vainio et al., 2008). We will refer to the first as object-to-object priming paradigms and to the second as action priming paradigms.

In object-to-object priming paradigms (see **Figure 11** for an example), participants are usually asked to perform a semantic or motor task on real objects or 2D pictures of objects presented following an object prime (Collette et al., 2016; Craighero et al., 1996, 1998; Helbig et al., 2006). For instance, Helbig et al. (2006) presented 2D pictures of manipulable objects as primes. In their study, primes either shared manipulation (e.g., plier – nut cracker) or visual shape (e.g., plier – horseshoe) with the object targets. Participants were asked to name both the prime and the target. Percentage accuracy for target object naming was analyzed. The authors observed higher accuracy in naming target objects when these last shared action manipulation with the prime compared to when they did not. These results were in line with multiple studies showing effects (i.e., facilitative or interfering) of motor properties of object primes on the processing of subsequent object target (Collette et al., 2016; Craighero et al., 1996, 1998). Additional results highlighted that the priming effect is already present with a 100 ms priming duration (Labeye et al., 2008). Altogether these studies support that action representations associated with manipulable objects (i.e., affordance) are quickly and automatically activated when perceiving a manipulable object and that they impact the processing of subsequent object properties (i.e., interfere or facilitate).

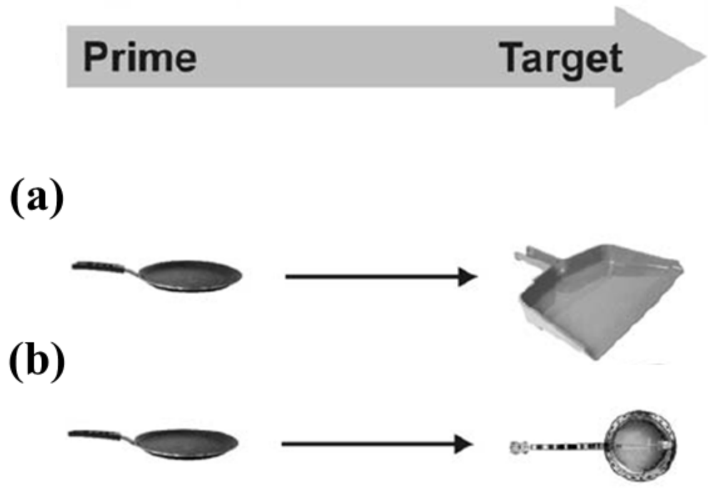

Figure 11. Examples of prime-target sequence for object-to-object priming paradigm. (a) Objects share similar action manipulation but not visual shape. (b) Objects share similar visual shape but not manipulation. *Figure from Helbig et al. (2006).*

To pursue on this line, in action priming paradigms (see **Figure 12** for an example), participants are usually asked to categorize object pictures that are primed by pictures of hand postures that could be compatible (e.g., orange – clench), incompatible (e.g., orange – pinch) or neutral (e.g., orange – palm) with the usual way to grasp or to use the object (Borghi et al., 2007; Bub et al., 2013; Godard et al., 2019; Helbig et al., 2010; Ni et al., 2018; Vainio et al., 2008). Such paradigms do not usually involve spatial compatibility. Faster response times are typically observed when object pictures are preceded by compatible hand primes compared to incompatible and neutral hand primes. For instance, Borghi et al. (2007) reported a priming effect with shorter response times (RTs) after compatible than incompatible action primes. Altogether, these studies support the hypothesis that perceiving manipulable objects automatically evokes the typical gestures associated with them.

Figure 12. Example of (a) hand posture primes and (b) manipulable object targets used in action priming paradigms. Primes are either compatible or incompatible with the typical grasping gesture associated with the object target. Figure from Ni et al. (2018).

To conclude, there is an increasing number of behavioral evidence that gathers around the hypothesis of an automatic activation of affordances during mere perception of manipulable objects. Nonetheless, some authors tackle this interpretation, highlighting numerous issues in employed methodologies or in theoretical interpretations (Borghi et al., 2007; Buxbaum & Kalénine, 2010; Riggio et al., 2008; Symes et al., 2005; Yang & Beilock, 2011). Although the priming paradigms are promising for revealing automatic activation of object affordances, some inconsistency in the results weakens their impact. For example, the facilitative effect on RTs after compatible compared to incompatible action primes reported from Borghi et al. (2007) was observed only when the grasping gestures presented in the primes were previously practiced by the participants, questioning the automaticity of affordance evocation. As already mentioned, these issues will be addressed and discussed in more details in the first chapter of "experimental contribution" part of this manuscript.

b. Neurophysiological evidence of affordance evocation during object perception

Neurophysiological studies are often used as an argument in support of the automaticity of affordance evocation. Indeed, several neuroimaging experiments have suggested that the perception or the identification of manipulable objects induces the activation of motor brain areas overlapping with brain networks involved in object-oriented actions (Chao & Martin, 2000; Creem-Regehr & Lee, 2005; Gerlach et al., 2002; Grafton et al., 1997; Grèzes et al., 2003; Johnson-frey et al., 2005; Muthukumaraswamy & Johnson, 2004). For instance, Chao & Martin (2000) showed that looking and recognizing pictures of tools induce a selective activation of the left ventral premotor cortex (vPMC) relative to pictures of animals, houses and faces. Authors suggested that the activation of the left vPMC reflects the retrieval of the action associated with the use of tools. This interpretation has been refined and extended to other categories of manipulable objects (e.g., Gerlach et al., 2002). Gerlasch et al. (2002) indeed showed that the activation of the left vPMC was not specific to tools but that it was also extended to natural (e.g., vegetable and fruit) and manufactured (e.g., article of clothing) objects when compared to non-manipulable manufactured objects and animals (cf. **Figure 13**). These activations of the left vPMC during perceptual and conceptual processing of manipulable objects have been usually interpreted as an automatic activation of actions associated with the conceptual representations of manipulable objects.

This interpretation has however been tackled (Mahon & Caramazza, 2008). Such activation could reflect an epiphenomenon, showing additional object processing. The activation of the left vPMC constitutes effectively good evidence for motor processing but it does not indicate whether this motor processing is an additional process or an actual activation of motor information from the conceptual representation of objects. By exposing this issue, Mahon & Caramazza (2008) actually question the functional contribution of motor information in object perceptual and conceptual processing. This question will not be directly addressed in the present thesis. However, the integration of motor information in conceptual representations of manipulable object is well supported by the literature on lesioned patients (see, Buxbaum & Kalénine, 2010; Kalénine & Buxbaum, 2015, for reviews), suggesting that motor information play a critical role in the conceptual representation of objects.

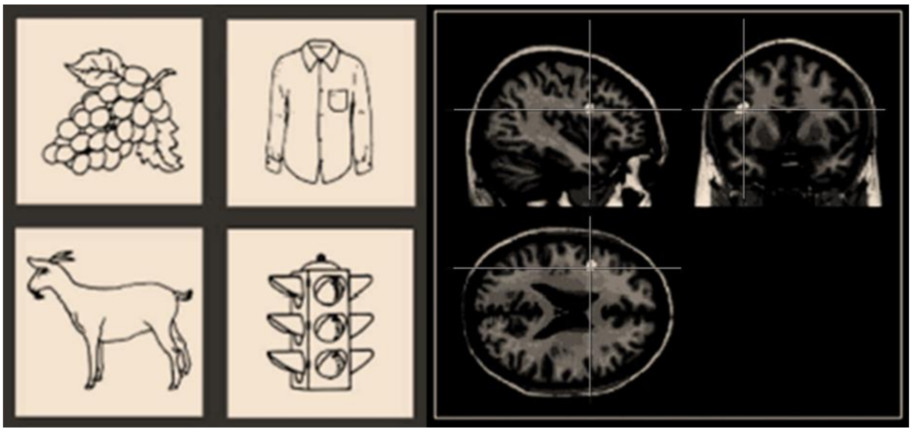

Figure 13. On the left, the stimuli used in the categorization task (i.e., *manufactured or natural?*) while recording the cerebral activation with positron emission tomography (PET). On the right, the activation of the left premotor cortex specifically associated with manipulable natural and manufactured objects. *Figure from Gerlasch et al. (2002).*

Studies using electroencephalography during manipulable object processing have also been used as an argument in support of the automaticity of affordance evocation. Indeed, multiple studies using electroencephalography (EEG) have investigated the involvement of motor regions in the processing of manipulable objects (e.g., Goslin, 2012; Kiefer et al., 2011; Proverbio, 2012; Proverbio et al., 2011, 2013; Vainio et al., 2014; Wamain et al., 2016, 2018). Usually, these studies analyze the electrical signal situated over the centro-parietal regions for assessing motor responses during object processing (**Figure 14**). In Kiefer et al. (2011), EEG signal was recorded while participants were presented with an object-to-object priming paradigm, similar to Helbig et al. (2006). They observed a modulation, occurring at 100 ms after target onset of the event related potentials (ERPs) recorded over the central regions, in response to prime congruency, with a higher amplitude for the incongruent priming condition (e.g., frying pan - ukulele) compared to the congruent priming condition (e.g., frying pan – dustpan). In Proverbio (2012), EEG signal was recorded while participants were presented with a tool vs. non-tool categorization task. The author used a time-frequency decomposition procedure to analyze the Mu (μ) rhythm desynchronization[9] over centro-parietal electrodes during the processing of tools and non-tools objects. They observed higher μ rhythm desynchronization for tools compared to non-tools, as early as 140 ms post-object presentation. These results are in line with a fast involvement of the motor regions in the conceptual processing of manipulable objects. Altogether, these studies highlight that the perception and identification of manipulable objects induce a fast and automatic activation of motor brain areas overlapping with brain networks involved in object-oriented action, supporting the automatic evocation of affordances.

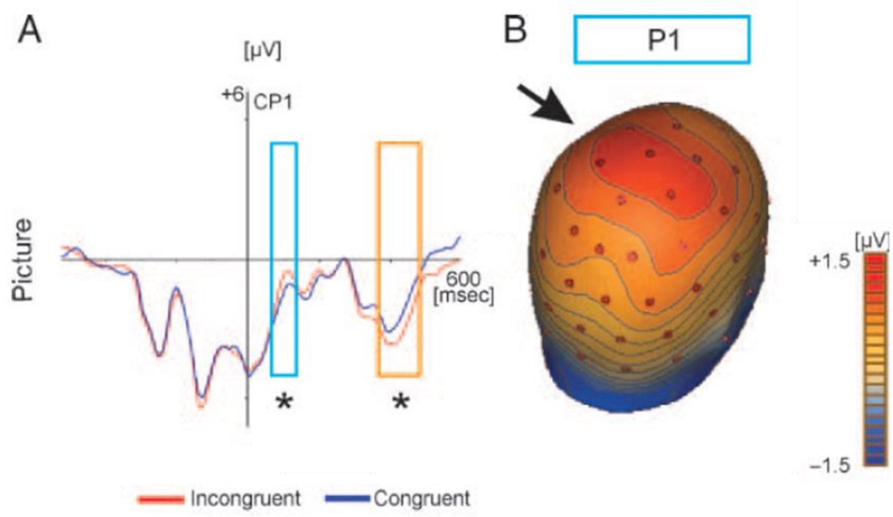

Figure 14. Modulation of ERPs as a function of priming congruency (i.e., congruent vs. incongruent). **(A)** ERP waveforms over the central sites for an early (P1: 85-115 ms) and late (N400: 380-480 ms) action priming effects. The y-axis indicates the onset of the target. **(B)** Topography of the action priming effects in the P1 window. Asterisks (ERP plots) and arrows (topographic maps) index significant action priming effects. *Figure and description from Kiefer et al. (2011).*

[9] The Mu (μ) rhythm desynchronization recorded over the centro-parietal regions with electroencephalographical (EEG) recordings is often interpreted as an activation of the motor system (Proverbio, 2012). See chapter 3 for more details on μ rhythm desynchronization during manipulable object perception.

2. Impact of context on the evocation of object affordances

Recent advances in affordance research have provided important nuances to the initial claim about the automaticity of affordance evocation during manipulable object perception. In particular, it has been proposed that affordance perception could be sensitive to the context in which the objects are perceived. For instance, affordance perception has been shown to vary between individuals, according for example to their sensorimotor experiences (Bellebaum et al., 2013; Chrysikou et al., 2017; Kiefer et al., 2007; Rüther et al., 2014; Watson et al., 2013; Yee et al., 2013), but also across individuals, according for example to the location of objects in space (Costantini et al., 2010, 2011; Ferri et al., 2011; Kalénine et al., 2016; Wamain et al., 2016, 2018). Additional studies have also highlighted that distinct affordances may be activated depending on the context (Costantini et al., 2011; Kalénine et al., 2014; Lee et al., 2012, 2018). First, we will review studies that highlighted an influence of motor experiences on affordance evocation during manipulable object perception. Then, we will review studies that highlighted space modulations of affordance evocation. Finally, we will review studies showing flexible evocation of distinct affordances depending on the context.

a. Between-individual modulations of affordance evocation: sensorimotor experience

In line with grounded approaches of conceptual knowledge (Barsalou, 1999), several authors have argued for a critical role of sensorimotor experiences in the acquisition of conceptual knowledge (e.g., Thill & Twomey, 2016; Wellsby & Pexman, 2014a, 2014b; Yee et al., 2013). Some have even proposed a new variable called “body-object interaction” (BOI) to encompass for the easiness to physically interact with word’s referents. Usually, these studies showed that individuals are better (i.e., faster, more accurate) to process high BOI concepts (e.g., frying pan, desk, bike) than low BOI concepts (e.g., cloud, traffic light). However, these studies focused on the acquisition of conceptual knowledge in general, including abstract concepts and language. Therefore, they are broader and mostly beyond the scope of the present thesis work. Nonetheless, we discussed in the first chapter that - according to grounded approaches of cognition - sensorimotor experiences are part of conceptual knowledge and that when one re-encounters a situation, simulation mechanisms will make inference about the sensorimotor properties that should be encountered in this situation. Therefore, if applied on manipulable objects, the aforementioned studies question the role of sensorimotor experiences in the evocation of motor information (i.e., affordances) during manipulable object perception.

We will thus review studies that have specifically investigated the role of motor experiences in the evocation of motor information (i.e., affordances) while processing manipulable objects (Bellebaum et al., 2013; Chrysikou et al., 2017; Kiefer et al., 2007; Rüther et al., 2014; Watson et al., 2013; Yee et al., 2013). For instance, in Kiefer et al. (2007), participants learned to recognize novel manipulable objects (i.e., naming) and to categorize them according to their common perceptual features. Participants were subdivided into two groups. While learning information about the novel objects, the first group was asked to perform pantomime actions according to object features and the second one was asked to point at these features. Participants' brain activity was recorded with EEG during a subsequent testing phase during which participants were asked to match the picture of the learned objects with their name or category. Authors reported an early involvement of motor regions (i.e., over central electrodes) for novel objects but only for the group that produced pantomime gestures during learning. These results support the hypothesis that motor experiences with manipulable objects affect the involvement of motor information while later perceiving them.

In a meta-analysis, Watson et al. (2013) addressed the role of motor experience in the involvement of motor brain regions while processing action information. While they observed systematic activation of motion-sensitive brain regions (i.e., left posterior middle temporal gyrus, pMTG), they reported inconsistency in the activation of the premotor and motor regions during action processing, with some studies showing the activation while others not. They suggested that this absence of systematicity in the activation of motor brain regions might reflect differences in motor experiences between individuals. Recent studies strongly support the modulation of motor brain involvement in affordance evocation according to long term (Chrysikou et al., 2017) and short term (Toussaint et al., 2021) changes in manipulation experiences. For instance, Chrysikou et al. (2017) used a handle-response compatibility paradigm (cf., Tucker & Ellis, 1998) without asking participants to perform hand responses. Instead, they asked participants to pronounce orally the typical gesture associated with the presented handled-objects (i.e., clench or pinch). They demonstrated that right-handed healthy participants and right-handed lesioned patients showing left-hand paralysis provided faster pronunciations when handles were oriented toward their dominant hand (i.e., right), but not when oriented toward their non-dominant hand (i.e., left). In other words, they demonstrated an affordance effect depending on their dominant hand (i.e., right). The reverse pattern was reported for originally right-handed lesioned patients showing right-hand paralysis. These patients provided faster pronunciations when handles were oriented toward their non-dominant hand (i.e., left), but not when oriented toward their original dominant hand (i.e., right). In other words, original right-handed participants demonstrated an affordance effect depending on their non-dominant hand (i.e., left), hand with which they experience novel sensorimotor interactions. This study highlights an important plasticity of the involvement of motor brain region in affordance evocation during manipulable object perception according to new motor experiences with objects.

To conclude, affordance evocation during manipulable object perception is shown to be sensitive to motor experiences. Motor experiences are thought to be partially responsible of the acquisition of conceptual knowledge in general (Smith, 2005; Thill & Twomey, 2016). They have also been shown to influence the integration of motor information associated with new learned objects and to modulate their later perceptual processing (Kiefer et al., 2007). Motor experiences might be responsible of the variability of responses of motor brain regions while perceiving manipulable objects (Watson et al., 2013). Finally, new motor experiences have been shown to modulate affordance effects produced by handled objects (Chrysikou et al., 2017). Altogether, these studies strongly support the idea that affordance evocation during manipulable object perception vary across individuals. It thus questions the role of the increasing number of motor experiences during individuals' development in affordance evocation. These developmental aspects will be evoked in more details in the second chapter of the "experimental contributions" part of this manuscript.

b. Within-individual modulations of affordance evocation: space context

In the first chapter, we emphasized that one of the strongest postulates of grounded approaches suggests that space perception is "*shaped by the body, the body's relation to the environment, and the body's potential for action"* (p. 625, Barsalou, 2008). In light of studies evaluating space perception, most researchers agree with the existence of a functional distinction between the peripersonal and extrapersonal spaces (Morgado & Palluel-Germain, 2015; Previc, 1998). As a reminder, the peripersonal space defines the reachable space around the observer, that includes direct action possibilities while the extrapersonal space is outside action possibilities. Specifically, the perception of the peripersonal space would be related to the representation we have of our body (Longo & Lourenco, 2007), the representation of constraints to which the organism must pay attention (Morgado et al., 2013) and the representation of simulated actions that we can perform on objects that are within reach (Witt et al., 2005; Witt & Proffitt, 2008). According to this functional distinction, researchers have wondered whether affordance evocation while perceiving manipulable objects was affected by these action constraints, specifically whether manipulable objects evoke affordances depending on where they are situated in the space around us (Costantini et al., 2010, 2011; Iachini et al., 2014; Kalénine et al., 2016; Tucker & Ellis, 2001; Wamain et al., 2016, 2018; Yang & Beilock, 2011). A classical way that has been used by researchers to assess space modulation of affordances is by splitting what is reachable by arm's length (i.e., the reachable space) and what it is not (i.e., the unreachable space).

Surprisingly, the first results in the literature suggest that affordances are perceived independently of the fact that objects are presented within reach or not (Tucker & Ellis, 2001). In their experiment Tucker & Ellis (2001) asked participants to categorize real objects, that could be small or large, as being manufactured or natural by producing precision or power grip responses on a specific response device (see **Figure 10**). They did not show any differences of grip compatibility effects whether objects were presented 15 cm (reachable space) or 200 cm (unreachable space) away from participants' hands. These first results did not support the hypothesis that affordance evocation is modulated by space perception. However, we highlighted that the common stimulus-response compatibility paradigms are under several critics (Buxbaum & Kalénine, 2010; Yang & Beilock, 2011) and most of recent evidence argue for a space modulation of affordance evocation (Cardellicchio et al., 2011; Costantini et al., 2010, 2011; Kalénine et al., 2016; Wamain et al., 2016, 2018; Yang & Beilock, 2011).

Costantini et al. (2010) indeed showed that the famous handle compatibility effect (Fischer & Dahl, 2007; Pellicano et al., 2010; Tucker & Ellis, 1998) depends on object position in space. They presented 3D-pictures of scenes displaying a mug on a table. Mugs were inserted in a handle compatibility paradigm. In two experiments, researchers manipulated the possibility to interact with the object (see **Figure 15**). In experiment 1, objects were presented either close to (i.e., peripersonal space) or far from (i.e., extrapersonal space) participants. In experiment 2, objects were presented close to the participants but either in front of (i.e., reachable) or behind (i.e., unreachable) a transparent obstacle. In both experiments, participants exhibited a handle compatibility effect but, only when it was possible for them to interact with the perceived object, that is when objects were presented in their peripersonal space or in front of the transparent obstacle. In two additional control experiments, Costantini et al. (2010) excluded the possibility to explain the effect by means of difference in retinal size (i.e., due to distance modulation in experiment 1) or visual salience (i.e., due to obstacle blurring in experiment 2). Yang & Beilock (2011) also ruled out the explanation of difference in retinal size by showing that objects presented at a constant distance (150 cm) induced handle compatibility effect after that participants reaching abilities were increased with a long tool but not with a short tool. A recent study of Iachini et al. (2014) also supports the modulation effect of action constraints on affordance evocation, showing that the impossibility to move (i.e., dominant arm blocked) prevents affordance evocation. Taken together, these results strongly suggest that manipulable objects evoke affordances depending on multiple action constraints (i.e., arm length, obstacle, possibility for action). These results extend what has been said in Chapter 1: the functional distinction between peripersonal and extrapersonal spaces constitutes a great opportunity for studying affordance evocation while perceiving manipulable objects.

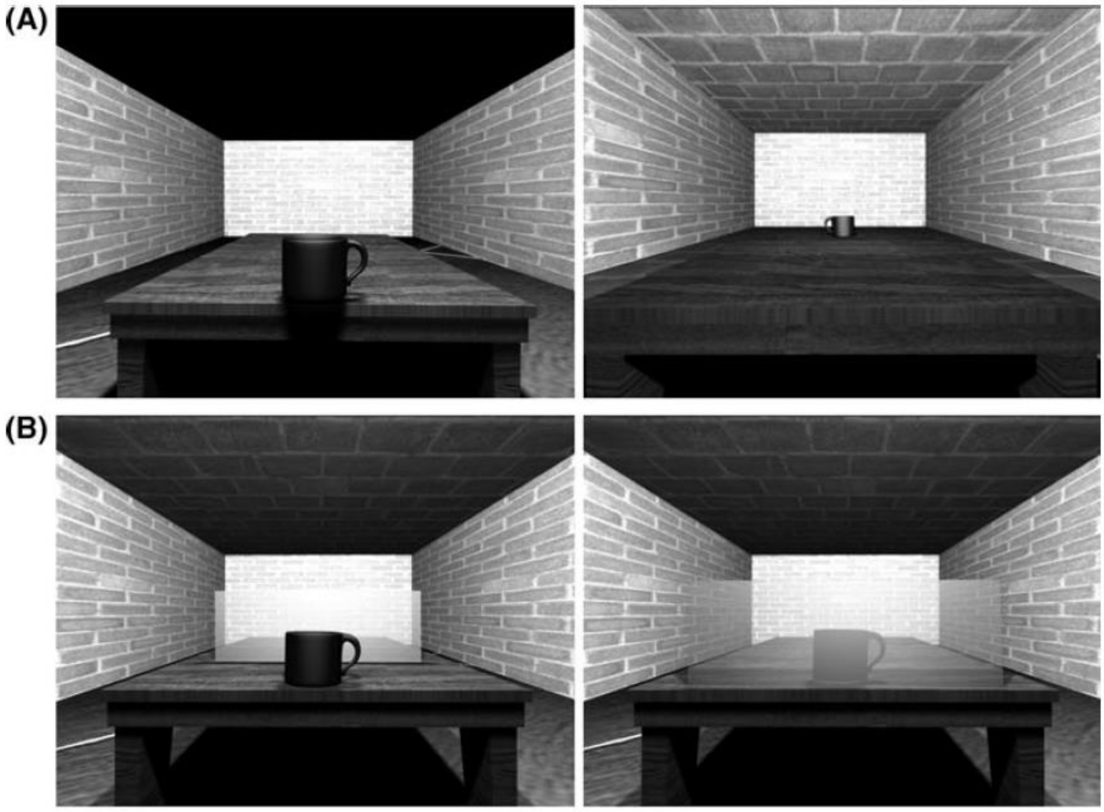

Figure 15. Experimental setting for studying space modulation of affordance evocation. **(A) Space modulation.** Objects are presented in the peripersonal (left) or extrapersonal (right) spaces. **(B) Reachability modulation.** Objects are presented in front of (left) or behind (right) a transparent obstacle. *Figure from Costantini et al. (2010).*

Additional studies highlighted that the activation of the motor brain system follows the space-sensitive behavioral patterns of affordance evocation (Cardellicchio et al., 2011; Wamain et al., 2016). For instance, Cardellicchio et al. (2011) recorded the motor evoked potentials (MEPs) of two muscles of participants' right hand following transcranial magnetic stimulation (TMS) of the left primary motor cortex, while participants were passively viewing stimuli (i.e., mug). Researchers reported larger MEPs amplitude when objects fell within reach than when presented outside of reach. Accordingly, Wamain et al. (2016)'s observed a specific involvement of the motor system when objects were presented in the peripersonal space, which consisted in a μ rhythm desynchronization following the presentation of manipulable objects compared to scrambled objects, but only when manipulable objects were presented in the peripersonal space. Considered together, these results showed that the motor system is preferentially activated when manipulable objects are presented within reach. These findings constitute a good parallel with the aforementioned studies that highlighted space coding of graspable objects by canonical neurons in the equivalent of the premotor cortex in monkeys (Bonini et al., 2014).

c. Distinct affordances for different contexts

On top of a contextual modulation of affordance evocation, it is not obvious which action properties of manipulable objects are activated and when. A single object may evoke different affordances in relation to different types of interactions that one may have with it (Borghi & Riggio, 2015; Buxbaum & Kalénine, 2010; Tucker & Ellis, 2004). In particular, it has been suggested that objects may afford both structural (i.e., grasping) and functional (i.e., using) affordances (Bub et al., 2008; Buxbaum & Kalénine, 2010). In action production context, structural (i.e., grasp-to-move) and functional (i.e., grasp-to-use) actions have been associated with different velocity in planification and kinematic execution, with grasp-to-use gestures being associated with longer planification (Osiurak et al., 2013; Valyear et al., 2011) but shorter peak grip aperture and movement duration (Valyear et al., 2011) in comparison with grasp-to-move gestures. At the brain level, it has been shown that structural and functional actions toward manipulable objects are associated with different neuroanatomical substrates (Buxbaum et al., 2006). Functional actions are particularly associated with ventro-dorsal brain regions, such as the left intraparietal cortex (IPL). Structural actions are particularly associated with dorso-dorsal brain regions, such as the superior parietal cortex (SPL). In similar vein and in regard to the distinction between stable and variable affordances (Borghi & Riggio, 2009, 2015), a recent meta-analysis has established strong evidence that stable affordances are processed by brain structures situated more ventrally than variable affordances (Sakreida et al., 2016, 2013). Taken together, these studies constitute multiple behavioral and neurophysiological sources of evidence for the existence of different attributes and processing associated with grasping and using actions of manipulable objects. Thus, they question whether these action properties might be differently evoked by the context. We will below review studies that investigated this issue in regard to the distinction between structural and functional affordances (Buxbaum & Kalénine, 2010).

It has been shown that structural and functional affordances are both evoked by manipulable objects (Bub et al., 2008). For instance, Bub & Masson (2008) presented objects associated with distinct volumetric (i.e., grasp) and functional (i.e., use) gestures to their participants. Participants were seated in front of a screen, with a specific device placed between them and the screen. The device was constituted by multiple shapes that triggered the four volumetric or the four functional gestures associated with their set of objects. In a training phase, participants learned to execute gestures on a part of the device depending on the color of the stimulus presented on the screen. In the test phase, participants were presented with pictures of the objects on the screen in different colors and were asked to perform the gesture associated with the color. The experimental manipulation created congruent conditions (e.g., performing a gesture associated with the object) and incongruent conditions (e.g., performing a gesture non-associated with the object). Authors reported congruency effect for both volumetric and functional gestures, characterized by shorter initiation times for producing the gesture when it was congruent with the object on the screen compared when it was not. These findings suggest that both structural and functional affordances are activated when perceiving manipulable objects. Nonetheless, as affordance evocation is context-dependent (Ambrosini et al., 2012; Costantini et al., 2010), it is worth questioning whether structural and functional affordances could be flexibly evoked depending on the context.

This question was addressed in several studies (Costantini et al., 2011; Kalénine et al., 2014). Costantini et al. (2011) presented object-verb sequences to their participants. Verbs were action verbs, referring to object manipulation (e.g., brush – ***to hold***), object function (e.g., brush – ***to comb***) or they could be observation verbs (e.g., brush – ***to gaze***). Participants were asked to judge the appropriateness of the verb according to the object presented just before it. Authors reported that the task was performed faster for function and manipulation verbs when the objects were presented in the peripersonal space compared to the extrapersonal space, but no difference in performance was observed for observation verbs. Going one step further, Ambrosini et al. (2012) reported similar results and showed that the effect was present for the actual reachable space (i.e., object reachable by arm length) but not for the perceived reachable space (i.e., participant reachability estimation), suggesting an actual body-centered representation of structural and functional affordances of manipulable objects. Taken together, these results suggest that when objects are within reach, they activate both their structural and functional affordances.

Following studies that emphasized the effect of visual context on affordance evocation during manipulable object perception (Borghi et al., 2012; Wokke et al., 2016), it has been shown that structural and functional affordances might be differently evoked depending on the visual scene (Kalénine et al., 2014). In their study, Kalénine et al. (2014) presented objects associated with distinct grasp-to-move and skilled use actions (e.g., kitchen timer) in a visual scene congruent with one of these actions (see **Figure 16**). Participants were asked to press and hold a button on a response box, which made a visual scene appear on the screen. After a certain delay, one of the objects in the visual scene was cued. Participants were asked to categorize the cued object as natural or manufactured by performing a clench or a pinch gesture on a cylinder. Initiation times were recorded. Authors reported faster initiation times to produce gestures congruent with the situation depicted by the visual scene, especially when it referred to skilled use actions (e.g., kitchen timer on a surface). These results demonstrate that structural and functional affordances are differently evoked depending on the situation in which manipulable objects are perceived.

Figure 16. Experimental setting for assessing visual scene modulation of structural and functional affordances. **(a)** Objects associated with distinct grasp-to-move and skilled use actions (e.g., kitchen timer) presented in a context congruent with a move action (left) and in a context congruent with a use action (right). **(b)** Response device. *Figure from Kalénine et al. (2014).*

Finally, recent studies have highlighted different temporal dynamics of structural and functional affordance evocation during manipulable object perception (Lee et al., 2012, 2018). For instance, Lee et al. (2012) presented 2D pictures of manipulable objects in a Visual World Paradigm. In this type of paradigms, target pictures are presented among three distractors. Each picture is distributed in one of four equal part of the screen. Among distractors, one distractor is related with the target properties while the other two distractors are completely unrelated with the target. Authors are usually interested in the effect of the related distractor on participants' performance. In a first experiment, Lee et al. (2012) presented a related distractor that shared structural affordances (i.e., grasping gestures) with the target (i.e., TV remote control – blackboard eraser). In a second experiment, they presented a related distractor that shared functional affordances (e.g., using gestures) with the target (e.g., key fob – computer mouse). Participants heard a sentence (e.g., “S/he saw the …”. The “…” were replaced by the name of a manipulable object) and then, they were asked to click with the computer mouse on the picture representing the manipulable objects evoked in the sentence. Authors recorded eye movements during the task and were interested in the fixations directed toward the related distractor compared to the unrelated distractors, obtaining what is called a competition effect. They reported significant competition effect for both structural and functional related distractors. However, they observed later, but higher and longer lasting competition effect for functional compared to structural related distractor (see **Figure 17**). These results support that manipulable objects evoke distinct structural and functional affordances and that both affordances possess different dynamics of evocation.

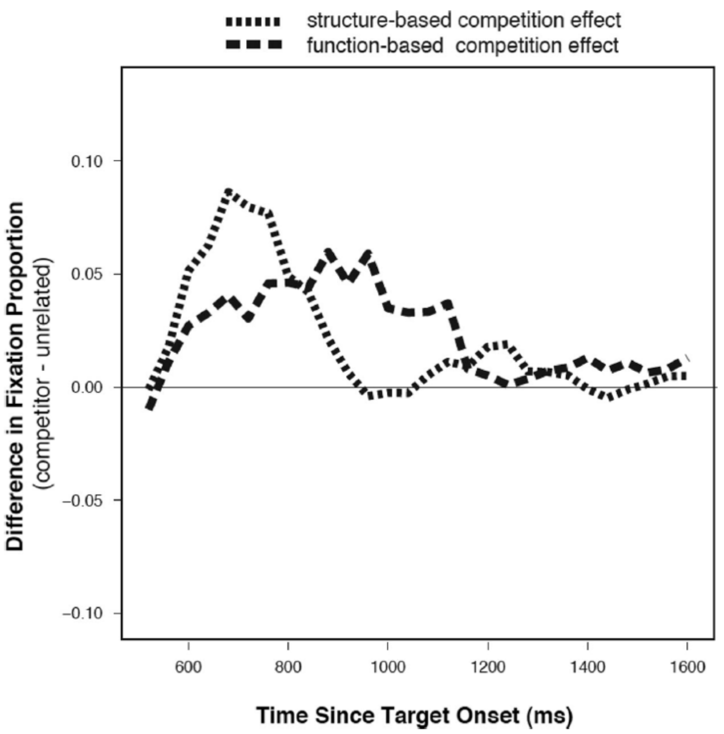

Figure 17. Differences of the competition effects (competitors – unrelated items) from the structure-based distractors (dotted line) and function-based distractors (dashed line). *Figure and description from Lee et al. (2012).*

Intermediate synthesis

When considering such an accumulation of evidence, it is mostly accepted that the perception of manipulable objects evokes the representation of the typical actions we performed with them (i.e., affordances). Initial studies have strongly suggested that perceiving manipulable objects induces an automatic evocation of their affordances. Different paradigms were designed for this purpose. However, these paradigms are facing multiple methodological and/or theoretical issues. Similarly, neuroimaging studies usually cited to support of the automaticity of affordance evocation are also under critics. Such issues have weakened the common conclusion of the studies on the automaticity of affordance evocation. As mentioned in **Box 1. Automaticity**, the automaticity of affordance evocation is in fact under debate. Here, we reviewed one of the typical arguments employed against the claim of automaticity, that is contextual modulations. We emphasized that affordance evocation is modulated by the motor experience of individuals, the spatial location of objects according to the observer, and that distinct affordances are evoked depending on the context in which manipulable objects are perceived. Even though we presented these arguments in opposition, we do not consider them as being contradictory. Again, although the existence of contextual modulations suggests that the consequences of affordance evocation on object processing are not automatic, it does not revoke that they are initially automatically activated.

Global Synthesis

Overall, recent representational conceptions of affordance evocation focus on the perception of manipulable objects. Affordances are usually seen as motor information emerging from the relation between the observer and the objects. Recent conceptions agree with Gibsonian's initial description of affordances by considering that affordance perception is flexible and can be actualized through novel motor experiences but they disagree when considering the involvement of neural representations in affordance evocation. The automaticity of affordance evocation, the nature of their cognitive representations and the cerebral system involved in their processing are under debates in the recent literature. Several authors even suggest the existence of multiple types of affordances (i.e., extrinsic vs. intrinsic, structural vs. functional and variable vs. stable) having different degrees of automaticity, different levels of representation and different brain correlates. According to the scope of the present thesis, we have oriented the discussion on the automaticity of affordance evocation. We reviewed behavioral and neurophysiological evidence consistent with the claim of an automatic evocation of affordances during manipulable object perception. However, we highlighted multiple methodological and/or theoretical issues in the initial investigations. We then reviewed empirical evidence about significant individual and contextual modulations of affordance evocation. Additionally, we emphasized that distinct affordances may be evoked from different contexts. To conclude, even though we presented arguments toward the automaticity of affordance evocation and contextual modulations in opposition, we do not take a clear-cut opinion against the automaticity of affordance evocation. Nonetheless, we stress the importance to consider the influence of affordance evocation on object processing in a flexible manner with noticeable inter-individual and intra-individual variabilities.

CHAPTER 3. CONSEQUENCES OF THE CO-ACTIVATION OF MULTIPLE AFFORDANCES

In Chapter 1, we highlighted that there exist close connections between action and visual perception. We emphasized that perception and action share several brain correlates and are integral parts of cognitive representations. In Chapter 2, we argued that in the context of manipulable object perception, most representational approaches now consider that perceiving manipulable objects may evoke the potential actions that we typically perform with them (i.e., affordances). We presented empirical evidence toward the automaticity of affordance evocation. We questioned the initial claim without taking clear-cut conclusion, by contrasting it with evidence highlighting significant contextual modulations of affordance evocation. Furthermore, we emphasized that manipulable objects evoke distinct affordances depending on the context. In Chapter 3, we will argue that affordance perception is sometimes detrimental for manipulable object perception. In particular, distinct affordances may be in certain cases co-activated from a single object, having negative consequences on manipulable object processing.

I. The affordance competition hypothesis

We already determined that perceiving manipulable objects may evoke the potential actions that we typically perform with them (i.e., affordances). We also emphasized that manipulable objects are associated with distinct affordances that can be activated depending on the context (Kalénine et al., 2014; Lee et al., 2012). Moreover, we can easily note that the environment is overgrown with many manipulable objects. If all objects evoke their affordance at once or if a single object evokes multiple affordances, how does the system deal with these invading activations and select among them to act properly? This question has been addressed by multiple models (see Thill et al., 2013 for review) and they all suggest that affordances compete for selection.

Hence, the question of multiple affordance perception has been addressed by different models, including non-human primate brain functioning models (Cisek, 2007; Cisek & Kalaska, 2010; Fagg & Arbib, 1998) but also models that account for specific effects associated with the cognitive human functioning (Caligiore et al., 2013, 2011; Caligiore & Borghi, 2010). They all assume that when multiple affordances are activated when perceiving manipulable objects, they compete against each other for further processing and the competition between affordances is undergoing biasing signals until the relevant affordance is selected. The different models stand out from each other according to two main aspects. The first aspect is the brain structures that are emphasized to explain the resolution of affordance competition. The candidates are either the parietal cortex and more precisely the anterior intraparietal cortex (AIP) for the FARS model (Fagg–Arbib–Rizzolatti–Sakata, Fagg & Arbib, 1998) or the prefrontal cortex (PFC) for the TRoPICALS model (Caligiore & Borghi, 2010). The second aspect is whether they are interested in the neural details (Fagg & Arbib, 1998) or functional aspects of the resolution of the competition (Caligiore & Borghi, 2010; Cisek, 2007; Cisek & Kalaska, 2010). Nonetheless, all of the models evoked above broadly agree with the functional role of each brain structure in the way action parameters are perceived in the environment, on how they are selected and what information is used for biasing the competition toward relevant affordances. In a sense, the discrepancies between models do not contradict each other but detail complementary aspects of affordance processing and control. We will below review the common propositions about how the system deals with multiple affordance perception and the functional role of each brain structure in the resolution of the competition between affordances by relying on the influent neurobiological model developed by Cisek (Cisek, 2007; Cisek & Kalaska, 2010). *See* **Figure 18** *below*.

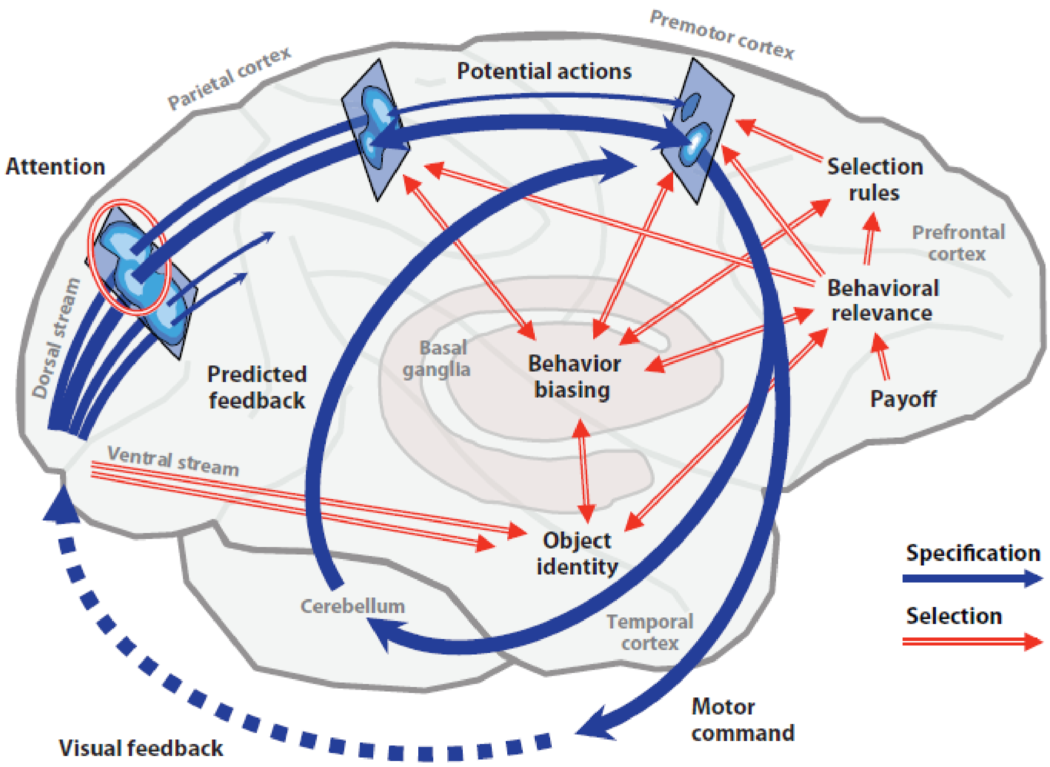

Figure 18. Sketch of the neurobiological model of *affordance specification* and *selection* developed by Cisek (Cisek, 2007; Cisek & Kalaska, 2010). Blue arrows represent *affordance specification* processes and red arrows represent *affordance selection* processes. Dash blue arrow reflects visual feedback. Simple red arrows represent direct processing and double red arrows represent communication between brain areas. *Figure and* description *from Cisek & Kalaska (2010).*

The main proposal of this model is that the activation of affordances from the environment (i.e., *affordance specification,* ***in blue*** *in* ***Figure 18)*** and the competition and biasing toward relevant affordances (i.e., *affordance selection,* ***in red*** *in* ***Figure 18***) are two parallel processes. It is assumed that when manipulable objects are perceived in the environment, their visual properties (i.e., affordances) are processed and transformed into representations of potential actions along the fronto-parietal dorsal stream (Culham et al., 2003; Goodale et al., 1992; Milner & Goodale, 1993, 2006) from the visual cortex to the parietal cortex. During the processing of the visual characteristics of objects, the information processed in the visual cortex undergoes early attentional modulations toward specific visual characteristics (Boynton, 2005). Then, represented actions based on those characteristics are specified along the parietal cortex, which is involved in controlling gaze movements (Snyder et al., 2000), arm reaching (Cui & Andersen, 2007; Jakobson et al., 1991; Kalaska & Crammond, 1995; Perenin & Vighetto, 1988; Pesaran et al., 2008; Scherberger & Andersen, 2007; Snyder et al., 2000) and grasping parameters (Baumann & Fluet, 2009) according to object size (Nakamura et al., 2001; Rizzolatti & Luppino, 2001) and location (Buneo et al., 2002). Additional brain structures provide information for the resolution of affordance competition, such as the temporal cortex that processes object identity (Pasupathy & Connor, 2002; Tanaka et al., 1991). To summarize, multiple pieces of information collected from the environment and from the actual observer state are involved in the resolution of affordance competition. The information collected is used to dynamically balance the weight of each potential affordance. Hence, two types of biasing signals have been emphasized for the resolution of affordance competition.

First, it is assumed that the prefrontal cortex plays an indirect top-down control (Sakagami & Pan, 2007; Tanji & Hoshi, 2001; Wise, 2008) for the selection of relevant affordances. To do so, the prefrontal cortex informs the basal ganglia for the relevant and irrelevant parameters to select. Parameters are determined according to contexts, goals, rewards and tasks (Barraclough et al., 2004; Hoshi et al., 1998). The basal ganglia increases, in turn, the weight of parameters associated with relevant affordances and decreases the weight of the others (Mink, 1996; Redgrave et al., 1999) for finally enabling one to act properly. Second, as the major part of the cortical connections (99%) are mediated by excitatory channels (Tamamaki & Tomioka, 2010), it is assumed that the direct biasing influences come only from local inhibition (Cisek, 2006; Leblois et al., 2006) between neural representations of parameters associated with affordances and actions. When affordance parameters are specified, the action to perform is selected and forwarded to the premotor cortex, then the action can be executed. The execution of the action produces a visual feedback and an internal predictive simulation through the cerebellum that helps for an online specification of relevant affordances and actions.

To summarize, when the system is confronted with multiple affordance perception, two parallels mechanisms are involved in order to specify and select relevant affordances. The parameters of each affordance are specified along the parietal cortex. Multiple sources of information are used to specify and select the relevant affordance parameters. When the system resolves the competition, the selected affordance is forwarded to the premotor cortex for action.

Unfortunately, unselected affordances are not easy to study because, as their name indicate it, they are not selected for action and thus not easily observable in behaviors. One solution for studying unselected affordances is to explore the impact of the co-activation of affordances on behaviors while perceiving multiple objects (Bub et al., 2018). In this situation, one might question the involvement of *affordance selection* and object selection. Actually, it has been suggested that object and action selection are not independent processes (Botvinick et al., 2009) and that object selection may interact with the selection of actions (Pavese & Laurel, 2002; Vainio & Ellis, 2020). To disentangle the influence of object from *affordance selection*, a second solution is to study the impact of the co-activation of affordances while perceiving a single object.

First, we will review the few behavioral studies in adults that have directly investigated the impact of the co-activation of multiple affordances on action planning (Bub et al., 2018; Jax & Buxbaum, 2010, 2013) and object perceptual processing (Kalénine et al., 2016). Second, we will review some neuroanatomical evidence for the involvement of parietal areas in *affordance specification* and for the involvement of more anterior brain areas (e.g., premotor, motor cortices) in *affordance selection* when perceiving object associated with distinct affordances (Schubotz et al., 2014; Watson & Buxbaum, 2016). Third, we will refer to recent work that have highlighted the relevance of using electroencephalographic methodology for studying the impact of the co-activation of distinct affordances on manipulable object perception (Wamain et al., 2018). Finally, we will anchor the problematic of the present thesis work according to this growing field of research.

Box 2. Definitions of conflictual and non-conflictual objects

The consequences of the co-activation of affordances presented below have been evidenced by studying objects associated with multiple affordances. Authors mainly focused their studies on objects associated with distinct grasping and using actions in the light of the distinction between structural and functional affordances evoked in Chapter 2 (Buxbaum & Kalénine, 2010).

For example, a calculator is associated with distinct grasping (usually a clench) and using (usually a poke) gestures and according to the affordance distinction of Buxbaum and Kalénine (2010), perceiving a calculator thus evokes distinct structural and functional affordances.

In the majority of studies presented below (Bub et al., 2018; Jax & Buxbaum, 2010, 2013; Kalénine et al., 2016; Lee et al., 2018; Wamain et al., 2018), objects associated with distinct structural and functional affordances have been called "conflictual" objects and sometimes compared with non-conflictual objects processing (i.e., object associated with similar structural and functional affordances, such as a glass).

The term "conflictual object" was initially employed by Jax and Buxbaum (2010, 2013) who highlighted that these objects are associated with conflicting potential actions.

Only one study mentioned below did not use conflictual object terminology while assessing the consequences of the co-activation of affordances (Schubotz et al., 2014). In this study, they were not interested in actions associated with size, shape or orientation of objects (i.e., structural affordances) but in actions associated with the use we have of these objects (i.e., functional affordances). For this purpose, they manipulated what they called the number of action codes (NAC) between object pairs. In this study, the NAC refers to the number of potential actions we can perform with an object pair.

For example, apple and knife form an object pair with 2 NACs: "cutting the apple" and "peeling the apple".

In the present thesis work, we will use the terms "conflictual" and "non-conflictual" objects following Kalénine et al. (2016) and Wamain et al. (2018). "Conflictual objects" will refer to objects that are associated with distinct structural and functional affordances in comparison with "non-conflictual" objects that are associated with similar structural and functional affordances. Even though, we choose to classify objects as "conflictual" and "non-conflictual", there is indeed a continuum between those two categories. Some objects will be more conflictual than others due to greater difference in the movement parameters associated with their grasping and using gestures.

II. Behavioral assessments of the co-activation of affordances

1. Impact of the co-activation of distinct affordances on action production

Classically, in the studies evaluating the impact of the co-activation of distinct affordances in action production (Bub et al., 2018; Jax & Buxbaum, 2010, 2013), participants are asked to produce actions toward objects and to place their dominant hand on the object as if they were going to use or grasp it (e.g., reach-and-use the cellphone, reach-and-grasp the cellphone). Reach-to-use and reach-to-grasp movements are alternatively produced across trials or blocks of trials to determine the influence of the pre-activation of one affordance over the other while planning the object-directed action. For the purpose of assessing these influences and avoiding the contamination of any differences in kinematic complexity between use and grasp movements, authors record initiation times. Initiation times correspond to the time interval between the onset of the trial (e.g., a cue-signal or when the object is under participant view) and the onset of the reaching movement to produce the action (or liftoff movement). As a result, authors are able to assess the influence of the co-activation of distinct affordances on the planning of object-directed action dissociated from movement execution. The stimuli are composed of real objects or response apparatus primed by picture of objects sharing similar visuomotor characteristics (see **Figure 19**). The objects employed are associated with different use and grasp gestures, hereafter called conflictual objects (e.g., a soap distributor) and the processing of those objects is usually, but not always, compared with the processing of objects associated with similar gesture for both kind of actions, hereafter called non-conflictual objects (e.g., a glass). Using this paradigm, it has been highlighted that the co-activation of structural and functional affordances modulates initiation times of object-directed actions (Bub et al., 2018; Jax & Buxbaum, 2010, 2013).

Figure 19. The experimental setup used by Jax & Buxbaum (2010). The participant wears occlusive eye glasses. Participant's right-hand rests on a button device during experimental sessions. Objects are positioned in front of the participants. At the signal (i.e., when eye glasses open), participants are asked to position their hand on the object as if they were going to grasp or use it, depending on the condition. Time between the signal and the onset of the movement (i.e., initiation time) are recorded. *Figure from Jax & Buxbaum (2010).*

Longer initiation times for conflictual than non-conflictual objects are usually reported, with some nuances in the results. In Jax & Buxbaum (2010), two groups of participants produced reach-to-use and reach-to-grasp movements in alternate blocks. They observed two patterns of interference for conflictual objects whereas no interference effect was observed for non-conflictual objects. The first interference effect was a *grasp-on-use interference*, characterized by longer initiation times for producing an using gesture on a conflictual object compared to the same action on a non-conflictual object, irrespective of the block of trials being performed first. The second interference effect was a *long-term use-on-grasp interference*, characterized by longer initiation times for producing a grasping gesture on a conflictual object compared to the same action on a non-conflictual object. Tellingly, this second interference was only present when the use gesture was produced in a first block suggesting that the effect was long-lasting. Bub & Masson (2018)'s study nuances these asymmetrical interference effects.

They observed equivalent *grasp-on-use* and *use-on-grasp interference* effects for switch of gestures on the same object (e.g., using the cellphone followed by lifting the cellphone) compared to switch of gestures on different objects (e.g., using the cellphone followed by lifting the pencil), independently of the order of gesture production. Overall, both studies highlight the negative impact of the co-activation of distinct affordances on the planning of object-directed actions. However, these studies do not inform us on the impact of the co-activation of affordances on mere object perception.

2. Impact of the co-activation of affordances on object perception

Recent studies investigated the impact of the co-activation of affordances on mere object perception (Kalénine et al., 2016; Wamain et al., 2018) with an experimental procedure inspired from Jax and Buxbaum (2010, 2013)'s studies, with objects presented in a 3D virtual environment (see **Figure 20**). Assuming that mere object perception must afford their typical actions (Borghi & Riggio, 2015; Buxbaum & Kalénine, 2010; Ellis & Tucker, 2000) and that affordances are activated depending on the action constraint of the observer (Iachini et al., 2014), authors decided to first determined individual reaching boundaries of participants. They asked participants to judge whether a cylinder presented at different distances on a virtual table was reachable or not. By means of their responses, they computed the individual perceived boundary of reachability. Therefore, the 3D images of objects used for the experimental procedure were generated for each individual - according to its perceived reachability boundary - in three spaces: the individual reachable and unreachable spaces and the limit of their borders. The second assumption was that, if the co-activation of distinct affordances, when perceiving a conflictual object, has a negative impact on the perceptual processing, then we should observe a cost for assessing visual characteristics of conflictual objects compared to non-conflictual objects, but only when affordances are activated, meaning in the reachable space of participants (Wamain et al., 2016). The stimuli employed were 3D virtual images of conflictual objects and non-conflictual objects (see **Box 2. Definitions of conflictual and non-conflictual objects** for details). Participants were asked to categorized the objects according to two different judgment tasks: "Is it reachable?" and "Is it a kitchen object?". The two judgement tasks were initially considered in order to evaluate whether affordance effects would be sensitive to the greater or lesser relevance of the task for action. Kalénine et al. (2016)'s results showed that, regardless of the task, participants exhibit longer response times for conflictual objects compared to non-conflictual objects but, as expected, this effect was only evidenced when objects were presented in the reachable space of participants. This finding demonstrates that the co-activation of distinct affordances induces a competition. This competition between distinct affordances creates a perceptual processing cost that depends on the possibilities of the observer to interact with the perceived objects.

Figure 20. On the upper part of the picture, a participant wearing an EEG cap in front of the system displaying the 3D virtual environment. On the lower part of the picture, two exemplars of object picture displayed for the experiment: a conflictual object (left) and a non-conflictual object (right). *Figure selected from Kalénine et al. (2016).*

Intermediate synthesis

Overall, those studies provide behavioral supports for the hypothesis that structural and functional affordances associated with a single object may compete with one another and this competition may be detrimental to action production and object perceptual processing in adults. However, although they constitute strong evidence toward the consequence of the co-activation of affordances on object perception, those studies do not inform us about the mechanisms at play in this processing cost. The processing cost observed during action production and object perception with conflicting affordances may be the consequence of different complementary mechanisms.

III. Neurophysiological assessments of the co-activation of affordances

1. Involvement of distinct neurocognitive mechanisms in affordance selection

Dissociations between the brain regions involved in *affordance specification* as opposed to *affordance selection* during the perception and performance of object-directed actions have been recently provided (Schubotz et al., 2014; Watson & Buxbaum, 2016). Watson & Buxbaum (2016) asked thirty-one left hemispheric stroke patients to perform pantomime tool-use actions for conflictual and non-conflictual objects. Lesion-behavior mapping analyses showed that stroke patients with lesions of posterior brain areas (e.g., posterior middle temporal gyrus, pMTG or anterior intraparietal cortex, AIP) tended to be impaired in the production of tool-use actions for both conflictual and non-conflictual objects. In contrast, patients with lesions of more anterior brain areas (e.g., supramarginal gyrus, SMG or inferior frontal gyrus, IFG) tended to be selectively impaired in the production of tool-use action for conflictual objects. These results suggest that posterior brain areas (e.g., pMTG and AIP) are involved in the processing of object affordances in general while anterior brain areas (e.g., SMG and IFG) reflects the competition between possible actions.

Schubotz et al. (2014) provided additional fMRI results on healthy participants. Their participants viewed movies of actions with object pairs. The number of action codes (NAC, see **Box 2. Definitions of conflictual and non-conflictual objects** for a complete description) that could be performed with each object pair was assessed before the experiment. Participants were asked to passively watch videos of actions performed with object pairs, some videos showing actions in compatible and some in incompatible situations. For the compatible situations, videos displayed an action performed with the appropriate object pair (e.g., peeling an apple with a knife) while in incompatible situations, videos displayed an action performed with the inappropriate object pair (e.g., a peeling movement but with inappropriate object-pair: a pencil and a sharpener). Brain activity was recorded while participants were watching the videos. Authors were interested in the brain response to NAC in compatible and incompatible situations. Results showed that the activity of posterior brain areas, namely the left anterior intraparietal cortex (AIP) and the left posterior middle temporal gyrus (pMTG), covaried with the NAC independently of the compatibility of the situation. In contrast, the activity of anterior brain area, namely the bilateral premotor cortex (PMC), covaries with the NAC in compatible situation. These results suggest that while posterior brain areas specify the number of potential actions, anterior brain areas reflect their exploitation to resolve the competition. Overall, these studies strongly support recent neurobiological models that account for affordance competition (Caligiore & Borghi, 2010; Cisek, 2007; Cisek & Kalaska, 2010; Fagg & Arbib, 1998) and suggest that *affordance specification* and *affordance selection* rely on at least partially distinct neurocognitive mechanisms.

2. Mu (μ) rhythm desynchronization as a marker of affordance selection

The involvement of the fronto-parietal dorsal stream in the resolution of the competition between affordances has also been approached with electroencephalographical methodology (Wamain et al., 2018). They focused their analyses on the μ rhythm desynchronization over centro-parietal regions. The μ rhythm corresponds to a 8 to 12Hz frequency range that is typically associated with the activity of the motor system (Pineda, 2005). Its desynchronization is thought to represent the motor resonance associated with the processing of motor information in the environment. It has been reported to be sensitive to planification and execution of actions (Babiloni et al., 1999, 2016; Llanos et al., 2013; Pfurtscheller et al., 2006; van Elk et al., 2010), action observation (Cochin et al., 1999; Moreno et al., 2013) and recently to mere object perception (Marini et al., 2019; Proverbio, 2012; Wamain et al., 2016, 2018).

In the context of object perception, it has been suggested that the μ rhythm desynchronization would reflect affordance perception (Proverbio, 2012; Wamain et al., 2016) and may even constitutes an interesting electrophysiological marker for studying *affordance selection* processing (Cisek, 2007; Cisek & Kalaska, 2010) during affordance competition (Wamain et al., 2018). More specifically, Proverbio (2012) observed an early μ desynchronization over the centro-parietal region while perceiving tools compared to non-manipulable objects. Wamain et al. (2016)'s study extended these results by showing that the μ rhythm desynchronization, associated with manipulable object perception, was dependent on motor capacities of the observer. To reach such a conclusion, they presented manipulable objects and scrambled version of these objects (see **Figure 21** for exemplars) in a 3D virtual environment at different distances. They observed a stronger μ desynchronization for objects compared to scrambled objects, when they were presented in the reachable space compared to the unreachable space of participants. Together, both studies suggest that the μ rhythm desynchronization would reflect affordance perception while perceiving manipulable objects.

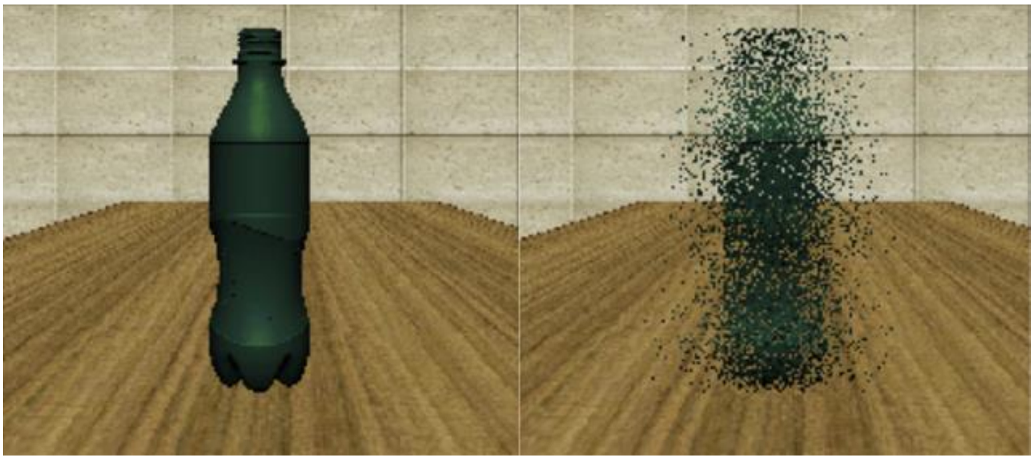

Figure 21. Exemplars of the 3D picture of an object and its scrambled version from Wamain et al. (2016).

In line with Kalénine et al. (2016)'s work, the study of Wamain et al. (2018) was conducted to evaluate the impact of the co-activation of distinct structural and functional affordances on μ rhythm desynchronization. They used a similar experimental procedure as in Kalénine et al. (2016) but they additionally recorded brain electrical activity using EEG. Participants were instructed to performed reach-to-grasp and semantic judgements on 3D objects presented at reachable and unreachable distances in a virtual environment. They were informed to respond only when a question mark followed object presentation. If μ rhythm desynchronization only reflects the activation of affordances, higher μ rhythm desynchronization for conflictual objects compared to non-conflictual objects would be expected, as conflictual objects are associated with more affordances. If the μ rhythm desynchronization reflects the activation of affordances and the sensitivity of the motor system to their competition, release of the μ rhythm desynchronization for conflictual objects would be expected. Wamain et al. (2018) observed a reduction and even a suppression of the μ rhythm desynchronization while perceiving conflictual objects compared to non-conflictual objects but only when objects were presented in the reachable space. Thus, their results suggest that the competition between distinct structural and functional affordances affects the motor resonance associated with the motor system. More precisely, they highlighted that the motor resonance of the motor system while perceiving manipulable objects would not exactly reflect overall affordance perception but instead *affordance selection* mechanism. Therefore, the μ rhythm desynchronization constitutes a relevant electrophysiological marker for studying *selection* processing during affordance competition.

Global synthesis

In this chapter, we described recent neurobiological models that account for the perception of multiple affordances. We discussed about the way action parameters are perceived in the environment, on how they are selected and what information is used for biasing the competition between those parameters toward relevant ones. We reviewed the few pieces of experimental evidence demonstrating consequences of the co-activation of distinct affordances on object processing. Specifically, we highlighted that structural and functional affordances associated with a single object compete with one another and this competition may be detrimental to production of object-directed actions and object perceptual processing in adults. Then, we determined that the processing cost observed during action production and object perception must involve distinct neurocognitive mechanisms, namely *affordance specification* and *affordance selection*. We finally suggested that the study of motor neural resonance (i.e., μ rhythm) using electroencephalography is a suitable methodology for studying the impact of the co-activation of distinct affordances on object perception. In the last part of the present chapter, we will anchor the scope of the present thesis work according to this growing field of research.

GOALS OF THE PRESENT THESIS

The present thesis project is directly in line with previous studies evaluating the impact of the co-activation of multiple affordances on object perceptual processing (Kalénine et al., 2016; Wamain et al., 2018) while perceiving a single object. The project aimed at assessing how intra- and inter-individual variabilities modulate the impact of affordance competition on object perception, through behavioral (i.e., response times) and electrophysiological (i.e., *µ* rhythm desynchronization) indicators. Regarding inter-individual variability, we sought to identify the age period(s) when individuals are more sensitive to affordance competition. Additionally, we explored the respective involvement of *affordance specification* and *affordance selection* mechanisms in age-related changes in affordance competition, through independent assessments. Regarding intra-individual variability, we sought to determine whether contextual information may modulate affordance competition and contribute to the resolution of the competition between affordances during perceptual processing of objects.

The project will be divided into three experimental chapters. The first chapter will present preliminary investigations that aim at clarifying the action properties that are actually evaluated with different paradigms designed for assessing affordance perception. The second chapter will evaluate how the impact of the co-activation of multiple affordances on object perceptual processing evolves across development, and will assess the involvement of *affordance specification* and *selection* mechanisms in affordance competition. Finally, the third chapter will report an electroencephalographic study exploring the influence of verbal context on the resolution of affordance competition by focusing on neural motor resonance (i.e., *µ* rhythm desynchronization). We below describe the main objectives of each experimental chapter in more detail.

The first chapter will concern the evaluation of affordance evocation. There is indeed considerable evidence that visually presented manipulable objects evoke motor information, supporting the existence of affordance effects during object perception. However, most arguments come from stimulus-response compatibility paradigms. Such paradigms have been largely criticized in the literature. Some argued about their potential contamination of spatial compatibility and other questioned the automaticity of the measured affordance effects. Several experimental paradigms have been then designed in order to measure affordance effects more purely. Indirect evidence suggest that certain versions of the stimulus-response compatibility paradigm, such as when implementing delayed handle-response compatibility, may overcome this limitation. Additionally, action priming paradigms are thought to overcome the issue of the contamination by spatial compatibility, but show less reliable results, possibly because affordance effects are moderated by additional factors. In Chapter 4, we will briefly report pilot investigations conducted in order to choose the appropriate paradigm to explore the involvement of the mechanism of *affordance specification* in affordance competition (see Chapter 5). Then, we will report a published study that investigated more precisely the action priming paradigm. Especially, we tested whether additional moderating factors, such as manipulable object category (i.e., manufactured or natural), could account for the weakness of action priming paradigm in demonstrating affordance effects.

The second chapter will concern the identification of the developmental trajectory of the consequence of the co-activation of multiple affordances on object perceptual processing. In light of recent affordance models (Cisek, 2007; Cisek & Kalaska, 2010), we assumed that the negative impact of affordance competition on object perceptual processing may result from the joint contribution of two mechanisms, *affordance specification* and *affordance selection* (Schubotz et al., 2014; Watson & Buxbaum, 2016), and may show a non-linear developmental trajectory. Five age groups from 8-year-olds to adulthood participated (N = 131). Like in previous adult studies (Kalénine et al., 2016; Wamain et al., 2018), participants performed perceptual judgements on different 3D objects in a virtual environment in order to assess their affordance conflict cost. Participants performed two complementary tasks, an action priming task and a Simon task to measure *affordance specification* and *affordance selection* mechanisms, respectively.

The third chapter will concern the influence of the verbal context on the resolution of affordance competition. There is indeed considerable evidence that affordance evocation is sensitive to several contextual factors (see Chapter 2). Affordances are mainly activated when objects are perceived within reach (Wamain et al., 2016), an effect enhanced in presence of a congruent verbal context (Costantini et al., 2011). At the neurophysiological level, the selective cost for conflictual object is reflected by a reduction of μ rhythm desynchronization, suggesting that competition between object affordances alters motor resonance during manipulable object perception (Wamain et al., 2018). Using EEG, we tested whether a congruent action verb could help the resolution of the competition between object affordances and induce a release of μ rhythm desynchronization during object perception. The study was conducted on 25 participants (recruitment interrupted by COVID-19). Participants had to make perceptual judgements on 3D conflictual objects (e.g., calculator, affording both clench and poke) presented at different distances in a virtual environment while EEG was recorded. Objects were preceded by an action verb congruent with their typical use action (e.g., compute) or a neutral verb (e.g., observe).

EXPERIMENTAL CONTRIBUTION

CHAPTER 4. MULTIPLE PARADIGMS ASSESSING AFFORDANCES: WHICH ONE SHOULD WE CHOOSE?

One of the main objectives of the present thesis was to investigate how inter-individual variabilities modulate affordance competition during manipulable object perception (see Chapter 5). In light of recent affordance models (Cisek, 2007; Cisek & Kalaska, 2010), we assumed that the negative impact of affordance competition on the perceptual processing of manipulable objects may result from the joint contribution of two mechanisms, *affordance specification* and *affordance selection* (Schubotz et al., 2014; Watson & Buxbaum, 2016). More particularly, we wanted to explore how both mechanisms are involved in the affordance competition, through independent assessments. As a reminder, *affordance specification* refers to the evocation of affordances from the environment and that *affordance selection* refers to the exploitation of affordances for action selection. In the present chapter, we will explore the evocation of affordances during manipulable object perception.

There is considerable evidence that manipulable objects that are presented visually evoke motor information which support the existence of affordance effects during object perception (i.e., *affordance specification*). However, most arguments come from stimulus-response compatibility paradigms, raising multiple issues. (1) Affordance effects measured by handle-response compatibility paradigms could be tainted by the spatial compatibility between the side of the response hand and the side of the object handle. (2) Affordance effects produced by direct perception of an object could be induced by the overlapping of size codes. (3) Finally, the use of specific motor responses questions the automaticity of affordance effects. Several experimental paradigms have thus been designed to measure object-based affordance effects more purely, with paradigms such as delayed handle-response compatibility or action priming. However, only indirect evidence suggests that the delayed handle-response compatibility paradigm may overcome the first limitation (i.e., spatial compatibility). As far as action priming paradigms are concerned, although they overcome most issues, results are less reliable, possibly because of the additional factors that moderate the affordance effects.

The present chapter will be divided into two sections. First, we will briefly describe a pilot study that was conducted in order to select an appropriate paradigm for assessing *affordance specification*. We chose to investigate two paradigms that have been classically used to this aim in the literature: the action priming paradigm (Borghi et al., 2007) and the delayed handle-response compatibility paradigm (Dekker & Mareschal, 2014). Second, we will report a study that investigate whether manipulable object category (i.e.,., manufactured or natural) could partially account for the weakness of action priming paradigm in demonstrating affordance effects (Borghi et al., 2007).

Section 1. Pilot study for selecting a paradigm assessing affordance evocation phenomenon

In the previous chapters, we acknowledged close connections between action and the perception of manipulable objects, according to grounded views of cognition (Barsalou, 2008, 2020). In particular, we established that object perceptual and conceptual processing are affected by the evocation of the typical gestures and motor interactions associated with objects (Osiurak et al., 2017; Thill et al., 2013). Such phenomena have been described as affordance effects, which refers to the activation of some action components during object perception (Borghi & Riggio, 2015; Buxbaum & Kalénine, 2010; Ellis & Tucker, 2000).

In Chapter 2 of the introduction, we mentioned that princeps studies on affordance effects used stimulus-response compatibility paradigms, either using compatibility between handled objects and lateralized responses (Fischer & Dahl, 2007; Pellicano et al., 2010; Tucker & Ellis, 1998) or compatibility between real size of objects and small or large grip responses using a specific device (Tucker & Ellis, 2001). In handle-response compatibility paradigm, response times for categorizing objects are typically faster when the handle is oriented toward the button to press, compared to when it is oriented toward the opposite direction. In the second paradigm, response times are usually faster when the responses are compatible with the grip evoked by object real size. In both cases, results are usually interpreted as an automatic activation of action components associated with the object during object perceptual processing. Yet we acknowledged that these interpretations face three challenges. We will raise them again below.

(1) First, the affordance effects measured by handle-response compatibility paradigms could be tainted by the spatial compatibility between the side of the response hand and the side of the object handle. There is indeed a huge literature on the so-called Simon effect, i.e., the fact that

people are faster to categorize a target when its spatial position (left or right part of the screen) is compatible with the hand of response (Simon, 1969). Hence, in handle-response compatibility paradigms, facilitation of handle-compatible responses could have occurred without evoking the specific grasping gestures of the objects and may be merely due to a spatial compatibility effect.

(2) Second, the affordance effects measured by the stimulus-response compatibility paradigm using the specific device (Tucker & Ellis, 2001) could not reflect the activation of the grip evoked by object real size. Indeed, real object perception provides direct visual information about object size (Heurley et al., 2020). Thus, affordance effects could occur without motor information being a part of the object conceptual representation and could merely be due to a visuomotor size matching.

(3) Third, the presence of a specific motor response questions the automaticity of affordance effects.

While the first challenge remains an issue and is still debated, the second and third challenges have been easily overcome. To prevent any direct visual information about object real size (2nd challenge), objects have been displayed in standard size (Borghi et al., 2007; Ni et al., 2018; Yu et al., 2014). Additionally, authors proposed alternative paradigms that do not involve specific motor responses (3rd challenge) to investigate affordance effects during object visual processing (Borghi et al., 2007; Dekker & Mareschal, 2014).

Yet, several experimental paradigms have been designed in order to disentangle affordance effects from spatial compatibility effect (1st challenge). In some cases, it was proposed to modulate how participants produce manual responses by asking them to complete the task with both hands crossed (Vergilova & Janyan, 2012) or by using two fingers of the same hand (Pappas, 2014). In other cases, it was proposed to modulate stimulus presentation, by varying stimulus location vertically (Saccone & Churches, 2016) or by adding a delay between stimulus presentation and response (Dekker & Mareschal, 2014; Phillips & Ward, 2002). In the present thesis, we had to select a paradigm that would be suitable to assess affordance evocation in children from 8 with ease. We chose to design the delayed handle-response compatibility paradigm from Dekker & Mareschal (2014) for two reasons. First, the implementation of the paradigm and the task (i.e., categorizing the color of a target cross) was easily achievable by children. Second, this paradigm already demonstrated affordance effects in children (Dekker & Mareschal, 2014). This paradigm consists in the presentation of a handled-object (e.g., a mug) and a color target cross. Participants have to respond according to the color of the cross irrespective of the direction of the object handle by pressing left or right response buttons. As it is generally admitted that spatial compatibility effects fade after 200 ms (Hommel, 1994b, 1994a), a delay has been introduced (400, 800 or 1200 ms) between the presentation of the handled object (e.g., a mug) and the target cross eliciting the response, assuming that effects observed for delays longer than 200 ms would mostly rely on affordance effects. Nevertheless, the spatial component is still present and the contamination of affordance effects by spatial compatibility cannot be definitively ruled out.

Another alternative to measure affordance effects is the action priming paradigm mentioned in Chapter 2 of introduction. Such paradigm does not involve any spatial compatibility (Borghi et al., 2007; Godard et al., 2019; Ni et al., 2018; Vainio et al., 2008). In this paradigm, participants are usually asked to categorize object pictures that are primed by pictures of hand postures that could be compatible (e.g., orange – clench), incompatible (e.g., orange – pinch) or neutral (e.g., orange – palm) with the usual way to grasp the object. Faster response times are typically observed when object pictures are preceded by compatible hand primes compared to incompatible or neutral hand primes. For instance, Borghi et al. (2007) reported a priming effect with shorter RTs for compatible than for incompatible hand primes, but only when the grasp presented in the prime had been previously practiced by the participants. Although the demonstration of priming effects is promising, the presence of prior action practice weakens the impact of priming results regarding the automaticity of affordance evocation.

However, many additional factors may explain the low reliability of action priming effects. For instance, affordance effects have been shown to be modulated by motor experience (Yee et al., 2013), visual scene (Kalénine et al., 2014), task demands (Sakreida et al., 2016, 2013) and object types (Ferri et al., 2011). Interestingly, when Ferri et al. (2011) asked participants to categorize objects as natural or manufactured using compatible or incompatible reach-to-grasp movements, they found affordance effects for manufactured objects but not for natural objects. Thus, the difficulty to highlight priming effects in studies such as Borghi et al. (2007) may also be due to the mix of different object categories, some of them showing the effect and some others do not. Hence, we faced two potentials paradigms to assess *affordance specification* from childhood. Nevertheless, both include their own issues. Therefore, we decided to conduct pilot investigations to select the most appropriate paradigm, to assess *affordance specification* mechanisms among the two paradigms.

Curiously, during the implementation of the delayed handle-compatibility paradigm, we encountered multiple issues (e.g., retinal persistence). When such issues were overcome, we were surprised that our preliminary results indicated only weak evidence for the existence of a handle compatibility effects as opposed to previously reported results (Dekker & Mareschal, 2014). Reasons for such discrepancies are not clear. The only difference between the protocols (see **Box 3. Implementation of the delayed handle-response compatibility paradigm.** for a detailed implementation of the paradigm) was that the 800 ms SOA was presented in isolation and not interleaved with other delays in the same block. A possible attenuation of the effect in the absence of jittering should be considered. The recent meta-analysis by Azaad et al. (2019)

indeed showed that the size of compatibility effects is sensitive to a certain range of habituation phenomena. Hence, the details of the implementation of the delayed handle-response compatibility paradigm should be considered carefully for affordance assessment. Therefore, we selected the action priming paradigm to assess evocation of affordances to study *affordance specification* mechanisms (see Chapter 5). We however bear in mind that action priming paradigm also involve issues. More specifically, action priming could be sensitive to manipulable object categories. In the following section, we will report a study that investigate whether manipulable object category (i.e., manufactured or natural) could partially account for the weakness of action priming paradigm in demonstrating affordance effects (Borghi et al., 2007).

Box 3. Implementation of the delayed handle-response compatibility paradigm.

Materials & Procedure

Participants were seated approximately 60 cm from a 27" computer screen (1920 x 1080 pixels, 120 Hz) in which stimuli were displayed using MatLab 9.2 (MathWorks Natiek, USA) and Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). They performed the task. They were instructed to respond for each trial by pressing the "q" and "m" keys of an AZERTY keyboard with their left and right hands, while accuracy and response times were recorded. Procedure is displayed on **Figure 22** below.

Delayed handle-response compatibility paradigm

The task was identical to the one developed by Dekker and Mareschal (2014), in the condition of delay were handle-response compatibility effects were the most reliable (800 ms). Two high resolution photographs of a dark grey mug (with the handle oriented toward the left or right) were selected from an open-source database (Pixabay). Pictures were presented at 12.5° of visual angle and were displayed in the middle of the screen on a grey background.

Mug pictures were inserted in a delayed handle-response compatibility paradigm. Each trial started with a fixation point presented in the center of the screen for 1500 ms followed by the picture of the mug for 800 ms. Then, a red or green cross was presented in superposition and centered on the mug (2.6° of visual angle) until participants' response or for a maximum of 2000 ms. Participants were asked to categorize the color of the cross by pressing the two response buttons with their left and right hand. Response mapping was counterbalanced between participants. Trials could be identified as compatible (i.e., when mug handle was oriented toward the response button to press) or incompatible (i.e., when the mug handle was oriented toward the opposite direction to the response button to press). Participants performed 258 trials (half compatible and half incompatible) randomly presented into two testing blocks and preceded by 20 practice trials.

Figure 22. Procedure of an **experimental** trial of the delayed handle-response compatibility paradigm. Two conditions: grasp compatible (left) vs. grasp incompatible (right).

Section 2. Do manufactured and natural objects evoke similar motor information? The case of action priming.

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Abstract: There is considerable evidence that visually presented manipulable objects evoke motor information, supporting the existence of affordance effects during object perception. However, most arguments come from stimulus–response compatibility paradigms, raising the issue of the automaticity of affordance effects. Action priming paradigms overcome this issue but show less reliable results, possibly because affordance effects are moderated by additional factors. The present study aimed to assess whether affordance effects highlighted in action priming paradigms could be affected by object category (manufactured or natural). A total of 24 young adults performed a semantic categorization task on natural and manufactured target objects presented after neutral (non-grasping hand postures) or action (congruent power or precision grips) primes. Results revealed a modulation of action priming effects as a function of object category. Object semantic categorization was faster after action than neutral primes, but only for manufactured objects. Results suggest that natural and manufactured objects evoke distinct types of affordances and that action priming paradigms favor the evocation of functional affordances during object semantic categorization. This finding fuels the debate on the nature of the motor information evoked by visual objects.

Keywords: Embodied cognition; priming; action representations; object concepts; semantic categorization

Introduction

The literature on visual perception highlights close connections between action and the perception and recognition of objects, in accordance with embodied and grounded views of cognition (e.g., Barsalou, 2008; Gallese & Lakoff, 2013). In particular, motor affordance effects show that object perceptual and conceptual processing is affected by the evocation of their typical gestures (Thill et al., 2013; van Elk et al., 2013, for review). At the neural level, affordance effects are supported by the activation of motor brain areas during perception and identification of manipulable objects (Gerlach et al., 2002).

Classically, the effects of object affordances on perceptual and semantic judgements are demonstrated in visuomotor tasks (Bub et al., 2018; Lindemann et al., 2007; Tucker & Ellis, 2001). In one first study, Tucker and Ellis (2001) showed activation of object motor properties during object semantic categorization using a stimulus–response compatibility paradigm. Real objects that could be small (i.e., grasped with a precision grip) or large (i.e., grasped with a power grip) were presented. Participants had to determine whether objects were natural or manufactured by grasping a device with either a precision or a power grip. Response times (RTs) were faster when the response grip was compatible with the grip evoked by object real size. Results were interpreted as automatic activation of the specific grasp gestures associated with the object when accessing the object concept. Yet this interpretation faces two challenges. First, real object perception provides direct visual information about object size. Thus, affordance effects could occur without motor information being a part of the object conceptual representation. The issue has been overcome by displaying objects in a standardized size (Borghi et al., 2007; Ni et al., 2018; Yu et al., 2014). Second, the presence of a specific motor response questions the automaticity of affordance effects. Some authors have thus proposed alternative paradigms that do not involve specific motor responses to investigate affordance effects during object visual processing.

Action priming paradigms may be particularly relevant in this regard (Borghi et al., 2007; Helbig et al., 2010; Kalénine et al., 2009; Ni et al., 2018; Perraudin & Mounoud, 2009). In one first priming study, Borghi et al. (2007) presented object pictures in their standardized size that were primed by pictures of hand postures. Each object was presented three times, once with a compatible hand posture (e.g., orange-clench), once with an incompatible hand posture (e.g., orange-pinch), and once with a nongrasping hand posture (e.g., orange-palm). Participants had to categorize target objects as manufactured or natural by pressing two different keys. When the prime displayed the palm posture, they had to refrain from responding (catch-trials). The authors reported a priming effect with shorter RTs after compatible than incompatible action primes, but only when the grasp presented in the prime had been previously practiced by the participants. Although the demonstration of priming effects is promising, the presence of prior action practice weakens the impact of priming results regarding the automaticity of affordance evocation.

However, many additional factors may explain the low reliability of action priming effects. For instance, affordance effects have been shown to be modulated by the visual scene (e.g., Kalénine et al., 2013), action intentions (e.g., Lee et al., 2012), task demands (e.g., Tipper et al., 2006), and object types (e.g., Ferri et al., 2011). Interestingly, when Ferri et al. (2011) asked participants to categorize objects as natural or manufactured using compatible or incompatible reach-to-grasp movements, they found affordance effects for manufactured objects but not for natural objects. Thus, the difficulty to highlight priming effects in studies such as Borghi et al. (2007) may also be due to the mix of different object categories, some of them showing the effect and some others not. The present study aims to assess whether manufactured and natural objects show similar affordance effects in action priming. An adaptation of Borghi et al.'s (2007) paradigm was used. If object category accounts, at least to some extent, for the vulnerability of action priming effects, then we should observe a modulation of action priming according to object category with greater (or even exclusive) priming for manufactured objects.

Method

Participants

A total of 24 adults (mean age = 25 years, age range = 18–53 years, 14 women) took part in the experiment[10]. All participants were right-handed and had normal or corrected-to-normal visual acuity. The entire protocol was approved by the ethical committee of the university and was in accordance with the Declaration of Helsinki (1964, revised in 2013). All participants gave written informed consent and were not paid for their participation.

Stimuli

Photographs of manipulable objects were selected from open-source database (Pixabay). Object size was standardized. Objects were displayed in a fictive square of 500 × 500 pixels on a black background centered on their horizontal axis. Among the 50 objects selected (40 for test-trials + 4 for catch-trials + 6 for practice-trials), 25 were manufactured (e.g., bowl) and 25 were natural (e.g., apple). In each category, half of the objects were usually grasped with a precision grip (e.g., cherry, marble) and half were usually grasped with a power grip (e.g., apple, bowl) according to their real size. The 40 test object pictures are presented in **Appendix 4.**and **Appendix 5.**)

Photographs of a hand in five different postures were designed and displayed on a black background. The center of the hand was placed in the middle of the screen. Among the five hand pictures, two displayed a grasping hand posture (power or precision grip) and three displayed a non-grasping hand posture (palm-up, palm down, and fist). All pictures were

[10] Sample size was determined using the power.t.test function of the pwr R package considering a medium effect size and a statistical power of 0.80 for the expected priming advantage for artefact versus natural objects.

displayed on a 27″ screen (1,920 × 1,080 pixels, 120 Hz) with MATLAB 9.2 (MathWorks, Natick, USA) and Psychophysics Toolbox extensions.

Controls of the stimuli. Thirteen additional participants judged the overall manipulability and the variability of manipulation of the 40 objects used in the experiment that were presented among 40 fillers selected from Salmon, McMullen, and Filliter (2010). They rated on a 5-point Likert-type scale (a) "the manipulability of the object according to how easy it is to grasp and use the object with one hand" and (b) "the extent to which the way you manipulate the object can vary for each manipulation." Natural and artefact objects were judged as highly and equally manipulable (median = 5 [range = 5–5] for natural objects and median = 5 [range = 5–5] for manufactured objects). Moreover, natural and artefact objects showed low and equivalent variability in the way they are manipulated (median = 2 [range = 1–2] for natural objects and median = 2 [range = 1–3] for manufactured objects).

Procedure

Participants were seated 60 cm from the screen. Stimuli were inserted in an action priming paradigm with hand pictures as primes and object pictures as targets. Each trial started with a fixation cross presented at the center of the screen for 500 ms followed by one of the hand primes for 500 ms (**Figure 23**). Then, the object target was presented until participants' response or for a maximum of 4,000 ms. Participants were asked to categorize the object as natural or manufactured by pressing the "q" and "m" keys of an Azerty keyboard with their left and right hands. Response mapping was counterbalanced between participants. RTs and errors were recorded.

During the test phase, each target object was presented twice, once with the appropriate grasping hand prime (power or precision grip) in the action priming condition and once with one of two non-grasping hand primes (palm down or fist) in the neutral priming condition, leading to 80 experimental trials. Eight additional catch-trials (10%) were designed using four additional target objects presented with the palm-up "no-go" prime. On catch-trials, participants were asked to refrain from responding to ensure that they paid attention to the primes. The 88 trials were randomly presented. Participants performed 20 representative practice trials beforehand involving six additional target objects.

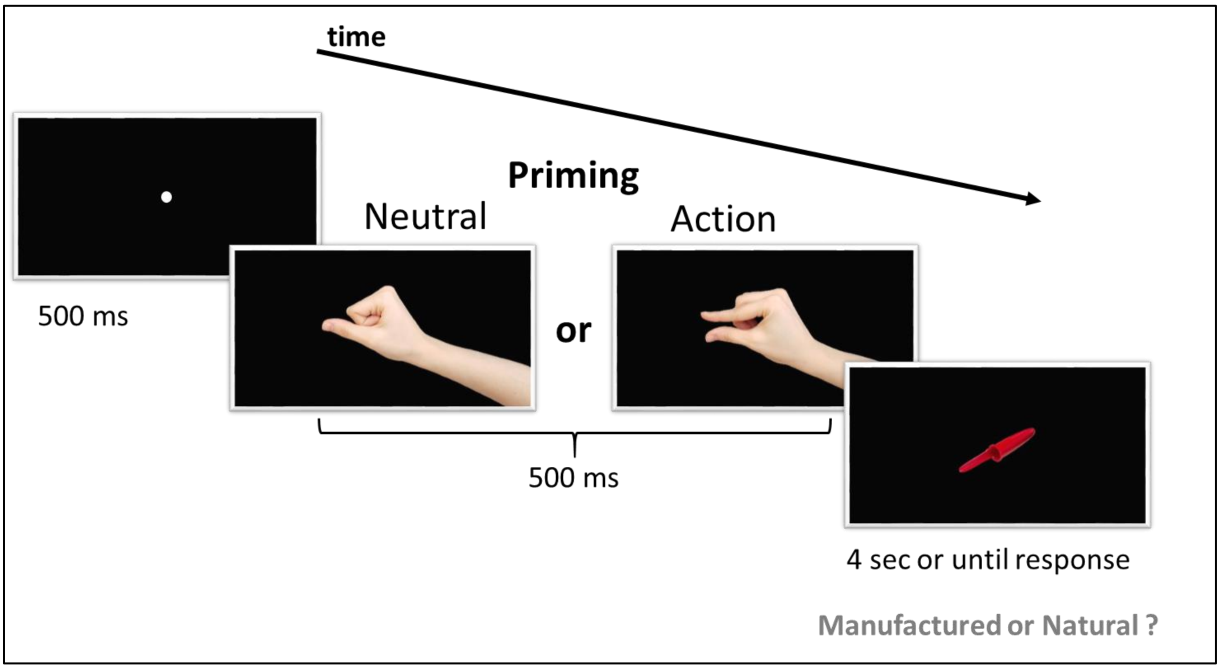

Figure 23. Procedure of an experimental trial in the two priming conditions: neutral priming (left) versus action priming (right).

Results

Performance on catch-trials was verified for each participant mean accuracy = 93%, minimum = 63%) but analyses were restricted to critical trials. RTs inferior to 200 ms and superior to 3,000 ms (1%) and RTs for incorrect responses (3%) were excluded from the analyses. RTs were finally trimmed by removing those exceeding 3 standard deviations from the participant's mean in each condition. Overall, 3.13% of RTs were excluded (3.96% for neutral priming for manufactured objects, 4.38% for action priming for manufactured objects, 2.71% for neutral priming for natural objects, and 2.08% for action priming for manufactured objects).

Mean RTs and standard deviations in the different conditions are reported in **Table 1**, and raw data are available at: https://osf.io/8qzkc/?view_only=4f0b14f72e3940f38bfff87bfa2499c0.

Logarithmic transformation was applied on RTs. Visual inspection of the distribution of residuals after log-transformation did not show important deviations from normality.

A mixed-effect model was used to analyze log-transformed RTs as a function of Priming (action, neutral) and Category (natural, manufactured). Mixed-effect linear models do not require prior averaging of the data and allow taking into account differences between individuals and variation in their sensitivity to the factors of interest (Baayen et al., 2008, "random intercepts" and "random slopes", see below). In the present experiment, there were 24 subjects × 20 items = 480 RTs in each Priming × Category condition. We also added Grasp Type (power grip, precision grip) to the model, as it has been shown to influence RTs (Borghi et al., 2007). Thus, fixed effects corresponded to the effect of Priming, Category, Grasp Type, and their interactions. We predicted possible main effects of Priming, Category, Grasp Type, and a Category × Grasp Type interaction but more critically, we excepted an interaction between Priming and Category. The random effect structure of the model included participants as random effect factor with random intercepts and random slopes for priming (analyses were conducted with lme4 3.0-1 package of R version 3.4.4).

Table 1. Mean RTs in milliseconds (SD) as a function of Category (Manufactured, Natural), Grasp Type (Power Grip, Precision Grip) and Priming (Action, Neutral).

Manufactured				Natural			
Power Grip		Precision Grip		Power Grip		Precision Grip	
Action	Neutral	Action	Neutral	Action	Neutral	Action	Neutral
650.4	716.1	641.8	681.6	641.5	657.2	656	639.9
(139.2)	(170.1)	(120.2)	(201)	(176.3)	(182.9)	(162.7)	(115.2)

LmerTest package (version 3.0-1) was used to obtain significance F-tests of fixed effects. Denominator degrees of freedom were approximated using Satterthwaite's approximations. A R-squared value for the whole model was provided using the r.squaredGLMM function of the MuMIn package (version 1.42.1). Cohen d effect sizes were computed for relevant t-tests as the ratio between the estimated mean difference between conditions and the square root of the sum of the residual variance and the variance of the random effects of the model, following Westfall, Kenny and Judd (Westfall et al., 2014).

The entire linear model explained 37% of variance ($R^2 = .37$). There was a main effect of Category, $F(1, 1826.02) = 13.08$, $p = .001$. RTs were shorter for natural than for manufactured objects (estimate [manufactured − natural] = $+1.7 \times 10 - 2$, SE = $.498 \times 10 - 2$, $d = .13$). Importantly, we observe a main effect of Priming, $F(1, 671.31) = 9.91$, $p = .002$. RTs were 26 ms shorter for correct than neutral action priming (estimate [neutral − action] = $+1.63 \times 10 - 2$, SE = $.5 \times 10 - 2$, $d = .12$). There was no main effect of Grasp Type, $F(1, 1826.03) = 0.68$, $p = .409$, but a marginal two-way interaction between object Grasp Type and Category, $F(1, 1826.02) = 3.76$, $p = .053$. The advantage of natural (n) objects over manufactured (m) objects tended to be greater for objects grasped with a power grip compared with precision grip (estimate [(m − n)power grip − (m − n)precision grip] = $+1.9 \times 10-2$, SE = $.957 \times 10-2$, d = .14). The predicted interaction between Priming and Category was significant, $F(1, 1826.02) = 4.17$, $p = .041$. As expected, the interaction was due to the presence of a priming effect for manufactured objects (estimate = $+1.4 \times 10-2$, $t = 3.66$, SE = $.7 \times 10-2$, $p = .001$, $d = .20$) but not for natural objects (estimate = $+0.2 \times 10-2$, $t = .79$, SE = $.7 \times 10-2$, $p = .427$, $d = .04$). No other effect was significant.

Discussion

The present experiment confirms that the evocation of motor information associated with manipulable objects affects their semantic processing. Results showed that, overall, object semantic categorization was faster after action primes than neutral primes. Specifically, the presentation of typical grasping postures facilitated object categorization, even when displayed in a standardized size that does not provide direct information about the appropriate grip aperture. Furthermore, the priming paradigm did not involve the execution of specific grasping responses, reinforcing the idea that grasping postures may be evoked in the absence of specific motor plan. The functional role of motor information in object concepts is still largely debated (Mahon & Caramazza, 2008). In this context, the present results support the hypothesis that some motor attributes evoked by visual objects, along with other perceptual and non-perceptual features, are integrated to object conceptual representations, in line with embodied and grounded views of concepts (e.g., Barsalou, 2008). Critically, the present experiment further demonstrates that the facilitative effect of action priming on object semantic categorization is modulated by object category. Overall, semantic categorization was faster for natural than artefact objects, consistent with previous priming studies and with an interpretation of category-specific deficits related to the higher structural similarity among natural than artefact objects (Gerlach, 2016). Yet natural objects did not benefit from action priming. In contrast, results showed that the advantage of action primes over neutral primes was driven by manufactured objects and was actually not present for natural objects. The difference of action priming effects between object categories could not be accounted for by differences in overall manipulability or variability in object manipulation between natural and artefact object categories, since natural objects were judged as highly manipulable and as steady in their manipulation as artefact objects. The methodological and theoretical consequences of this distinction are discussed below.

Although Borghi et al. (2007) used a similar priming protocol, their priming results were not as clear-cut. In particular, they did not succeed to highlight action priming effects when the participants had no motor practice with the hand primes. The need of motor practice nuances the role of affordances in object concepts and may be a drawback for strong embodied views. At least, it suggests that action priming effects are not very robust. In the light of the present results, one possibility is that action priming effects in Borghi et al. (2007) are minimized with the use of different object categories. However, the authors did not report any modulation of the action priming effect by object category. The discrepancy may therefore originate from methodological choices. First, Borghi et al.'s (2007) protocol involved more object repetitions, which may have reduced the impact of action primes on target processing. Second, priming effects were computed using different baselines: incongruent action primes in their study (e.g., precision grip-orange) and neutral non-action primes (e.g., fist-orange) here. A more continuous activation of action information may have limited the activation of object-specific motor information (e.g., power or precision grip) on a trial basis and diminish priming effect amplitude. In Borghi et al.'s (2007) experiment 2, motor practice may have decreased the impact of repetition by increasing attention to the primes and trained the motor system to differentiate the two specific grasping postures, facilitating the emergence of priming effects. Consistent with this explanation, facilitative action priming effects have been observed with dynamic action primes (Vainio et al., 2008). In this study, participants performed a similar natural/manufactured semantic categorization task on object pictures that were preceded by several frames of the grasping movement. Although it benefitted to action priming, important motor simulation of the action primes was not sufficient to highlight a modulation of action priming effect by object category in none of the studies. One interpretation is that it changes the nature of the motor information evoked by hand primes. The theoretical interpretation of the category effects proposed below might be consistent with this possibility.

Theoretically, the impact of object category on action priming effects is highly relevant as it addresses the critical issue of the nature of the motor information evoked during conceptual processing of visual objects. Recent development of affordance theories has proposed a distinction between several types of affordances (Borghi & Riggio, 2015; Buxbaum & Kalénine, 2010). If natural and manufactured objects evoke distinct types of affordances and this type of action priming paradigm favors the perception of one type of affordances over the other, then action priming effects should be differentially visible depending on object category. Borghi and Riggio (2015) disentangled stable from variable affordances. Stable affordances correspond to affordances that are not context dependent, such as those related to object usual size. Variable affordances correspond to affordances that are context-dependent, such as those related to object orientation or location in space. In a similar line, Buxbaum and Kalénine (2010) distinguished functional from structural affordances. Functional affordances correspond to the evocation of the gestures associated with the typical use of the object (such as when manipulating the object according to its typical function). In contrast, structural affordances correspond to the evocation of the gestures associated with the typical grasp of the object (such as when picking-up the object according to its structural shape). The definition of functional affordances may overlap to a certain extent with that of stable affordances above, although it may be more restrictive: all functional affordances should be stable but not all stable affordances are functional (e.g., size-related motor information).

In the light of these recent distinctions, we suggest that the type of affordances evoked in the present action priming paradigm using hand primes are stable and more specifically functional affordances. As natural objects are usually not associated with specific use actions, functional affordances are the privilege of manufactured objects. Thus, the presence of category-selective action priming effects indicates that accessing object semantic involves the evocation of functional - but not structural - affordances. In other words, results suggest that the information related to how picking-up the object (structural affordance) does not participate in object semantic categorization while motor information related to how using the object (functional affordance) does lead to different action priming effects for natural and artefact object categories. This interpretation is consistent with the very recent priming results reported by Ni et al. (2018). Although Ni et al. (2018) did not directly compare priming effects between natural and manufactured categories, they showed that naming manipulable objects affording both functional and structural actions (e.g., a gun affording trigger and power grip actions) is facilitated by functional action primes but not structural action primes. The present results reflect the consequences of the functional/structural distinction between affordances on the relation between action and object semantic categories. It further suggests that functional affordances are critical for accessing not only single concepts of manufactured objects but also their superordinate category, despite previous evidence of weaker facilitative effects of action priming on superordinate compared with basic-level categorization (Kalénine et al., 2009). The superordinate categorization of manufactured objects would rely in part on the perception of their functional affordances, a phenomenon that may induce an additional cost. This cost may be reduced by the prior activation of functional gesture representations.

To conclude, we report facilitative action priming effects on object semantic categorization. Importantly, the effect was driven by manufactured objects and was not present for natural objects. The modulation of action priming by object category is consistent with recent distinctions between affordances and suggests that the paradigm assesses the evocation of functional affordances during object semantic categorization. Action priming paradigms may thus be a promising direction to refine affordance theories (e.g., Thill et al., 2013) while taking into account the different nature of the motor information evoked by natural and manufactured object categories.

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Conflict of interest statement

The authors declare no conflict of interest.

END

Global synthesis

One of the main objectives of the present thesis is to investigate how inter-individual variabilities modulate affordance competition during manipulable object perception (see Chapter 5). More particularly, we want to explore the involvement of *affordance specification* and *affordance selection* mechanisms in affordance competition, through independent assessments. In the present chapter, we explored paradigms evaluating affordance evocation during manipulable object perception (i.e., *affordance specification*) with the aim of selecting the most suitable paradigm for assessing *affordance specification* mechanisms from childhood in Chapter 5. We chose to design and test two experimental paradigms that have been classically used to this aim in the literature: the action priming paradigm (Borghi et al., 2007) and the delayed handle-response compatibility paradigm (Dekker & Mareschal, 2014). The present chapter was divided into two sections. The first section related pilot findings during the design of both paradigms. The second section related a published study that suggest potential modulations of action priming paradigm by manipulable object category (i.e., manufactured or natural).

During the design of both paradigms, we encountered multiple issues in implementing the delayed handle-response compatibility paradigm and some discrepancies with the results obtained in previous implementations of the paradigm (Dekker & Mareschal, 2014). We suggested that such discrepancies could be due to methodological issues, such as the absence of jittering (Azaad et al., 2019). Hence, we favored the action priming paradigm for assessing affordance evocation in Chapter 5. But first, we decided to investigate the involvement of potential modulating factors in the weakness of action priming paradigm when demonstrating affordance effects. Our implementation of the action priming paradigm showed an action priming effect, demonstrating that the present paradigm was suitable for assessing affordance evocation. Additional results indicated that the action priming effect may be modulated by object category (natural or manufactured) and suggest that our implementation of the action priming paradigm is likely to assess stable affordances (Borghi & Riggio, 2015), and possibly a subset of them, that is functional affordances (Buxbaum & Kalénine, 2010).

CHAPTER 5

DEVELOPMENTAL MODULATIONS OF THE COMPETITION BETWEEN AFFORDANCES DURING OBJECT PERCEPTION

In the previous chapter, we explored paradigms evaluating affordance evocation during manipulable object perception (i.e., *affordance specification*) with the aim of selecting the most suitable paradigm for assessing the *affordance specification* mechanism in the present chapter. We encountered some issues while implementing one paradigm: the delayed-handle response compatibility paradigm. Moreover, although we reported that manipulable object category (i.e., manufactured or natural) is a moderating factor that may account for the weakness of action priming paradigms in demonstrating affordance effects, our implementation of the action priming paradigm effectively assesses affordance evocation during visual object processing. Hence, we favored the action priming paradigm for assessing the *affordance specification* mechanism in the present chapter.

In the first section of the present chapter, we will investigate how inter-individual variabilities modulate the impact of affordance competition on object perception (i.e., first section). More particularly, we will evaluate the developmental trajectory of the consequence of the co-activation of multiple affordances on object perceptual processing. We assume that the negative impact of affordance competition on object perceptual processing may result from the joint contribution of two mechanisms, *affordance specification* and *affordance selection*, and may show a non-linear developmental trajectory. Participants will perform perceptual judgements on different 3D objects in a virtual environment in order to assess their affordance conflict cost. Participants will also perform two complementary tasks in two additional paradigms: an action priming paradigm and a Simon paradigm to measure *affordance specification* and *affordance selection* mechanisms, respectively. In a second section, we will briefly present a complementary experiment that was conducted on adult participants to assess the involvement of potential confounded variables (i.e., visual complexity) in the emergence of the affordance conflict cost.

Section 1. How competition between affordances affects object perception during development

The article below presents the developmental study

as initially submitted to JECP (Journal of experimental child psychology).

Godard, M., Wamain, Y., Delepoulle, S., & Kalénine, S. (submitted).

How competition between affordances affects object perception during development.

____________________ Submitted paper ____________________

Abstract: Recent evidence in adults indicates that object perceptual processing is affected by the competition between affordances. In the absence of specific motor plan, objects presented within reach and evoking distinct structural (grasping) and functional (using) affordances (e.g., calculator) elicit slower judgements than objects evoking similar affordances. The aim of the present study was to identify the development of this affordance conflict cost. In light of recent affordance models, we assumed that the affordance conflict cost may result from the joint contribution of two mechanisms, affordance retrieval and affordance exploitation, and may show a non-linear developmental trajectory. Five age groups from 8-year-olds to adulthood participated (n = 131). Like in previous adult studies, participants performed perceptual judgements on different 3D objects in a virtual environment in order to assess their affordance conflict cost. They were also proposed two complementary tasks, an action priming task and a Simon task to measure their abilities to retrieve affordances and monitor conflict, respectively. Main results demonstrate that the affordance conflict cost is present in children as young as 8 and follows a U-shape developmental trajectory between 8 and adulthood. Results from the complementary tasks further show a similar U-shape development of action priming effects, suggesting that the affordance conflict cost relies on affordance retrieval, which witnesses important changes during early adolescence. The role of general conflict monitoring abilities in affordance exploitation and in the emergence of the affordance conflict cost is less clear and requires further investigation. Findings will fuel theoretical developments on object affordances.

Keywords: Affordances; Manipulable objects; Visual perception; Action priming; Child development; Embodied perception

Introduction

Since Gibson (1986) has defined the term “affordance” to refer to the action possibilities that are provided by the environment to an organism depending on its own action capabilities, the term has been used in many different ways (see Osiurak et al., 2017, for review). In the context of object perception, most approaches now consider the perception of affordances as the evocation of action components (such as reaching, grasping and what the observer usually does with the object) from object visual presentation (see for examples, Borghi & Riggio, 2015; Buxbaum & Kalénine, 2010; Ellis & Tucker, 2000). At the behavioral level, the phenomenon of affordance evocation has been classically demonstrated by showing that judgements about object general characteristics are facilitated when object visual properties, such as object size (Borghi et al., 2007; Ellis & Tucker, 2000) or spatial orientation (Fischer & Dahl, 2007; Pellicano et al., 2010; Tucker & Ellis, 1998) are compatible with some action components irrelevant for the judgement task. For example, categorizing a cherry as a natural object is faster when responding with a precision rather than a power grip (Ellis & Tucker, 2000) or when the presentation of the cherry is primed by a precision rather than a power hand posture (Borghi et al., 2007). So-called affordance effects have contributed to the claim that the motor properties of visual objects are automatically activated, even when the observer does not plan any action toward the object. However, as we will review next, affordance effects are not as automatic as previously thought and not even always beneficial for object perception. Despite a possible detrimental impact on object perceptual processing, affordances effects have been mostly studied in adults, with very little interest on how this may affect the development of children’s representation of objects. The general aim of the present study was to shed light on the influence of the evocation of affordances on object perception throughout development.

Recent advances in affordance research in adults have provided important nuances to the initial claim about the automaticity of affordance evocation during object perception. First, the literature points instead toward significant contextual modulations. Specifically, affordance evocation has been shown to be sensitive to task demands (Harel et al., 2014; Wamain et al., 2016), visual context (Kalénine et al., 2014; Wokke et al., 2016; Wurm et al., 2012), or location of the object in space (Costantini et al., 2010, 2011; Ferri et al., 2011; Kalénine et al., 2016; Wamain et al., 2016). For instance, Costantini et al. (2010) presented a picture of a mug at different distances that was preceded by the picture of a grasping gesture. The orientation of the mug handle could be compatible or incompatible with the grasping gesture. Results showed facilitative effects for compatible situations when compared to incompatible situations, but only when the mug was presented close to the participants, i.e., in their peripersonal space. Such finding demonstrates that affordance evocation is dependent on object position in space, more particularly on whether it would be possible or not, for the observer, to interact with the perceived object. Second, it is not obvious which action properties of visual objects are actually activated and when. A single object may evoke different affordances in relation with different types of interactions that one may have with it (Bub et al., 2018; Kalénine et al., 2016; Wamain et al., 2018). In particular, objects may afford both structural and functional actions (Buxbaum & Kalénine, 2010). Structural affordances refer to action components associated with the volumetric characteristics of objects (e.g., typical size, shape) typically involved in grasping actions. In contrast, functional affordances refer to action components associated with the functional use of objects. For some objects, structural and functional affordances are similar (e.g., a glass is associated with the same clench for grasp and use), but for many others they differ (e.g., a calculator is associated with clench for grasp but poke for use). Therefore, what does the perception of a calculator evoke? A clench, a poke, both? Several studies indicate that structural and functional affordances of a given object may be flexibly activated depending on the context (Ferri et al., 2011; Kalénine et al., 2014; Lee et al., 2012). Yet, both structural and functional affordances may be in certain cases co-activated from a single visual object, with consequences on object processing.

Recently, a few studies in adults have directly investigated the impact of the co-activation of different structural and functional affordances on action planning (Bub et al., 2018; Jax & Buxbaum, 2010, 2013) and object perceptual processing (Kalénine et al., 2016; Wamain et al., 2018). In these studies, the authors compared the processing of objects associated with distinct structural and functional affordances (e.g., a calculator, hereafter "conflictual" objects) with the processing of objects associated with similar structural and functional affordances (e.g., a glass, hereafter "non-conflictual" objects). They highlighted selective action production cost (Bub et al., 2018; Jax & Buxbaum, 2010, 2013) and selective perceptual cost (Kalénine et al., 2016; Wamain et al., 2018) for objects evoking distinct grasping and using gestures (i.e., conflictual objects). For example, Kalénine et al. (2016) instructed participants to make judgements about perceptual characteristics of conflictual and non-conflictual objects (e.g., "is it reachable?", "is it a kitchen object?") presented at different distances in a 3D virtual environment. Longer response times were observed for conflictual objects compared to non-conflictual objects, but this effect was only evidenced when objects were presented in the peripersonal space of the participants. This finding demonstrates that the activation of multiple affordances induces a perceptual processing cost that depends on the possibilities of the observer to interact with the perceived objects. Together, these results suggest that when activated, different affordances associated with a single object compete with one another and this competition may be detrimental to object perceptual processing, at least in adulthood. One critical question is how such competition between affordances may affect the development of children's processing of visual objects. Therefore, the present study aims at identifying the development of the processing cost entailed by affordance competition during childhood.

The processing cost observed during the perception of objects with conflicting affordances may be the consequence of different complementary mechanisms. The influent neurobiological model developed by Cisek (2007) proposes that action selection involves two parallel processes: the activation of affordances from the environment (*specification*) and the competition and biasing toward relevant affordances (*selection*). Dissociations between the brain regions involved in the retrieval of affordances as opposed to the exploitation of affordances during the perception and execution of object-directed actions have been provided in support of this model (Schubotz et al., 2014; Watson & Buxbaum, 2016). Therefore, we hypothesized that the processing cost reported during the perception of manipulable objects also results from the joint contribution of affordance retrieval and affordance exploitation. The perception of conflictual objects (e.g., calculator) within reach entails a strong co-activation of structural and functional affordances (affordance retrieval) and, as the two affordances differ (e.g., clench and poke), they highly compete with one another (affordance exploitation). If the two processes show different developmental trajectories, then a non-linear development of the processing cost resulting from the perception of conflicting affordances may be anticipated, with periods when children easily retrieve affordances but poorly exploit them showing the maximum cost.

Relevant to the development of affordance retrieval, it has been highlighted that even young children exhibit sensitivity to the action potential associated with object visual properties. This sensitivity has been highlighted when children have to explicitly categorize or recognize visual objects (Anelli et al., 2012; Collette et al., 2016; Kalénine et al., 2009; Liuzza et al., 2012; Mounoud et al., 2007) and even when they perform a task irrelevant to object perception (Dekker & Mareschal, 2014). For instance, Dekker & Mareschal (2014), using a handle-compatibility paradigm, asked children to categorize the color of a cross by pressing left or right lateralized response buttons. The target cross was preceded by a picture of a mug with the handle oriented toward the left or the right. As adults, six- and eight-year-old children showed faster response times when the handle orientation was compatible with the button they had to press. These results suggest that affordance retrieval is already present in children, as young as six, and may affect their visual perception. However, some of these studies also suggest that affordance retrieval may not be equivalent at all age periods (Collette et al., 2016; Kalénine et al., 2009). For instance, Collette et al. (2016) asked to 8, 9, 10-year-old children and young-adult to name objects that were primed by a related or unrelated object according to their manipulation (e.g., piano preceded by a computer, both objects evoking taping gestures). They observed a linear decrease of the facilitative effect of the related prime on denomination from 8- to 10-year-olds that became an interfering effect from 10 until adulthood. Similarly, Kalénine et al. (2009) found a modulation of the pattern of action and context priming effects on categorization of objects around 9-year-olds. Taken altogether, developmental studies assessing affordance perception in children indicate that from the beginning of elementary school, children activate affordances from visual objects. However, whether affordance perception further changes between elementary school and adulthood is less clear-cut.

To our knowledge, there is no data directly assessing to the development of affordance exploitation. Nonetheless, the maturation of more general conflict monitoring abilities has been largely documented (see for example Hämmerer et al., 2014 for review), especially via the study of spatial congruency effects obtained with different versions of the Simon task (Davidson et al., 2006; Erb & Marcovitch, 2018, 2019; Hämmerer et al., 2014). In the Simon task (Simon, 1969), participants are usually asked to categorize stimuli according to a basic-level property (e.g., color, shape) by pressing left or right lateralized response buttons. Stimuli are displayed in left or right part of the screen, generating congruent and incongruent conditions. The difference in mean response times or in percentage of errors between those conditions constitute the so-called Simon effect or spatial congruency effect, and would reflect the ability of the individual to select relevant information in the environment to perform appropriate actions (monitoring abilities). In both of their studies, Erb and Marcovitch (2018, 2019) showed that six- to eight-year-old children exhibit a stronger Simon effect than 10- to 12-year-old children and young adults, who did not differ from each other. Even though these results suggest that monitoring abilities may be efficient by ten, Davidson and al. (2006)'s results highlighted that the consolidation of this process is still ongoing until 13-year-olds. Moreover, using a different paradigm Hämmerer and al. (2010) showed that 14-year-old children exhibit less efficient monitoring abilities than young adults. Taken altogether, these results suggest a progressive improvement of affordance exploitation from 8-year-olds to adulthood, with processing in adolescents (14-year-olds) probably not reaching adult-level.

To sum up, the main goal of the present study was to specify the development of the object processing cost entailed by the perception of conflicting affordances during childhood. As an important cost should be observed when affordance retrieval is important and affordance exploitation is poor, we anticipated that the affordance conflict cost may follow a non-linear development. We recruited five groups of participants from 8-year-olds to young adults who performed perceptual judgements on objects presented in a 3D environment (paradigm from Kalénine et al., 2016) in order to assess the developmental trajectory of the affordance conflict cost. Moreover, we also wanted to evaluate to what extent the processes of affordance retrieval and affordance exploitation could be estimated by performance on tasks commonly used in the domain of affordance perception and conflict monitoring, and serve as developmental predictors of the conflict cost. Therefore, the same participants took part in two additional tasks: one assessing stable affordance retrieval (i.e., action priming paradigm from Borghi et al., 2007) and one assessing conflict monitoring (Hommel, 2011; Simon, 1969).

Method

Participants

One hundred and sixty-one volunteers took part in the experiment. They were divided into five age groups: 8-to-9-year-olds (3rd grade, n = 34, M = 8.66 years; SD = 0.33; 10 females); 10-to-11-year-olds (4th grade, n = 30, M = 10.99 years; SD = 0.51; 17 females); 12-to-13-year-olds (5th grade, n = 25, M = 12.93 years; SD = 0.51; 14 females); 14-to-15-year-olds (6th grade, n = 30, M = 14.63 years; SD = 0.45; 15 females); and young adults (n = 42, M = 20.55 years; SD = 2.3; 33 females). Left-handed participants were excluded, as well as participants with reported neurological history. The final sample included 133 participants. All were right-handed, confirmed by the school teacher for the two younger groups (8-to-9 and 10-to-11-year-old children), or assessed by Edinburgh handedness questionnaire (Oldfield, 1971) for the three older groups (12-to-13-year-olds: 0.80, 14-to-15-year-olds: 0.81; young adults: 0.77). All participants had normal or corrected-to-normal visual acuity. Children were recruited in two elementary schools in Lille urban area (France), and in one middle school in Péronne (France). Adults were undergraduate students of Lille University. Participants provided written informed consent and were not paid for their participation. Parents of minor participants gave authorization for their children to participate at the study. The protocol was approved by the Ethical Committee of the University of Lille and was conducted in accordance with the declaration of Helsinki. Due to technical reasons, two participants were discarded from further analyses, which were finally performed on 131 participants.

Materials and procedure

Participants performed the main 3D object perception task assessing affordance conflict cost first. Then, they performed the two complementary action priming and Simon tasks assessing affordance retrieval and conflict monitoring. The order of the two complementary assessments was counterbalanced between participants. Note that the same response mapping was used between tasks requiring similar responses for a given participant (Yes/No responses), but response mapping was counterbalanced across participants. The whole session lasted about an hour.

Main assessment: affordance conflict cost during 3D object perception

The virtual reality paradigm used to assess affordance conflict cost during 3D object perception was adapted from Kalénine et al. (2016) and Wamain et al. (2018).

Stimuli

Stimuli were composed of three-dimensional images of 40 common manipulable objects created with Blender software and the images were produced with a photorealistic rendering method. Among the 40 objects, half were “conflictual” and involved distinct hand postures for move and use actions (e.g., calculator) and half were “non-conflictual” and involved similar hand postures for move and use actions (e.g., drinking glass, **Figure 24** and Supplementary materials). In each category, half of the object were categorized as kitchen objects and half were non-kitchen objects. Objects were displayed in a virtual scene composed of a wooden table in a neutral room (**Figure 24**) at different distances from the participant. Nine distances were sampled for each age group according to the average arm length at this age from -55% to 55% of the arm length. The nine distances were separated in near (-55%, -50% and -45%), limit (-5%, mean arm length, +5%) and far (+45%, +50% and +55%) spaces (see **Table 2**). This procedure ensured that regardless of the group and the individual perceived reaching boundary computed offline (see Result section), most participants would see objects both within reach and out of reach. Images were generated prior to the experiment by taking into account the distance to the screen (40 cm) and the mean arm length for each age group (see **Table 2** for more details).

Table 2. The nine distances of presentation (in centimeters) according to mean arm length (maL) and group (Gr1: 8-to-9-year-olds, Gr2: 10-to-11-year-olds, Gr3: 12-to-13-year-olds, Gr4: 14-to-15-year-olds and Gr5: young adults).

	- 55%	- 50%	- 45%	- 5%	maL	+ 5%	+ 45%	+ 50%	+ 55%
Gr1	36	40	44	76	80	84	116	120	124
Gr2	40	45	49	85	89	93	129	134	138
Gr3	44	49	54	93	98	103	142	147	152
Gr4	47	52	57	98	104	109	150	155	161
Gr5	49	55	60	104	109	114	158	164	169

Pretest of the stimuli

Objects were chosen to be familiar for young children from 8 years of age. All object nouns except 3 compound nouns could be found in the French Larousse Dictionary Junior for elementary school children and 2D picture identification was further verified on a representative sample of six 8-9-year-old children. Note that a familiarization phase with the objects was systematically provided to the participants prior to the experiment in any case (see below).

Twelve additional right-handed young adult participants were recruited in order to pretest the actions and contexts associated with objects. The pretest consisted on the presentation of 2D screen-captures of the object images. The 2D pictures were presented one by one on the screen and participants were asked to show the way they would position their hand on the object in order to (1) move it and (2) use it. Hand postures were classified into 6 categories (clench, pinch, horizontal trigger, vertical trigger, poke and palm) by two judges (one naïve and one expert). The degree of agreement was satisfying (Cohen's kappa = 0.87). Each object was associated with a conflict index corresponding to the similarity between hand postures made for move and use gestures, 0 meaning low conflictual object (identical hand postures) and 100 meaning high conflictual object (completely different hand posture). Conflictual and non-conflictual objects had a mean index of 89.17 (SD = 15.32 [range: 50-100]) and 7.08 (SD = 9.85, [range: 0-25]), respectively. Finally, participants were asked to determine the room of the house in which the object was typically found and to name the object. Half of the objects were typically found in the kitchen.

3D immersive virtual reality system

Participants were seated in front of an LCD screen (1920 x 1080 pixels, 120 Hz) with their hands resting on the armrest of the chair. A pedal response device was positioned under their feet. Stimuli presentation was controlled by custom software using MATLAB 9.2 (MathWorks, Natiek, MA, USA) and Psychophysics Toolbox extensions (Brainard, 1997). Active 3D eyewear (NVIDIA 3D vision 2, P1431) was used for producing 3D image perception. Two different images of each stimulus were computed and presented 8.33 ms alternatively to each eye. Normal fusion created the illusion of viewing a single object. Relative size and perspective cues as well as binocular disparity were used to induce a 3D perception of the visual scene and objects.

Reach-to-grasp and semantic judgement tasks

Before the starting of the experimental session, the 40 selected objects were presented and named one by one to the participant in order to make sure that each participant correctly identified the different objects. The experimental session was composed of two blocks, which were counterbalanced between participants. In each block, participants performed a different type of perceptual judgement on objects. In the reach-to-grasp judgement task, they had to judge whether they could reach and grasp the object with their right hand without performing the movement. In the semantic judgement task, they were asked to judge whether the object could be found in the kitchen or not. In both blocks, the object appeared at a given distance and remained displayed on the screen until participant's response. Inter-stimuli intervals were composed of a blurred virtual environment without object, and randomly varied between 1500 and 1900 ms. The object remained displayed until the participant's response. There were 360 experimental trials (40 objects x 9 distances) randomly presented in each block, preceded by 20 practice trials.

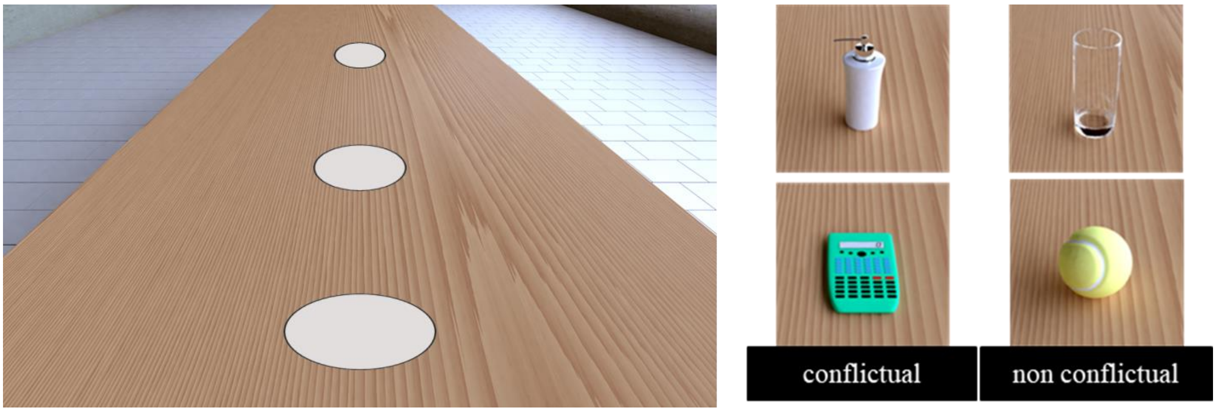


Figure 24. Experimental setting of the immersive virtual reality system. On the left are represented the different distances (e.g., near, limit of reachability, far) at which stimuli are presented in the virtual scene. On the right are displayed examples of conflictual and non-conflictual objects from both object categories (top: kitchen objects; bottom: non-kitchen objects). Participant's task was to judge object category ("is it a kitchen object?") or object reachability ("is it reachable?"), responding with foot pedals.

Secondary assessments: affordance retrieval and general conflict monitoring

Two secondary assessments were conducted to assess separately affordance retrieval during object processing (independently from conflict and space contribution) and general conflict monitoring abilities. Their order was counterbalanced between subjects. We chose two paradigms that have been classically used to this aim in the literature: the action priming paradigm associated with object semantic categorization (Borghi et al., 2007; Godard et al., 2019) and the Simon paradigm (Hommel, 2011; Simon, 1969).

Assessment of affordance retrieval

We used the same action paradigm as Godard et al. (2019) in order to obtain, at the group and individual level, an estimation of action priming effects. The aim of the paradigm is to evaluate to what extent visual object categorization is facilitated by the prior presentation of hand pictures displayed in a congruent grasping posture.

Stimuli

Fifty high resolution-colored photographs of objects were selected from an open-source database (Pixabay). Half were manufactured (e.g., bowl) and half were natural (e.g., apple). 2D object pictures were displayed in the middle of the screen in a fictive square of 500 x 500 pixels on a black background (see Supplementary materials). Among the fifty photographs, forty were used as experimental trials while the ten remaining pictures were used as practice trials. Half of the objects used as experimental trials were usually grasped with a precision grip (e.g., hazelnut, pen cap) while the other half were usually grasped with a power grip (e.g., apple, bowl) according to their typical size. In addition, colored photographs of five different hand postures of 1920 x 1080 pixels on a black background were designed. Among hand postures, two displayed a grasping hand posture (power or precision grip) and three displayed a non-grasping hand posture (palm-up, palm-down and fist).

Procedure

Stimuli were inserted in an action priming paradigm with hand pictures as primes and object pictures as targets. Each trial started with a fixation cross presented in the center of the screen for 500 ms on a black background followed by one of the hand primes for 500 ms (**Figure 25**). Then, the object target was presented until participants' response or for a maximum of 4000 ms. Participants were asked to categorize the target object as natural or manufactured by pressing one of the two response buttons with their left and right hand. Response mapping was counterbalanced between participants.

During the experimental phase, each target object was presented twice, once with the appropriate grasping hand prime (power or precision grip) in the action priming condition and once with one of the two non-grasping hand primes (palm-down or fist) in the neutral priming condition, leading to 80 experimental trials. Eight additional catch-trials (10%) were designed using four additional target objects presented with the palm-up "no-go" prime. On catch-trials, participants were asked to refrain from responding in order to ensure that they paid attention to the primes during the procedure. Participants performed 88 trials (40 action priming conditions, 40 neutral priming conditions and 8 catch-trials) presented in random order and preceded by 20 practice trials involving six additional target objects (three of each category).

Assessment of general conflict monitoring abilities

We used the common Simon paradigm similar to those presented in literature (Hommel, 1994a, 2011; Simon, 1969), in order to obtain, at the group and individual level, an estimation of general conflict monitoring abilities. The aim of the paradigm is to evaluate to what extent visual stimulus categorization is impeded when the location of the stimulus is in conflict with the location of the motor response required to perform the task.

Stimuli

Two pictures of shapes were created, one picture displaying a white square of 100 x 100 pixels and one displaying a white circle of 100-pixel diameter. Four stimuli were designed, two for each shape. Stimuli consisted of a black background with a white fixation point at the center and a shape on the left or on the right part, 300 pixels away from the center, on the horizontal axis.

Procedure

The stimuli were inserted in a spatial congruency paradigm. Each trial started with the presentation of a fixation point in the middle of a black background for 300 ms, followed by the presentation of one of the stimuli. The stimuli remained on the screen until participants' response or for a maximum of 2000 ms (see **Figure 25**). Participants had to classify the shape on the stimuli as a square or a circle irrespective of the shape position by pressing two lateralized buttons. The response mapping was counterbalanced across participants. Participants were instructed to fixate the central fixation point during all the experiment. According to the position of the shape and the lateralized button the participants had to press for its classification, trials could be identified as congruent (i.e., when shape position and button location were in accordance) or as incongruent (i.e., when shape position and button location were not in accordance). A black screen of 500 ms was presented between two trials. In total, participants performed 258 trials (half congruent and half incongruent) randomly separated into two testing blocks for a total duration of 10 minutes each. Twenty practice trials were performed before the task.

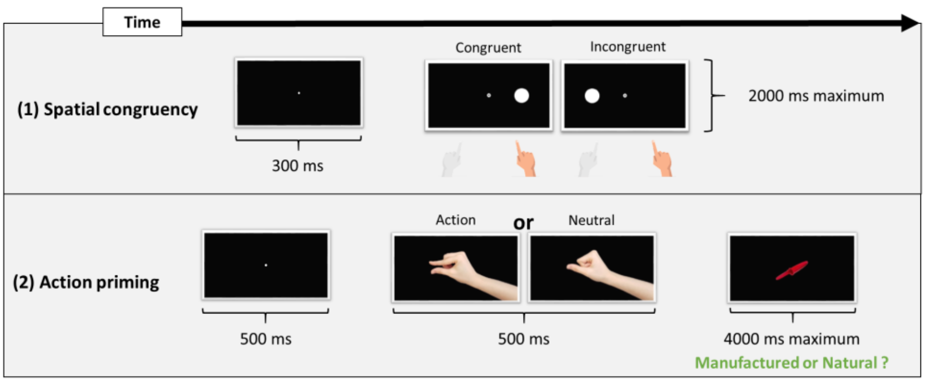


Figure 25. Procedure of an experimental trial for the spatial congruency (Simon) and action priming paradigms. (1) Simon paradigm with the two conditions: congruent (left) vs. incongruent (right) and (2) Action priming paradigm with the two priming conditions: action priming (left) vs. neutral priming (right).

Data Analyses

Determination of individual perceived reachability boundary in the 3D object perception paradigm

The different distances were divided into reachable and unreachable spaces at the individual level according to the perceived boundary of the peripersonal space of each participant. The individual perceived boundary was determined a posteriori on the basis of individual responses in the reaching task ("Yes, it is reachable" vs. "No, it is not"). A maximum likelihood fitting procedure was used to obtain the logit regression model that best fit the reachable/unreachable responses of the participant with respect to the distance. The individual perceived reachability boundary corresponds to a fifty percent chance for the participant to say "yes, it is reachable". Two separate reachable and unreachable spaces could not be identified in 11 out of 131 participants (3 in 8-year-olds, 7 in 10-year-olds, 1 in adults), who were excluded from further analyses. Overall, the mean perceived reachability boundary in the present virtual paradigm was of 97 cm with no significant effect of age [$F(4,115) = 18.85$, $p = .12$], 89 cm (SD = 19 cm) in 8-year-olds, 100 cm (SD = 16 cm) in 10-year-olds, 94 cm (SD = 22 cm) in 12-year-olds, 102 cm (SD = 18 cm) in 14 year-olds and 100 cm (SD = 20 cm) in young adults.

Group-level analyses to qualify developmental trajectories

The first goal of the study was to evaluate the general developmental trajectory of the conflict cost between affordances. With this aim in mind, we used mixed-effect linear models of response times (RT) in the 3D perception paradigm. Log-transformed RTs were analyzed as function of Age group (8-year-olds, 10-year-olds, 12-year-olds, 14-year-olds and adults), Space (reachable, unreachable) and Object type (conflictual, non-conflictual). We did not include the Task (semantic, reach-to-grasp) in the model, as it did not modulate the interaction between Space and Object type in a previous study using the same paradigm (Kalénine et al., 2016).

Fixed effects corresponded to the effects of Age group, Space, Object type and their interactions. The interaction between Space and Object type reflected the cost of the competition between distinct object affordances during object processing and was the effect of interest. The random effect structure of the model included participants as random effect factor with random intercepts and random slopes for space and object type. Polynomial contrasts (linear, quadratic, cubic, quartic) were first evaluated to qualify the shape of the developmental trajectory. We then documented the presence of a conflict cost in each age group separately.

Similar mixed-models were conducted on the data from the secondary assessments, action priming and Simon paradigms, in order to evaluate the developmental trajectories of affordance retrieval and general conflict monitoring. For action priming data, correct log RTs for categorizing manufactured objects were analyzed as function of Age group, Priming (correct, neutral) and Object usual grasp (clench, pinch) since it has been shown to influence RTs (Borghi et al., 2007). Analyses were restricted to manufactured objects, as sensitivity of object categorization to action priming was maximum for this category in a previous study (Godard et al., 2019). Fixed effects corresponded to the effects of Age group, Priming, Object usual grasp and their interactions. The main effect of Priming reflected affordance retrieval during object processing and was the effect of interest. The random effect structure of the model included participants as random effect factor with random intercepts and random slopes for priming. For the data from the Simon task, correct log RTs were analyzed as function of Age group and Congruency (congruent, incongruent). Fixed effects corresponded to the effects of Age group, Spatial congruency and their interaction. The main effect of Spatial congruency (i.e., the Simon effect) reflected general conflict monitoring abilities and was the effect of interest. The random effect structure of the model included participants as random effect factor with random intercepts and random slopes for spatial congruency.

All mixed-effect linear model analyses were conducted with the lme4 package (version 1.1-21) of R software (version 3.6.1). LmerTest package (version 3.1-1) was used to obtain significance F-tests of fixed effects. Denominator degrees of freedom were approximated using Satterthwaite's approximations. Log-likelihood ratios (LL) goodness-of-fit measures were provided as measures of effect size for fixed effects by comparing models with and without the corresponding fixed effect. Cohen's d effect sizes were computed for relevant t-tests as the ratio between the estimated mean difference between conditions and the square root of the sum of the residual variance and the variance of the random effects of the model, following Westfall, Kenny, and Judd (2014) and Brysbaert and Stevens (2018).

Individual-level analyses to evaluate relations between tasks in each age group

The secondary goal of the study was to evaluate to what extent individual action priming and Simon effects could reflect the processes of affordance retrieval versus exploitation and predict the magnitude of the affordance conflict cost in the 3D perception paradigm. Considering the number of participants and the distribution of effects in each group, we opted for non-parametric regression analyses. We used the Kendall-Theil Sen Siegel robust line non-parametric regression (see for an introduction, Granato, 2006; and the original paper, Siegel, 1982), a simple regression method that is both powerful and very robust to outliers (Farooqi, 2019; Maronna et al., 2019). For these regression analyses, we reported the slope estimates with its median absolute deviation (MAD), a robust estimator of variability (Howell, 2014), and finally the p-value significance of the slope. This was done with the R package mblm version 0.12.1. Two sets of regression analyses were conducted, one with action priming as predictor and one with the Simon effect as predictor of the affordance conflict cost, for each of the five different age groups (8-year-olds, 10-year-olds, 12-year-olds, 14-year-olds and adults). The action priming effect (targeting affordance retrieval) and the Simon effect (assessing the sensitivity to conflict) were supposed to be positively related to the affordance conflict cost (the greater the activation of affordances and the greater the sensitivity to conflict, the greater the cost).

Results

Development of affordance conflict cost during 3D object perception

As responses were sensitive to participant's subjectivity in both experimental tasks (e.g., reach-to-grasp judgments at the boundary of peripersonal space, or semantic judgments for some objects like a soap distributor), accuracy was not considered in the analysis. Response times (RTs) inferior to 200 ms and exceeding 5 times the median by age group were excluded from the analysis. Then, RTs were trimmed by removing those exceeding 3 standard deviations from the participant's mean in each condition. Overall, 3.58 %, 2.52 %, 2.79 %; 2.58 % and 2.50 % of trials were excluded from the analyses for 8-year-olds, 10-year-olds, 12-year-olds, 14-year-olds and young adults, respectively. Six participants out of 120 (1 in 8-year-olds, 1 in 12-year-olds, 1 in 14-year-olds, and 3 in adults) still showed mean RTs above 2 standard deviations of the mean RT of their age group and were considered outliers. They were excluded from further analyses that were conducted on the remaining 114 participants. Mean RTs and standard deviations in the different conditions are reported in **Table 3**.

Table 3. Mean RTs (and SD) in milliseconds as a function Space (Reachable, Unreachable) and Object (C = conflictual, NC = non-conflictual) and mean (and SD) affordance conflict cost (ACC: [conflictual – non-conflictual] in reachable - [conflictual – non-conflictual] in unreachable) for each age group (Gr1: 8-year-olds, Gr2: 10-year-olds, Gr3: 12-year-olds, Gr4: 14-year-olds and Gr5: young adults).

	Reachable		**Unreachable**		
	C	**NC**	**C**	**NC**	**ACC**
Gr1	1353.77 (227.71)	1292.81 (190.03)	1497.60 (240.35)	1515.46 (246.16)	78.83 (145.30)
Gr2	1152.52 (213.73)	1146.56 (202.76)	1346.57 (269.46)	1338.04 (270.54)	-2.57 (108.78)
Gr3	1110.11 (244.90)	1113.39 (259.64)	1190.02 (251.30)	1205.66 (269.09)	12.36 (105.01)
Gr4	997.37 (164.95)	961.70 (156.21)	1058.03 (166.18)	1038.49 (171.56)	16.13 (85.14)
Gr5	821.30 (134.85)	800.01 (139.72)	847.48 (128.18)	846.02 (144.67)	19.84 (36.08)

The mixed effect linear model analysis of log transformed correct RTs revealed a main effect of Age group [F(4, 109.0) = 34.81, p = 0.001, LL = 81.42], that was due to a significant reduction of RTs with age (linear contrast estimate = -37.36×10^{-2}, SE = 3.31×10^{-2}, t = -11.29, p = 0.001, d = 0.94). There was a main effect of Space [F(1, 108.7) = 166.74, p = 0.001, LL = 81.76]. RTs were 107 ms shorter in the reachable space compared to the unreachable space (estimate [unreachable – reachable] = $+9.25 \times 10^{-2}$, SE = 0.72×10^{-2}, d = 0.23). There was also a main effect of Object type [F(1, 109.0) = 10.34, p = 0.002, LL = 8.03]. RTs were 13 ms shorter for non-conflictual objects compared to conflictual objects (estimate [conflictual – non-conflictual] = $+1.03 \times 10^{-2}$, SE = 0.32×10^{-2}, d = 0.03). There was no interaction between Object type and Age group [F(4, 108.9) = 1.35, p = 0.25, LL = 5.92]. The two-way interaction between Space and Age group was significant [F(4, 108.7) = 7.79, p = 0.001, LL = 28.40], and was due to a decrease of the advantage of reachable over unreachable space with age (linear contrast estimate = -7.84×10^{-2}, SE = 1.52×10^{-2}, t = -5.17, p = 0.001, d = 0.20). As expected, the two-way interaction between Space and Object type was significant [F(1, 23836.4) = 7.60, p = 0.006, LL= 9.33], and was due to a 25 ms difference between conflictual and non-conflictual objects in reachable space (estimate = $+1.75 \times 10^{-2}$, SE = 0.41×10^{-2}, t = +4.30, p = 0.001, d = 0.04) that was not evidenced in unreachable space (estimate = $+0.31 \times 10^{-2}$, SE = 0.42×10^{-2}, t = +0.75, p = 0.46, d = 0.01). Crucially, there was a marginal three-way interaction between Age group (8 year-olds, 10 year-olds, 12 year-olds, 14 year-olds and adults), Space and Object type [F(4, 23452.1) = 2.00, p = 0.09, LL= 8.05]. As illustrated on **Figure 26**, the interaction was due to the presence of a quadratic developmental trajectory (estimate = -2.24×10^{-2}, SE = 1.12×10^{-2}, t = -2.00, p = 0.046, d = 0.06). Moreover, the cubic contrast almost reached significance (estimate = 2.19×10^{-2}, SE = 1.22×10^{-2}, t = -1.79, p = 0.073, d = 0.06), which might reflect the subtle asymmetry of the developmental curve at the extremities.

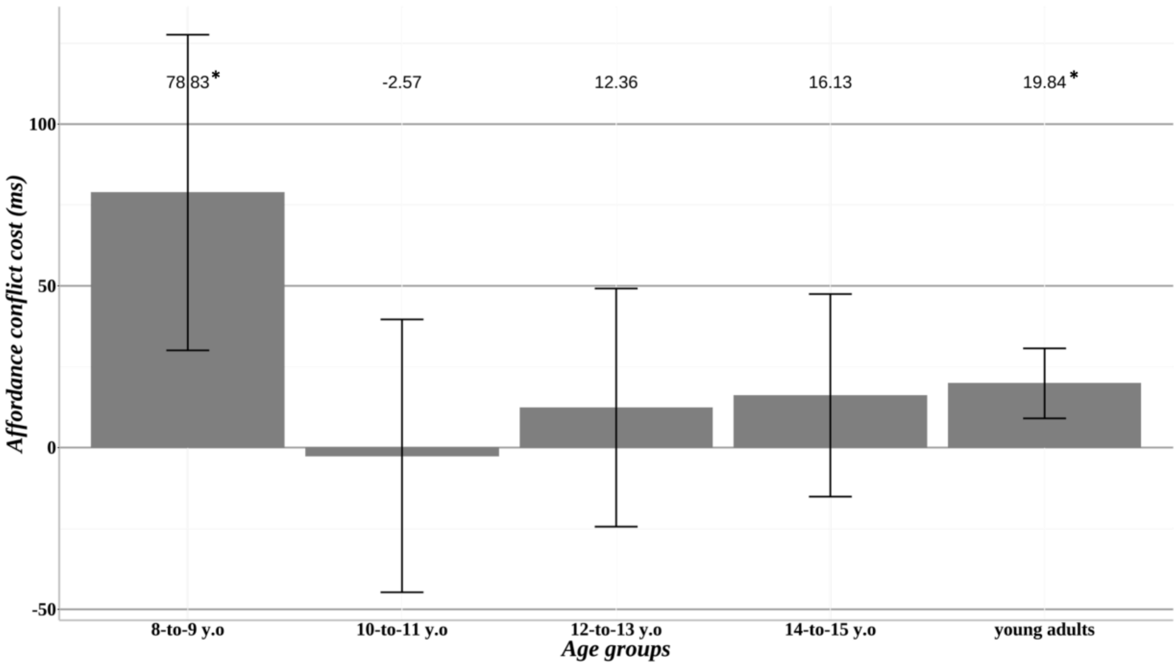


Figure 26. Mean affordance conflict cost [95% CI] for the different age groups. The affordance conflict cost is computed as the difference between responses times (in milliseconds) to conflictual minus non-conflictual objects presented within reach, in comparison to the same difference when objects are presented out of reach. * indicates significant differences at $p < .05$.

When tested in each age group, the evaluation of the two-way interaction between Space and Object type revealed a significant 79 ms conflict cost in 8-year-olds [$F(1, 2723.55) = 9.97$, $p = 0.002$, LL = 9.59] and a significant 20 ms conflict cost in young adults [$F(1, 4591.5) = 4.14$, $p = 0.042$, LL = 3.99]. However, the conflict cost was not significant in 10-year-olds [$F(1, 8632.4) = 0.24$, $p = 0.63$, LL = 0.25], 12-year-olds [$F(1, 15283.0) = 0.45$, $p = 0.50$, LL = 0.45] and 14-year-olds [$F(1, 3285.3) = 1.56$, $p = 0.21$, LL = 1.54]. Therefore, the quadratic developmental trajectory of the conflict cost between 8-year-olds and adulthood reflects a disappearance of this processing cost between 10 and 14-year-olds.

In the action priming paradigm, response times for incorrect responses and RTs inferior to 200 ms and superior to 3000 ms were excluded from the analyses. RTs were finally trimmed by removing those exceeding 3 standard deviations from the participant's mean in each condition. Overall, 10.10 %, 6.81 %, 7.16 %; 3.13 % and 2.83 % of trials were excluded from the analyses for 8-year-olds, 10-year-olds, 12-year-olds, 14-year-olds and young adults, respectively. Mean RTs and standard deviations in the different conditions are reported in **Table 4**.

Table 4. Mean RTs (and SD) in milliseconds as a function of Action priming condition (Action, Neutral) and mean (and SD) action priming effect (neutral – action) in milliseconds for each age group (Gr1: 8-year-olds, Gr2: 10-year-olds, Gr3: 12-year-olds, Gr4: 14-year-olds and Gr5: young adults).

	Neutral prime	**Action prime**	**Action priming effect**
Gr1	1253.19 (193.91)	1199.01 (213.87)	54.17 (148.02)
Gr2	1031.43 (208.93)	1038.13 (211.21)	-6.70 (168.72)
Gr3	943.57 (206.38)	976.22 (286.95)	-32.65 (123.59)
Gr4	745.80 (160.53)	713.11 (151.11)	32.69 (78.75)
Gr5	650.38 (125.76)	631.84 (109.83)	18.54 (59.54)

The mixed effect linear model analysis of log transformed correct RTs in the action priming paradigm showed a main effect of Age group [F(4, 109.0) = 34.81, p = 0.001, LL = 114.06], that was due to a significant reduction of RTs with age (linear contrast estimate = -50.6×10^{-2}, SE = 3.64×10^{-2}, t = -13.88, p = 0.001, d = 1.47).

There was also a main effect of Priming [F(1, 104.7) =3.98, p = 0.048, LL = 4.60]. RTs were shorter in the action priming condition when compared to the neutral priming condition (estimate [action – neutral] = $+1.89 \times 10^{-2}$, SE = 0.95×10^{-2}, t = 2.00, p = 0.048, d = 0.06). The predicted two-way interaction between Age group and Priming did not reach significance [F(4, 104.4) = 1.81, p = 0.13, LL = 8.51]. However, the a priori-determined polynomial contrasts indicated quadratic (estimate = 3.79 x 10^{-2}, SE = 2.05 x 10^{-2}, t = 1.85, p = 0.067, d = 0.11) and cubic (estimate = -4.06 x 10^{-2}, SE =2.21 x 10^{-2}, t = -1.84, p = 0.069, d = 0.12) developmental trends, as visible on **Figure 27**. There was no main effect of object usual grasp [F(1, 4059.1) =0.09, p = 0.75, LL = 1.61] and object usual grasp did not interact with any other factor. When tested in each age group, the main effect of Priming was significant in 8-year-olds [F(1, 248.43) = 5.99, p = 0.015, LL = 6.69] and approached significance in 14-year-olds [F(1, 308.29) = 3.43, p = 0.07, LL = 3.24]. The main effect of Priming was not significant in 10-year-olds [F(1, 16.48) = 0.05, p = 0.82, LL = 0.14], 12-year-olds [F(1, 48.97) = 0.24, p = 0.26, LL = 0.21] and 18-to-25-year-olds [F(1,276.07) = 2.24, p = 0.14, LL = 1.90]. As for the development of the affordance conflict cost, the quadratic developmental trajectory of the action priming effects reflected a disappearance of priming effect between 10 and 14-year-olds.

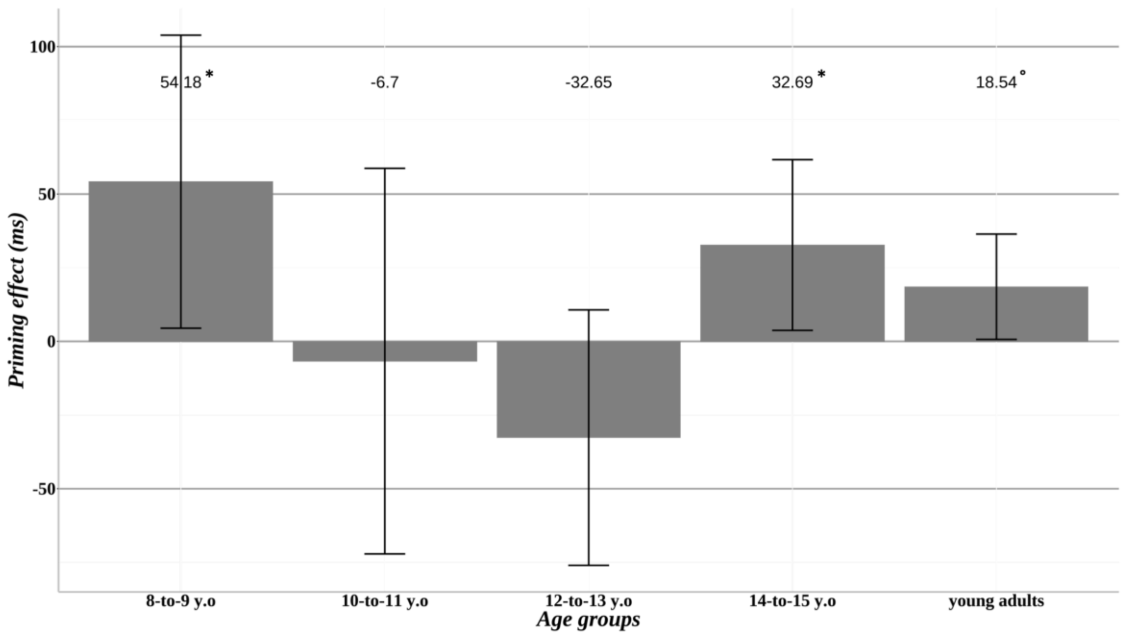


Figure 27. Mean action priming effect [95% CI] for the different age groups. The action priming effect is computed as the difference between responses times (in milliseconds) to objects preceded by neutral versus action primes. * indicates significant differences at p < .05.

In the Simon paradigm, response times for incorrect responses and RTs inferior to 200 ms were excluded from the analyses. Then RTs were trimmed by removing those exceeding 3 standard deviations from the participant's mean in each condition of congruency. Overall, 11.88 %, 7.49 %, 7.33 %, 5.43% and 4.83 % of trials were excluded from further analyses, for 8-year-olds, 10-year-olds, 12-year-olds, 14-year-olds and young adults, respectively. Mean RTs and standard deviations (SD) in the different conditions are reported in **Table 5**.

Table 5. Mean RTs (and SD) in milliseconds as a function of Spatial congruency (Congruent, Incongruent) and mean (and SD) spatial congruency effect (incongruent – congruent) in milliseconds for each age group (Gr1: 8-year-olds, Gr2: 10-year-olds, Gr3: 12-year-olds, Gr4: 14-year-olds and Gr5: young adults).

	Incongruent	**Congruent**	**Spatial congruency effect**
Gr1	803.31 (98.42)	781.35 (98.08)	21.96 (45.12)
Gr2	709.93 (120.20)	681.21 (106.81)	28.72 (44.52)
Gr3	635.80 (95.42)	610.05 (93.45)	25.75 (30.48)
Gr4	538.76 (74.01)	518.11 (81.23)	20.65 (32.24)
Gr5	484.45 (51.27)	460.58 (53.87)	23.87 (27.20)

The mixed effect linear model analysis of log transformed correct RTs in the Simon paradigm revealed a main effect of Age group [F(4, 108.99) = 61.50, p = 0.001, LL = 132.89], that was due to a significant reduction of RTs with age (linear contrast estimate = -39.57×10^{-2}, SE = 2.55×10^{-2}, t = -15.54, p = 0.001, d = 1.5). There was a main effect of Congruency [F(1, 108.69) =96.18, p = 0.001, LL = 73.53]. RTs were shorter in the congruent than incongruent conditions (estimate [incompatible – compatible] = $+4.76 \times 10^{-2}$, SE = 0.485×10^{-2}, d = 0.18). However, there was no interaction between Age group and Congruency [F(4, 108.68) = 0.48, p = 0.75, LL = 1.96]. No polynomial contrast was significant, suggesting no specific developmental trajectory of the Simon effect (see **Figure 28**). When evaluated in each age group, the main effect of Congruency was significant in all age groups: 8-year-olds [F(1, 22.88) = 13.65, p = 0.001, LL = 11.07], 10-year-olds [F(1, 16.78) = 12.9, p = 0.002, LL = 10.18], 12-year-olds [F(1, 20.76) = 30.41, p = 0.001, LL = 19.74], 14-year-olds [F(1, 19.06) = 15.10, p =

0.001, LL = 11.71] and adults [F(1, 28.92) = 33.99, p = 0.001, LL = 23.27]. This indicates that the Simon effect was present with a similar magnitude (about 20 ms) in all age groups.

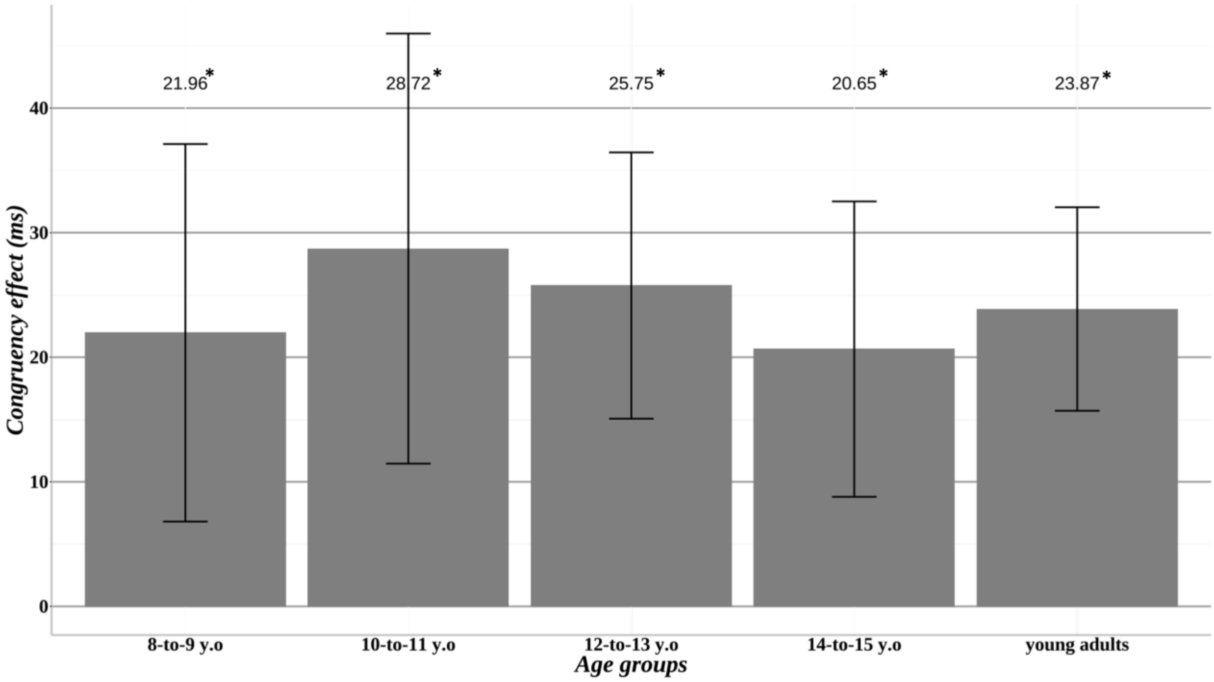


Figure 28. Mean Simon effect [95% CI] for the different age groups. The Simon effect is computed as the difference between responses times (in milliseconds) to stimuli in the incongruent versus congruent conditions. * indicates significant differences at $p < .05$.

Relations between affordance conflict cost and action priming and Simon effects

The Kendall-Theil Sen Siegel regression analyses with the action priming effect as predictor showed the expected positive relation between action priming effects and affordance conflict costs in 10-year-olds (estimate = 0.68, MAD = 0.31, p = 0.002). Moreover, action priming negatively predicted the affordance conflict cost in adults (estimate = -0.20, MAD = 0.30, p = 0.03) and, at the trend level, in 8-year-olds (estimate = -0.25, MAD = 0.37, p = 0.07). Action priming effects did not predict affordance conflict costs at 12-year-olds (estimate = -0.12, MAD = 0.22, p = 0.19) or at 14 (estimate = 0.10, MAD = 0.53, p = 0.81).

The Kendall-Theil Sen Siegel regression analyses with the Simon effect as predictor showed the expected positive relation between Simon effect and affordance conflict cost at 12 (estimate = 0.16, MAD = 0.92, p = 0.05). As for action priming, the Simon effect negatively predicted the affordance conflict cost in adults (estimate = -0.43, MAD = 0.76, p = 0.03). Simon effects did not predict affordance conflict costs in the other groups (at 8: estimate = 0.37, MAD = 1.76, p = 0.45; at 10: estimate = 0.27, MAD = 1.63, p = 0.64; at 14: estimate = 0.23, MAD = 0.60, p = 0.15).

Discussion

The present developmental study aimed at identifying the developmental trajectory of the processing cost induced by the competition between affordances during object perception. The affordance conflict cost was assumed to result from the joint contribution of affordance retrieval and affordance exploitation, two key processes in the recent theoretical development on affordances (Cisek, 2007; Thill et al., 2013). As affordance retrieval and affordance exploitation mechanisms may follow different developmental timelines from childhood to adulthood, we anticipated a non-linear development of the affordance conflict cost during this period. Five age groups (8-year-olds, 10-year-olds, 12-year-olds, 14-year-olds and young adults) participated in the study in order to assess the developmental trajectory of the selective cost entailed by the perception of objects with conflicting affordances in a 3D virtual environment (cf. Kalénine et al., 2016). Affordance retrieval and general conflict monitoring abilities were also evaluated in the same participants using action priming (Borghi et al., 2007; Godard et al., 2019) and Simon paradigm (Hommel, 2011; Simon, 1969), respectively. These complementary data were used to investigate to what extent the affordance conflict costs could be predicted by action priming and/or Simon effects in the different age groups. The main results highlight a non-linear, U-shape developmental trajectory of the affordance conflict cost between 8 years of age and adulthood. While both 8-year-old children and adults exhibited an important processing cost when conflictual objects were perceived within reach, the cost completely disappeared at 10 and did not become reliable again before adulthood. It is important to note that the identification of such a non-linear trajectory was made possible by assessing different age groups between mid-elementary school children and adults including young teenagers, which has rarely been done. Many studies (including from our research group) concluded about linear developmental changes after evaluating elementary school children and adults. In adults, the presence of an affordance conflict cost of about 20 ms nicely replicates our previous findings (Kalénine et al., 2016) with a different virtual set up and a different set of stimuli. Critically, results also demonstrate a significant affordance conflict cost of about 80 ms in the youngest group. Eight-year-old children, like adults, judged the properties of conflictual objects with distinct structural and functional affordances much more slowly than those of non-conflictual objects with similar affordances, but only when they perceived the objects within reach. As the difference between the two types of objects is selective to peripersonal space, we can rule out the possible confounds related to potential differences between object types (object familiarity, object visual complexity, etc.). Therefore, this result indicates that young children perceive both structural and functional affordances and are strongly impacted by the competition that may arise between them. Despite an increasing literature stressing the relevance of dividing object affordances into different subtypes, to our knowledge the sensitivity of young children to separate subtypes of affordances had never been documented. In particular, as the motor experience of young children with object use is somewhat limited, it was still unclear whether they activated functional affordances from visual objects. Manipulation priming has been documented in children as young as 5 (Collette et al., 2016; Mounoud et al., 2007). Yet without dissociating structural and functional actions, it is not possible to ensure that the perceived affordance is functional (i.e., related to object use), rather than structural (i.e., based on the adequation between object size/shape and the grasping action). This is the case for many non-conflictual, handled objects (e.g., hammer, mug). In the present study, the emergence of an affordance conflict cost requires the co-activation of the two types of affordances and indicates that functional affordances, dissociated from structural affordances, may be already perceived at 8. Then, what happened from 10, when the affordance conflict cost disappeared until adulthood? Before considering the mechanisms related to the retrieval and exploitation of affordances, it is important to look at how the different age groups process objects in space, independently from their affordances. The distinction between the reachable space and the non-reachable space was adequately performed by the different age groups with the mean perceived reachability boundary falling within the intermediate distances selected, clearly delimiting two distinct reachable and unreachable spaces for all groups. Moreover, judgements were overall faster when objects were presented in the reachable than non-reachable space and this advantage decreased linearly with age. The diminution of the effect of space with age is consistent with previous results showing that younger children are less efficient in the processing of objects in their extrapersonal space (e.g., Gabbard et al., 2007). Regardless, this linear decrease with age does not match the developmental U-shape of the affordance conflict cost. It is thus very unlikely that space perception alone may account for developmental changes in the cost entailed by the competition between object affordances.

Developmental changes in the conflict cost were assumed to reflect the joint development of the mechanisms of affordance retrieval and exploitation. The quadratic trajectory identified between 8-year-olds and adulthood is compatible with at least two interpretations. First, performance in affordance retrieval and exploitation both continue to increase with age, but affordance exploitation develops later and shows a softer slope. This would lead to important affordance conflict cost in the youngest children (affordance exploitation absent) and in adults (affordance retrieval outreaching affordance exploitation abilities), whereas intermediate age groups would benefit from a better-balanced involvement of affordance retrieval and exploitation. Second, affordance retrieval and/or exploitation abilities also show a U-shape developmental trajectory. Although this may not have been predicted from the related developmental literature, it would account for the observed trajectory of the affordance conflict cost. We will turn to the results from the secondary tasks in the action priming and Simon paradigm to discuss these possibilities.

At the group-level action priming effects, measured to evaluate affordance retrieval, showed a surprisingly similar developmental trajectory to the affordance conflict cost, with a disappearance of affordance priming between 10 and 12. In contrast, Simon effects, used to assess general conflict monitoring abilities that may be at play in affordance exploitation, were systematically present and showed a similar amplitude between 8 and adulthood. Therefore, group results from the complementary tasks suggests that developmental changes in the ability to perceive and activate affordances from visual objects are involved in the developmental changes in the cost entailed by affordance competition during object processing. Affordances are sufficiently perceived to generate an action priming effect and a conflict cost at 8, but are not activated anymore at 10. In addition, in contrast to the other groups, 10-year-olds were the only children showing the expected positive relation between the amplitude of the conflict cost and the amplitude of the action priming effect in the regression analysis. Then what happens to affordance perception at the end of elementary school? Two lines of speculative explanations may be put forwards. First, the perception of object motor properties from their visual presentations may remain stable across age groups, but their relative contribution to object processing may change. The evocation of use gestures associated with object manipulation has been shown to be sometimes interfering with (rather than facilitating) semantic decisions on objects (Borghi et al., 2012; Collette et al., 2016). Interestingly, in Collette et al. (2016), the facilitation of object naming elicited by the prior presentation of an object with a similar manipulation at 8 years of age turned into an interference from 10. With age and education, the balance of motor and non-motor information (mainly learned from language) in object concepts may change in the favor of non-motor information, at least during the years witnessing a high increase in verbal knowledge acquisition in school and education. This interpretation also echoes certain unexpected results in developmental studies on affordances around 10-year-old (see for example, the absence of superiority of action priming over context priming on object identification at 9, contrary to 7 and adults in Kalénine et al., (2009). During the early teenage years, motor information may be activated from visual objects but may be given less weight in object semantic categorization (action priming paradigm) and in the evaluation of object perceptual and semantic properties (3D object perception paradigm, especially in the semantic task). Alternatively, development may directly affect the activation of affordances rather than their influence on object processing, in relation to the important body-related changes that occur during early adolescence. Novel tool use and physical growth may affect the body schema, an internal representation of the body in action (Assaiante et al., 2014; Maravita et al., 2003; Martel et al., 2016). The very rapid changes in the size and abilities of the child body between 10 and 14 may lead to limited motor resonance from visual stimuli and poor affordance perception. This may, in turn, extinguish both action priming effects and affordance conflict cost during this period. Using a similar action priming paradigm in 7- to 10-year-old children, Liuzza et al. (2012) found greater action priming effects on object categorization when the hand prime displayed corresponded to a child hand in comparison to an adult hand, demonstrating that resonance effects at play in action priming are sensitive to the match between the representations of the participant's own body and the one currently perceived. Moreover, body schema disturbances impact motor control and adolescents show a weaker coupling between perception and action than adults (Choudhury et al., 2007). Accordingly, consequences of affordance retrieval on object processing may not be visible during this period, whether it be in the form of action priming effects or affordance conflict costs, but effects reappear in young adults when perception-action coupling become steadier. In young adults, unexpectedly, action priming effects were negatively related to affordance conflict costs. The reasons for this result remain unclear. For age groups in which effects were reliable at the group-level and exhibited by most individuals, it is a priori not clear to what extent the magnitude of the effect matters, beyond the mere presence of priming effect or conflict cost. Moreover, the same surprising negative relation was found between Simon effect and affordance conflict cost in the adult group, suggesting a possible more general common factor underlying the relation between performance in the main task and in the complementary tasks in this group. Yet, further interpretations of this unexpected result would be too speculative at this point.

In contrast to an interesting parallel between the development of action priming effects and affordance conflict costs, our attempt to explore the contribution of conflict monitoring abilities to the cost of affordance competition during object perception was not conclusive. Contrary to what was expected (e.g., Davidson et al., 2006; Hämmerer et al., 2010), Simon effects used to reflect general conflict monitoring performance did not show any developmental changes from 8 to adulthood in the first place. With the Simon task, we aimed at evaluating general conflict monitoring abilities without focusing on a particular mechanism of cognitive control, but age-related changes may rather affect the different control processes and their balance rather than a general homogeneous ability (e.g., Ambrosi et al., 2016; Erb & Marcovitch, 2019; Gonthier et al., 2019). Alternatively, subtle methodological choices (e.g., lack of time pressure to respond in the Simon task, evaluation of conflict monitoring abilities after the 3D object perception task) might account for this lack of developmental sensitivity of the general Simon effect. Regardless, the absence of age-related difference in the Simon task does not allow any conclusion about whether conflict monitoring abilities contribute to affordance conflict costs. Although the magnitude of Simon effects positively predicted the magnitude of conflict costs in 12-year-olds, this single expected relation between individual effects should be considered with caution in the absence of other similarities in the developmental patterns. Moreover, from a theoretical point of view it is still unknown whether affordance exploitation (i.e., resolving the competition and selecting between affordances) may relate to domain-general conflict monitoring abilities that may be assessed with any conflict task. The issue of whether the mechanisms underlying stimulus-response compatibility (such as in the Simon task) and stimulus-stimulus compatibility (such as in the Stroop task) largely overlap remains a matter of debate (Hommel, 2011; Li et al., 2014). Stroop effects might better predict affordance conflict costs than Simon effects. Therefore, an important open question for future research concerns the specification of affordance exploitation when there is no specific action to perform (perceptual tasks) and its relation with domain-specific and domain-general conflict monitoring processes.

Conclusion

The present developmental study demonstrates that the competition elicited by the perception of distinct affordances during object processing induces a cost in children as young as 8. This finding extends previous results in adults showing a similar impact of affordance competition on perceptual judgements and reinforce the relevance to consider action-perception relations for a better understanding of the development of object perception. Critically, the development of the affordance conflict cost shows a U-shape trajectory between 8-year-old and adulthood, with a disappearance of the detrimental effect between 10 and 14-year-old. The non-linear trajectory highlights separate periods of high sensitivity to affordance competition and suggests complex changes in affordance retrieval and/or exploitation during the early teenage years. Preliminary results on the relative contribution of the mechanisms of affordance retrieval and affordance exploitation to the affordance conflict cost indicate that affordance retrieval, showing a similar non-linear developmental trajectory, is likely subject to critical changes during early adolescence and probably participate in the modifications of affordance conflict costs. The role of conflict monitoring abilities in the context of affordance exploitation in perception requires further investigation. Overall, the present findings provide novel insights into the development of affordance competition that may help enriching recent theoretical views on affordances (Cisek, 2007; Thill et al., 2013).

END

Section 2. Complementary experiment. Does the visual complexity explain the affordance conflict cost?

Introduction

Recently, Bub et al. (2018) questioned[11] the involvement of object visual complexity in the emergence of the affordance conflict cost (i.e., the fact that non-conflictual objects are categorized faster than conflictual objects when presented in peripersonal space compared to extrapersonal space). For Bub et al. (2018), the selective cost observed for conflictual objects over non-conflictual objects in peripersonal space can be explained by the visual complexity of the objects used by Kalénine et al. (2016). Actually, it has been shown that visual complexity can modulate performance on object perceptual processing depending on task demands (Gerlach & Marques, 2014). For instance, Gerlach & Marques (2014) showed that visual complexity increases the time needed to categorize objects as real or not. Therefore, we can ask whether visual complexity could account for the longer judgement times associated with conflictual objects. The visual complexity would induce deeper visual processing and thus, harder decisions. In addition, visual complexity differences would be exacerbated in peripersonal space where visual objects are larger. In such framework, the conflictual cost would become a visual complexity cost.

Even though we must all agree for saying that a calculator (i.e., conflictual object) is definitively more complex visually than a ball (i.e., non-conflictual object), if we ask one to say "how", we can expect to get multiple answers. Actually, the role of the environmental complexity has been strongly investigated and argued when considering visual perception (see Donderi, 2006 for a review). Since Snodgrass & Vanderwart (1980) proposed norms for visual

[11] *"We should note that the mere discrepancy in the speed of responding to "conflict" versus "non-conflict" objects is not necessarily indicative of the presence of competing affordances"* (Bub et al., 2018, p.36).

complexity of a large set of pictures, much has been written about dimensions that differentiate categories of objects belonging to their set of stimuli (see Marques et al., 2013 for a listing of dimensions). Therefore, it was hard to choose the right dimensions to control to compare conflictual and non-conflictual objects. In order to provide an initial answer, we checked at the distinction of visual characteristics between conflictual and non-conflictual objects that Bub et al. (2018) referred to.

> *"For instance, a baseball, various kinds of bottles or containers, a vase (these examples of "non-conflict" objects are all taken from Kalénine et al. 2016) have* ***few if any parts****, whereas a remote control, scissors, tape dispenser and calculator (examples of "conflict" objects) are* ***visually more complex****".*
> Cited from Bub et al. (2018)

Hence, the present work was interested in the influence of two subjective assessments of the visual complexity for conflictual and non-conflictual objects: the number of parts and the overall visual complexity. The number of parts assessment was similar to Lloyd-Jones and Nettlemill (2007)'s decomposability assessment. In their study, the decomposability was assessed by asking participants to evaluate how many visual parts composed each presented picture. The visual complexity assessment was inspired from Snodgrass & Vanderwart (1980)'study, by asking participants to evaluate the visual complexity of each picture on a 5-point Liker scale. Nonetheless, a recent principal-component analysis (Marques & Raposo, 2011) demonstrated that visual complexity is a grouping of multiple factors that are closely interconnected. Thus, both subjective assessments are likely to be influenced by other factors, such as the familiarity of objects.

Noteworthy, there exist computerize alternatives to assess image features that could provide a more objective visual complexity proxy that takes into account brain visual processing (Riesenhuber & Poggio, 1999; Zhang et al., 2011). For instance, FSIM is a feature similarity index that is computed based on the assumption that the visual processing of images is realized based on low-level visual features (Zhang et al., 2011). In contrast, HMAX is a model of higher-order visual processing consistent with neurophysiological data of the hierarchical functioning of the inferotemporal cortex (Riesenhuber & Poggio, 1999).

We therefore ran a complementary test to evaluate the influence of the visual complexity of objects on the occurrence of the conflict cost effect in object perception. We evaluated the visual complexity of objects through subjective (i.e., overall visual complexity, number of parts) and algorithm (i.e., FSIM, HMAX) measurements. A sample of 15 young adult participants was recruited to rate the overall visual complexity of conflictual and non-conflictual objects. Assuming that the number of parts associated with each object was a less subjective assessment, only two independent judges were consulted. FSIM and HMAX indexes were computed for each objects (Riesenhuber & Poggio, 1999; Zhang et al., 2011). First, we investigated whether conflictual and non-conflictual objects differ on the different assessments of visual complexity. Second, we evaluated the influence of visual complexity on the emergence of affordance conflict cost when it was observed, that is in 8-year-old children and young adults.

Method

Participants

Fifteen volunteers took part in the experiment (n = 15, M= 31 years, SD = 13.55) for assessing visual complexity of objects. Two independent judges evaluated the number of parts of each object.

Stimuli

Object stimuli were obtained from the stimuli used in the development study (see **Appendix 7.** and **Appendix 8.**). They were images of 40 common manipulable objects presented on a wooden table. Among the 40 objects, half were "conflictual" and involved distinct hand postures for grasping and using gestures (e.g., calculator) and half were "non-conflictual" and involved similar hand postures for grasping and using gestures (e.g., ball).

Subjective assessments: Visual complexity and number of parts

Visual complexity

Two PowerPoint diapositives of the 40 objects (i.e., 20 non-conflictuals and 20 conflictuals) were built. Diapositives were composed of cropped screen captures of the objects. The objects were randomly presented in each diapositive to counterbalance the order effects. PowerPoint diapositives were presented on a screen for each volunteer, alone. Each participant was presented with the diapositive twice: one for being familiarized with the images and second for judging the overall visual complexity of object.

Participants had to judge the visual complexity of objects on a 5-point Likert-scale. The exact instruction was "*Object pictures will be presented successively. Note on the scale, the visual complexity of the object. 1 = no complex, 2 = low complex, 3 = medium, 4 = complex, 5 = very complex*". Oral precision was given to the participant, telling them to take care of using all the scale to evaluate the visual complexity.

Number of parts

Two independent judges evaluated the number of distinct parts of each object. For an example, the camera was judged to possess 3 parts (i.e., the screen, the zoom and the body).

Algorithm assessments: FSIM and HMAX

FSIM assessment

An objective index of perceptual similarity between the wooden table alone and objects was computed using the FSIM algorithm (Zhang et al., 2011). The computation of the index was made by considering two image characteristics: the phase congruence and the amplitude of image gradient. Both concerns the change in the contours: one considering patterns in image composition (i.e., phase congruence) and the other considering directional change in image intensity and color (i.e., image gradient). Each object image was compared to the image of wooden table alone. The FSIM index provides a measure of low-level perceptual similarity between the wooden table alone and objects. The upper limit of the index is one: closer to one is the index, more similar are the pictures, less complex is the visual complexity.

HMAX assessment

An objective index of neuron activation pattern was computed using the HMAX algorithm (Riesenhuber & Poggio, 1999). The HMAX algorithm reproduce the hierarchical brain functioning of the inferotemporal cortex. Low-level visual features (e.g., orientation) are processed and combined to form complex visual-features. The HMAX index provides a measure of the level of activation of the C2 cell layer: higher the index, higher the resources required to process the images, higher the visual complexity.

Data analysis and results

Comparisons of conflictual and non-conflictual objects

FSIM, HMAX, visual complexity and number of parts were analyzed as a function of Object Category (conflictual, non-conflictual). Considering the distribution of effects, we opted for non-parametric Wilcoxon comparison tests. One comparison test was conducted to compare conflictual and non-conflictual objects for each of the three assessments of visual complexity.

Wilcoxon tests indicated that conflictual and non-conflictual objects are different on their overall visual complexity (W = 323.5, p = 0.001) and on their number of parts (W = 274, p = 0.03). Conflictual objects were judged as more complex visually and to possess more parts than non-conflictual objects. Both objects did not differ on FSIM assessment (W = 141.5, p = 0.95), neither on HMAX assessment (W = 161, p = 0.86). Median and MAD (median absolute deviation) values are reported in **Table 6** below.

Table 6. Median and (MAD) values of the four assessments of visual complexity (i.e., visual complexity, number of parts, FSIM and HMAX) as a function of conflictual and non-conflictual objects.

	Conflictual	**Non-conflictual**
Visual complexity	3 (*1.48*)	1.5 (*0.74*)
Number of parts	2 (1.48)	2 (0)
FSIM	$78.444 * 10^{-2}$ ($0.82 * 10^{-2}$)	$78.78 * 10^{-2}$ ($\mathit{0.46} * 10^{-2}$)
HMAX	1.15 (*0.08*)	1.19 (*0.16*)

Involvement of visual complexity in the emergence of affordance conflict cost

Conflictual and non-conflictual objects differ on the subjective assessments of visual complexity and number of parts. However, the number of part assessment was not a very sensitive measure, as highlighted by equivalent medians and low variability. We thus decided to only control for the influence of overall visual complexity on the emergence of the affordance conflict cost. Yet, the subjective assessment of visual complexity was conducted on adult participants, thus controlling its influence for 8-year-old children was not an optimal decision.

We thus decided to make a second verification, by controlling the influence of the FSIM algorithm index as it reflects a measure of difference in low-level visual characteristics[12] and tended, as expected, to be negatively correlated to overall visual complexity judgments (r: -0.26, p = 0.10). To this aim we used the same mixed-effect linear models on Log-transformed RTs of each group, described in the data analyses of the developmental study for the 3D perception paradigm.

Log-transformed RTs were analyzed as function of Space (reachable, unreachable) and Object types (conflictual, non-conflictual). We added the assessments (i.e., visual complexity judgements or FSIM index) as a cofounder in the model. Two models were built for each group, one for adding each assessment as a covariable. Fixed effects corresponded to the effects of "Visual complexity" (i.e., visual complexity or FSIM index), Space, Object type and Space x Object interaction. The interaction between Space and Object type reflected the cost of the competition between distinct object affordances during object processing and was the effect of interest. The random effect structure of the model included participants as random effect factor with random intercepts and random slopes for space and object type. We documented the presence of a conflict cost in each age group separately and for each visual complexity assessment added as a covariable. All mixed-effect linear model analyses were conducted with the lme4 package (version 1.1-21) of R software (version 3.6.1). LmerTest package (version 3.1-1) was used to obtain significance F-tests of fixed effects. Denominator degrees of freedom were approximated using Satterthwaite's approximations.

When controlled for the subjective assessment of visual complexity, the evaluation of the two-way interaction between Space and Object type was still significant in 8-year-olds [F(1, 2725.1) = 9.97, p = 0.001] and was still significant in young adults [F(1, 4573.5) = 4.42, p =

[12] HMAX index is a measure of higher order visual processing (i.e., inferotemporal cortex) which is more likely to evolved through development.

0.04]. When controlled for the FSIM, the evaluation of the two-way interaction between Space and Object type was still significant in 8-year-olds [$F(1, 2724) = 9.99$, $p = 0.001$] and was still significant in young adults [$F(1, 4562.6) = 4.14$, $p = 0.04$].

Discussion

The present work aimed at identifying the involvement of visual complexity on the emergence of the affordance conflict cost during the 3D perception paradigm. The visual complexity was assumed to account for the differences in judgment times between non-conflictual and conflictual objects (Bub et al., 2018). As conflictual objects would be more complex visually and would possess more parts than non-conflictual objects, they would require deeper visual processing, resulting in harder decision to categorize them. Visual complexity was evaluated through a subjective assessment (i.e., overall visual complexity) made by 15 young adults. Two independent judges evaluated the number of parts of each object. Additional objective indexes were computed with algorithm alternatives (i.e., FSIM and HMAX). We compared conflictual and non-conflictual objects based on the different assessments of visual complexity. Then, we evaluated the influence of the visual complexity of objects on the emergence of affordance conflict cost in 8-year-old children and young adults.

Our first results highlight that conflictual and non-conflictual objects differed in their visual complexity, but only when considering the subjective assessments of visual complexity and their number of parts. Hence, conflictual objects were judged as more complex visually and to possess more parts than non-conflictual objects. However, conflictual and non-conflictual objects did not differ on FSIM index, neither on HMAX. Even though, the work was conducted on new versions of conflictual and non-conflictual stimuli, it supports partially what Bub et al. (2018) have emphasized about the stimuli used in Kalénine et al. (2016), that is, overall conflictual objects are more complex visually and possess more parts.

More importantly, results highlight that even when the effect of visual complexity was controlled, the affordance conflict cost was still present in 8-year-old children and young adults. Thus, our findings did not support that the selective cost observed for conflictual objects over non-conflictual objects in the peripersonal space can be explained by the visual complexity of objects (Bub et al., 2018). Findings constitute an argument for saying that the discrepancy in the speed of responding to “conflict” versus “non-conflict” objects is indicative of affordance competition, even in young children. The mere presence of a non-linear developmental trajectory constitutes a second argument against the influence of visual complexity on the emergence of the affordance conflict. There are no specific reasons to believe that sensitivity to visual complexity in 8-year-old children would follow a U-shape developmental trajectory.

Global synthesis

Overall, the present chapter provides demonstrations about how inter-individual variabilities modulate the impact of affordance competition during manipulable object perception. We identified two age periods when individuals are more sensitive to affordance competition, that is in young children (8-year-olds) and in young adults (replication of results from Kalénine et al., 2016). The involvement of *affordance specification* in affordance competition is clearer than the involvement of *affordance selection* mechanisms. A complementary experiment demonstrated that conflictual and non-conflictual objects are different according to their visual complexity, even though it was not visible in all types of visual complexity assessments. Furthermore, we highlighted that the reported affordance conflict cost in 8-year-old children and young adults remains after controlling for the visual complexity of conflictual and non-conflictual objects. Overall, the present findings provide additional support for the interpretation that the selective cost for conflictual objects in peripersonal space reflects affordance competition. In the next chapter, we will investigate how intra-individual variabilities modulate the impact of affordance competition on manipulable object perception. More particularly we will try to determine whether contextual information may modulate affordance competition and contribute to the resolution of the competition between affordances during perceptual processing of objects.

CHAPTER 6. CONTEXTUAL MODULATION OF NEURAL MECHANISMS UNDERLYING COMPETITION BETWEEN AFFORDANCES DURING OBJECT PERCEPTION

In the previous chapter, we investigated how inter-individual variabilities may modulate the impact of affordance competition on object perception. We identified the age periods when individuals are more sensitive to affordance competition, that is in young children (8-year-olds) and young adults. More particularly, the selective cost for conflictual objects follows a U-shape developmental trajectory between these two age periods. We provided additional evidence that *affordance specification* shows a similar U-shape development, suggesting that the affordance conflict cost relies on *affordance specification*. Results about *affordance selection* mechanism are less clear, as no developmental trajectory was observed. A complementary experiment contributed in refuting the involvement of potential confounded variables (e.g., visual complexity) in the emergence of the affordance conflict cost that was used for revealing affordance competition.

In the present chapter, we will investigate how intra-individual variabilities modulate the impact of affordance competition on object perception. More particularly, we will evaluate the effect of a verbal context on affordance competition. It must be reminded that the selective cost for conflictual objects is reflected by a reduction of μ rhythm desynchronization, suggesting that competition between object affordances alters the motor resonance during manipulable object perception (Wamain et al., 2018). Using EEG recording, we will test whether a congruent action verb could help the resolution of the competition between object affordances and induce a release of μ rhythm desynchronization during object perception.

The present experiment is part of a larger investigation including behavioral and electrophysiological experiments that are not fully completed (COVID-19 interruption). The present work reports exploratory analyses.

Introduction

As aforementioned, only few studies in adults have directly investigated the impact of the co-activation of distinct affordances during the perception of a visual object (Bub et al., 2018; Jax & Buxbaum, 2010, 2013; Kalénine et al., 2016; Wamain et al., 2018). These studies have highlighted a selective action production cost (Bub et al., 2018; Jax & Buxbaum, 2010, 2013) and a selective perceptual cost (Kalénine et al., 2016; Wamain et al., 2018) for visual objects evoking distinct grasping and using gestures (i.e., conflictual objects). At the behavioral level, Kalénine et al. (2016) demonstrated that the activation of multiple affordances induces a perceptual processing cost that depends on the possibilities of the observer to interact with the perceived objects. They instructed participants to make judgements about the perceptual characteristics of conflictual and non-conflictual objects (e.g., "is it reachable?", "is it a kitchen object?") presented at different distances in a 3D virtual environment. Longer response times were observed for conflictual objects compared to non-conflictual objects, but this effect was only evidenced when objects were presented in the peripersonal space of the participants. At the neurophysiological level, the typical μ rhythm desynchronization associated with manipulable object perception (Proverbio, 2012; Wamain et al., 2016) is reduced – and even suppressed – when conflictual objects are presented within reach (Wamain et al., 2018). Together, these studies suggest that when activated, distinct affordances associated with a single object compete with one another and, that this competition is detrimental to the object perceptual processing, highlighted at the behavioral and neurophysiological levels. Wamain et al. (2018) suggested that the μ rhythm desynchronization, in addition to its classical interpretation as a brain indicator of motor resonance during the object perceptual processing (i.e., affordance *perception*), may also reflect action selection processes at the cerebral level during object perception (i.e., affordance *competition*). Then, it is interesting to question whether at the cerebral level, competition between affordances may be modulated during the processing of conflictual objects.

Another aspect we stated before about affordances is that they are context-dependent (Ambrosini et al., 2012; Borghi et al., 2012; Costantini et al., 2011; Kalénine et al., 2014; Lee et al., 2012; Wokke et al., 2016). For instance, Costantini et al. (2011) demonstrated that when objects are within reach, they activate both their structural and functional affordances (Ambrosini et al., 2012; Costantini et al., 2011). They presented object-verb sequences to their participants. Verbs could correspond to object manipulation (e.g., brush – **to hold**), object function (e.g., brush – **to comb**) or they were observation verbs (e.g., brush – **to gaze**). Participants were asked to judge the appropriateness of the verb according to the object presented just before it. Authors reported shorter response times when objects were presented in the peripersonal space compared to the extrapersonal space for function and manipulation verbs, but no difference for observation verbs. Thus, we can assume that conflictual objects evoke their structural and functional affordances while presented in peripersonal space. In the case of conflicting structural and functional affordances, it is therefore relevant to question whether context verbs could orient the perceptual processing of conflictual objects toward one affordance in detriment of the other, therefore reducing their competition. The present study aims at evaluating whether the visual context may influence the competition of affordances by adding a verbal context around (before and after) the presentation of conflictual objects (Wamain et al., 2018).

In the case of the present study, we decided to manipulate the visual context by using verbal information as it has been shown that verbs induce a reactivation of their associated motor properties (Buccino et al., 2016). The association between verbal and motor information has been particularly observed while investigating action verbs (Aravena et al., 2012, 2014; Boulenger et al., 2008; Hauk et al., 2004; Pulvermüller, 1999; Pulvermüller et al., 2001; Tomasino et al., 2010; Vukovic et al., 2017). These studies have shown that the presentation of action verbs facilitates the motor responses associated with the effector evoked by the verb (e.g., “to grasp” reduces time to produce manual responses). Neurophysiological data supports these discoveries, revealing a somatotopic activation of the motor brain networks (i.e., premotor and motor cortex) in response to the action verb presentation (Hauk et al., 2004; Pulvermüller, 1999). Accordingly, we assumed that the presentation of an action verb - before or during the object perceptual processing - would activate motor information that would interact with the affordances of the object. Therefore, we anticipated an influence of the presentation of a verbal context on the competition between affordances during the perceptual processing of conflictual objects. We assumed that presenting an action verb evoking the typical use gesture associated with conflictual objects would orient the processing of such objects toward their functional affordances, hence reducing affordance competition.

To sum up, the main goal of the present study is to evaluate whether the verbal context can bias the competition between affordances. The perception of conflictual objects reduces the typical μ rhythm desynchronization associated with the perception of manipulable object in peripersonal space. Thus, we expected that the presentation of an action verb would resolve the competition and increase the μ rhythm desynchronization associated with conflictual objects when perceived in the peripersonal space of the observer. We recruited twenty-five young adults who performed reach-to-grasp judgments on conflictual objects presented in a 3D environment (paradigm from Kalénine et al., 2016; Wamain et al., 2018) in different verbal contexts (i.e., functional action and neutral), in order to assess the influence of the verbal context on the resolution of affordance competition. Compared to the developmental study, participants performed only a reach-to-grasp judgement task in order to keep the duration of the experiment reasonable. Note that although affordance competition was expected to be stronger in the highly action-relevant reach-to-grasp judgment task at first, no modulation of competition effects by the task was observed in previous investigations (Kalénine et al., 2016; Wamain et al., 2018), or in the developmental study described earlier.

The present experiment is part of a larger investigation including behavioral and electrophysiological experiments that are not fully completed. The experiments were designed in order to assessed the influence of a verbal context on the processing of conflictual objects. The verbal context was presented either following or preceding the presentation of conflictual objects. The present work only reports exploratory analysis that were realized on the experimental conditions where objects were preceded by verbs, and did not report analysis for the experimental conditions where objects were followed by verbs.

Method

Participants

Twenty-five volunteers took part in the experiment (mean age = 21.4 years; SD = 3.89; 17 females). Participants were all right-handed (mean handedness quotients: 0.75%, range: 33 - 100 %), as assessed by the Edinburgh handedness inventory (Oldfield, 1971). They all reported normal or corrected-to-normal vision. They reported no history of psychiatric or neuropsychological disorders. They provided written informed consent and were paid 20 € for their participation. The protocol was approved by the Ethical Committee of the University of Lille (see **Appendix 2.**) and was in accordance with the declaration of Helsinki (1964, revised in 2013). Due to technical reasons, two participants were discarded from further analyses. One additional participant was excluded due to her misunderstanding of the experimental instructions. Therefore, further analyses have been conducted on the data provided by the 22 remaining participants.

Stimuli

Three-dimensional images of twenty common manipulable objects were created with Blender software and generated with a photorealistic rendering method. The twenty images corresponded to the conflictual objects generated for the developmental study (cf. Experimental contribution/Chapter 5, see also **Appendix 8.**). Conflictual objects were displayed in a virtual scene generated with Blender software. The virtual scene was composed of a wooden table in a neutral room (**Figure 29**).

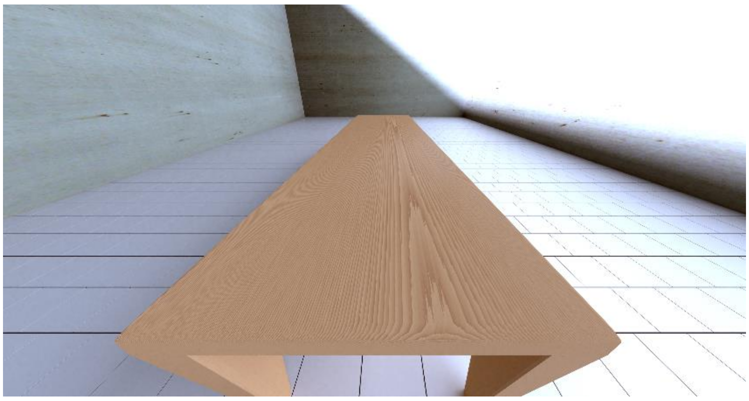


Figure 29. 3D virtual scene of the neutral room in which objects were presented.

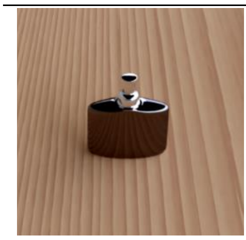
Objects were presented on the virtual table at different distances from the participant, along the vertical medial axis. Nine distances were sampled. The nine distances were separated in near (-70%, -60% and -50%), limit (-10%, mean arm length, +10%) and far (+50%, +60% and +70%) spaces (see **Table 7**). This procedure ensured that regardless of the individual perceived reachability boundary - computed offline (see Result section) - most participants would see objects both within and out of reach. Images were generated before the experiment by taking into account the distance from the screen (100 cm) and the mean reachability boundary of adults (81 cm) from a previous investigation (Kalénine et al., 2016).

Table 7. The nine distances of presentation (in centimeters) according to mean reachability boundary (mR).

- 70 %	**- 60%**	**- 50%**	**- 10%**	**mR**	**+ 10%**	**+ 50 %**	**+ 60 %**	**+ 70%**
24	32	41	73	81	89	122	130	138

Two verbs have been selected for each of the 20 conflictual objects: one action verb and one neutral verb. Action verbs were selected to reflect the typical gesture associated with the functional use of the object and neutral verbs were observation verbs (see **Table 8** below for two examples). Verbs were presented in the imperative form, as it has been shown that verbal forms that induce an action in the moment cause the most motor activation (Aravena et al., 2014), such as when verbs are presented in affirmative (Aravena et al., 2012) or imperative (Tomasino et al., 2010) forms.

Table 8. Examples of action and neutral verbs for two conflictual objects (see the full-list of object-verb associations in **Appendix 9.**)

Objects	**Action verb**	**Neutral verb**
 **Calculator**	Compte (to count)	Regarde (to look at)
 **Perfume**	Vaporise (to spray)	Observe (to observe)

Pretest and control of the verbal stimuli

Twelve additional right-handed young adults were primarily recruited in order to select the appropriate verbs for each object. The survey was conducted to assess the typical use of objects. Participants were presented with object-verb associations one by one and had to respond to the following question: "To what extent this verb describes the typical use of the object?" by rating on a 7-point Likert scale (from 1: strongly agree, to 7: strongly disagree). Three object-verb associations were presented for both action and neutral verbs.

Subsequently, one action verb and one neutral verb for each object were chosen to reconcile two different aspects: (1) the rating on the survey and (2) some control variables typically considered when manipulating verbal stimuli. For the rating on the survey, we ensured to have a median rating as low as possible for action verbs (close to 1, strongly agree). The action and neutral verbs differed on the extent of their association with objects. Action verbs were highly associated with objects (median = 1 [range = 1 – 2.5]) while neutral verbs were weakly associated (median = 6.5 [range = 4 – 7]). In addition, the neutral verbs were selected so that they were paired with action verbs on frequency, letter numbers and syllable numbers (see **Table 9** for pairing values).

Table 9. Mean (and SD) values for frequencies, letter and syllable numbers for action and neutral verbs. The values for each verb were obtained in a lexicon database (see http://www.lexique.org/).

	Frequency	**Letter number**	**Syllable number**
Action verbs	21.82 (28.00)	6.45 (1.76)	1.7 (0.80)
Neutral verbs	27.19 (60.65)	7.05 (1.00)	2.1 (0.55)

Perception in 3D immersive virtual reality system

The virtual scene was presented in 3 dimensions to the participants (cf. **Figure 30**) via a 2×4 m rear projection screen using a 3D stereoscopic projector (Christie Mirage 4K35) generating images at 120 Hz with a 4K spatial resolution (3840 x 2060 pixels). Active 3D eyewear (Christie) was used for producing 3D image perception. Images were generated taking into account the participants' height (i.e., eye-level kept at 60 cm from the ground) and were displayed with MatLab 6.5 (MathWorks, Natiek, MA, USA) and the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). Two different images of each stimulus were computed and presented 8.33 ms alternatively to each eye. Normal fusion created the illusion of viewing a single object. Relative size and perspective cues as well as binocular disparity were used to induce a 3D perception of the visual scene and objects.

Figure 30. Picture of a participant wearing the active 3D eyewear in front of the scene used during the experimental task.

Before the beginning of the experimental session, the 20 selected objects were presented in 2 dimensions and named one by one to the participant in order to make sure that each participant correctly recognized the different objects. Participants were seated approximately 100 cm from the screen wearing the Active 3D eyewear and an EEG cap. Participants were positioned so that their eyes were positioned at 120 cm from the ground. A device with two pedals was placed under participants' feet in order to collect the responses. They were instructed to respond with their feet by clicking on the pedals.

Each trial started with the presentation of blurred version of the visual scene with the wooden table, during 1000 ms followed by an image of one of the 20 conflictual objects at one of the nine distances for 500 ms. In half of the trials (360 trials), the object was preceded by a verb (i.e., verb-object trials) and in the other half (360 trials), the object was followed by a verb (i.e., object-verb trials). The present work will only report analysis conducted on verb-object trials. In verb-object trials[13], a verb was presented 500 ms before object presentation and for a duration of 200 ms. Both presentations were thus separated by the presentation of the wooden table alone for 300 ms. Verbs were presented horizontally to be read as easily as possible (Byrne, 2002). Verbs were superimposed to a blurred pictured of the virtual scene, in front of the participant's eyes (in 10° visual angle according to the central vision and at participant eye-level: 120 cm to the ground) in order to reduce signal contamination by saccadic eye-movements.

[13] Object-verb trials were not analyzed in this work. In these trials, a verb was presented just after object presentation and for a duration of 200 ms. Both trials were constructed in order to evaluate whether the timing at which contextual information is delivered could modulate competition between affordances.

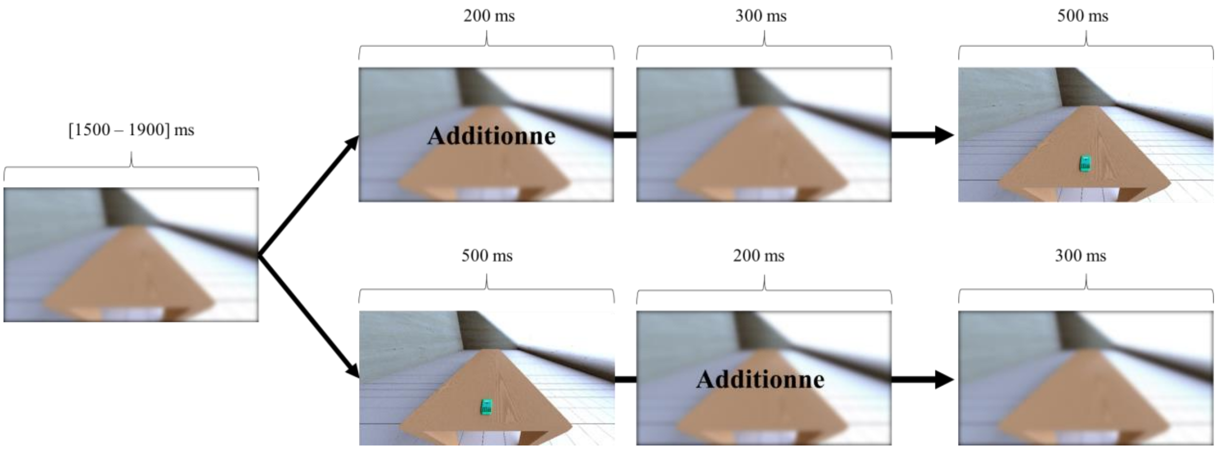


Figure 31. Experimental procedure of the EEG study. The upper-part corresponds to the condition with the verb preceding the object (i.e., condition analyzed below). The lower-part correspond to the condition with the verb following the object (NOT ANALYZED IN THIS THESIS). The blurred scene with the table alone remains on the screen, except for when the object is presented.

The participants were asked to perform reach-to-grasp judgements by judging whether they could reach and grasp the object with their right hand without performing the movement. Responses were given by clicking on the pedals. The response mapping was counterbalanced between participants. To avoid any EEG signal contamination, participants were instructed to respond only when the object presentations ended on a question mark, corresponding to 10% additional trials (72 trials) from which the associated EEG signal was not further analyzed. Inter-stimuli intervals (ITI) randomly varied between 1500 and 1900 ms. During ITI, a blurred picture of the visual scene without object was displayed (see **Figure 31** for the entire procedure). The experimental session was composed of seven blocks of approximately 5 minutes each. There were 720 experimental trials (20 objects x 9 distances x 2 verbs x 2 object-verb orders) randomly presented in each block, preceded by 20 practice trials.

Data Analyses

Determination of individual perceived reachability boundary

The different distances were divided into reachable and unreachable spaces according to the perceived boundary of the peripersonal space of each participant. The individual perceived boundary was extracted a posteriori from the reaching task according to individual responses made in the 72 additional trials characterized by a question mark ("yes, it is reachable" vs. "no, it is not"). A maximum likelihood fitting procedure was used to obtain the logit regression model that best fits the reachable/unreachable responses of the participant with respect to the distance. The individual perceived reachability boundary corresponds to a 50% chance for the participant to say "yes, it is reachable". The mean perceived reachability boundary in the present virtual paradigm was 79 cm (SD = 23 cm), which corresponded to an overestimation of about 14% of their actual capacities (mean arm length = 68 cm, SD = 6 cm).

EEG recording and preprocessing

EEG data were continuously collected during the reach-to-grasp judgment task from 128-channel Biosemi ActiveTwo (Biosemi B.V., Amsterdam, Netherlands) at a sampling rate of 1024 Hz with the ActiView software. Electrode caps covering the whole head with equidistant layout were used. Electrode offset was kept below 20 µV. The offset values were the voltage difference between each electrode and the CMS-DRL reference. Two additional electrodes were placed at lateral canthi and below the eyes in order to monitor eye movements and blinks. Offline EEG preprocessing were performed with EEGLAB software. Continuous EEG signal was filtered (1–100 Hz) using two successive filters: a high pass filter (1 Hz) followed by a low pass filter (100 Hz). The choice of a relatively restrictive high pass filter of 1 Hz was constrained by the ICA procedure used to correct for blink artifacts (see below). After identifying noisy electrodes, the continuous EEG signal was re-referenced based on the average reference (Delorme & Makeig, 2004). This procedure was required after using the free reference recording method done by the Biosemi system. Then, ICA-based artifact correction (runICA algorithm) was used in order to correct for blink artifacts (Delorme et al., 2007). Electrodes with excessive electrical noise were not included (mean = 2; range: 1-6) in referencing and ICA procedure and were, when possible, interpolated after blink artefact correction. The signal was then segmented into periods of 3000 ms around the onset of the target object (1500 ms pre-target and 1500 ms post target onset). Visual inspection of the signal allowed to reject epochs with excessive noise artifacts (mean = 138 [19%]; range: 22 – 314). At this step, four additional participants were discarded from further analyses due to excessive rejection of trials (> 25 %). Therefore, reported analyses have been conducted on data provided by the 18 remaining participants.

Event-related changes in the oscillatory activity were quantified using a time-frequency wavelet decomposition of the continuous EEG signals between 1 and 30 Hz by step of 1 Hz (complex Morlet's wavelets, ratio fo/σf=7) implemented in Fieldtrip (Oostenveld et al., 2011). Following the recommendations of Hobson and Bishop (2016), mean spectral power was computed on the entire time window and transformed with a base 10-logarithm function. This transformation was applied to make electrodes with various maximum power and frequency bands comparable. Then, in order to evaluate power modulation induced by object presentation, the pre-event period (from −1500 ms to -1000 ms) of each trial was considered as a baseline and was subtracted from each time point for a given frequency and participant for the rest of the trial. The pre-event period included the inter-stimulus interval (ITI) and the time window before the verb presentation.

We focus our analysis on μ rhythm (8-12 Hz) desynchronization. The desynchronization of the μ rhythm is believed to reflect the activity of motor neural network (Proverbio, 2012; Wamain et al., 2016, 2018) when assessed over centro-parietal electrodes. Based on topography of μ rhythm desynchronization (see **Figure 32**), we select electrodes corresponding to the centro-parietal site (channels A1, A2, A3, B1, B2, D15, D16). The spectral power of the 7 centro-parietal electrodes was averaged for the analysis. In order to control for attentional modulation, we averaged the spectral power of a set of 7 electrodes at a posterior site (A14, A15, A22, A23, A24, A27, A28).

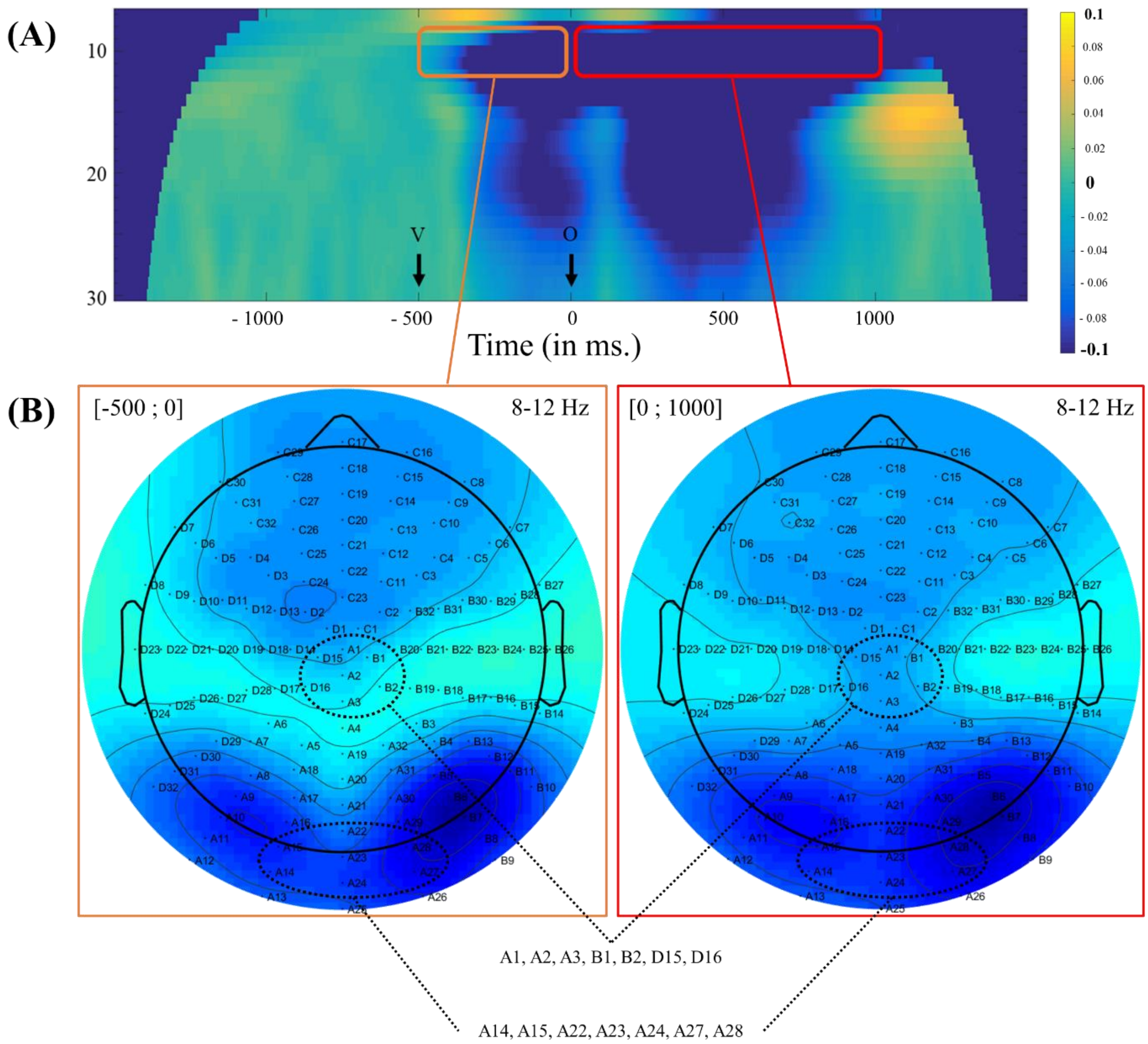


Figure 32. (A) Time frequency representation of 7-30 Hz power change under all electrodes, averaged across participants and conditions during the entire time window of epochs (1500 ms pre-object and 1500 ms post object onset). (B) Topographical representations of 8-12 Hz power change under all electrodes, averaged across participants and conditions during the 500 ms post--verb presentation (left) and 1000 ms post-object presentation (right). The desynchronization of 8-12 Hz rhythm at centro-parietal and posterior sites will be further analyzed as a function of experimental conditions.

Statistical analysis

We anticipated that the verbal context of action will orient the processing of object motor information toward the typical use of conflictual objects. Thus it should facilitate the resolution of the competition between affordances during conflictual object perception. As a consequence of the resolution, we should observe a reduction of the typical effects observed when affordances compete. As a reminder, conflictual object perception reduces the typical μ rhythm desynchronization reported when perceiving non-conflictual objects within reach (Wamain et al., 2018). If the verbal context of action resolves the competition, then we should observe a release of μ rhythm desynchronization for reachable conflictual objects in the action context. This effect should be reflected by a greater difference in μ rhythm desynchronization between reachable and unreachable spaces in the neutral context compared to the action context. Accordingly, we focused our statistical analysis on the Space x Verb interaction. However, we also reported main effects of Verbal context and Space. Reported analysis have been conducted on the 8-12 Hz power change over the centro-parietal and posterior sites, to assess motor and attentional modulations.

To evaluate the effect of Space, Verbal context and the interaction between Space and Verb on the mean 8-12 Hz power change at centro-parietal and posterior sites over the trial, we conducted pairwise comparisons at each time point of the time window starting at 500 ms pre-object presentation onset (i.e., onset of verb presentation) and ending at 1000 ms post-object presentation onset, as follow:

$$Verbal\ context\ effect = Neutral\ verb - Action\ verb$$

$$Space\ effect = Reachable\ space - Unreachable\ space$$

$$Interaction = (Reachable - Unreachable)_{Neutral} - (Reachable - Unreachable)_{Action}$$

Accordingly, when the main effect of Verbal context is positive, it highlights higher 8-12 Hz desynchronization for action verbal context compared to neutral verbal context. Similarly, when the main effect of Space is positive, it highlights higher 8-12 Hz desynchronization for unreachable space compared to reachable space. Finally, when the Space x Verb interaction contrast is positive, it highlights greater effect of space for neutral context compared to action context. In the following pages, we will present the aforementioned comparisons for the 8-12 Hz band frequency over centro-parietal (see **Figure 33** and **Figure 34**) and posterior sites (see **Figure 35** and **Figure 36**).

Permutation tests and Wilcoxon tests were conducted in parallel as two alternatives for pairwise tests in the context of multiple comparisons. Since there is no consensus in the best, most conservative approach for this type of test, most attention will be given for convergent results between the two tests.

The permutation tests were conducted according to Phipson & Smyth (2010)'s recommendations. The second formula of Phipson & Smyth (2010) was used to compute an approximation of the exact p value for each time point, as we selected a large number of permutations (i.e., ≥ 10 000). Hence, at each time point, the exact p-value was computed as follow:

$$p_e = \frac{b+1}{m+1} - \int_0^{\frac{0.5}{m_t+1}} F(b;m,p_t)dp_t.$$

Where, *b* is the total number of statistic values exceeding t_{obs} (i.e., the observed test statistic for a given hypothesis), *m* is the selected number of permutations (i.e., 10 000) and *mt* is the possible number of permutations. The second part of the equation is the integral of the cumulative probability function of the binomial distribution, with $p_t = \frac{b+1}{m+1}$ (see Phipson & Smyth, 2010, for more details, http://www.statsci.org/webguide/smyth/pubs/permp.pdf).

Wilcoxon tests were computed at each time point. The p value was corrected with the False Discovery Rate (FDR) controlling procedure proposed by Benjamini & Hochberg (1995).

Results

Mu (8-12 Hz) over centro-parietal sites

The main effects of Verbal context and Space over the centro-parietal site (μ rhythm) are presented on **Figure 33**. According to the permutation test, the effect of Verbal context was visible as soon as the verb appears (-500 ms) and remains obvious until approximatively 100 ms post-object presentation. It suggests that action verbs induced a higher μ rhythm desynchronization than neutral verbs during the 600 ms post-verb presentation. However, FDR correct Wilcoxon tests did not highlight a similar difference, questioning the reliability of the effect.

As expected, an effect of Space was also supported by both permutation and FDR corrected Wilcoxon tests. It indicated that objects induced a higher μ rhythm desynchronization when presented in unreachable space compared to reachable space. Significant differences were found after object presentation, between 160-180 ms and 580-640 ms post-object presentation. Additional differences between reachable and unreachable spaces were highlighted in the -180 to -30 ms time window preceding object presentation, but only with permutation tests.

More interestingly, we observed the expected Space x Verb interaction over centro-parietal site (see **Figure 34**). The interaction was visible in two time windows after object presentation. In these two time windows, the μ rhythm desynchronization results highlighted a greater effect of space for neutral contexts compared to action contexts. The first time-window extended from about 30-70 to 435-480 ms post-object presentation. The second time-window extended from about 540-590 ms to 820-860 ms post-object presentation. For both time-windows, the effect seemed robust as it is supported by both permutation and FDR corrected Wilcoxon tests.

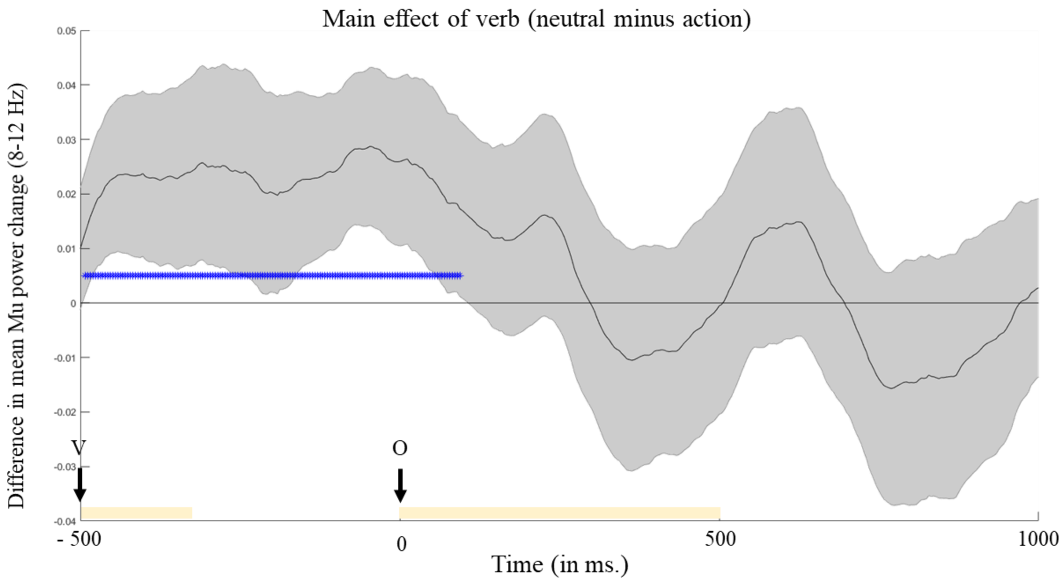
Alpha (8-12 Hz) over posterior sites

The main effects of Verbal context and Space over the posterior site (α rhythm) are presented on **Figure 35**. The effect of Verbal context started at the verb presentation (-500 ms) and remained until approximatively 400 ms post-object presentation. The effect was also visible in the 750-870 ms time window following object presentation. It indicates that action verbs induced a higher α rhythm desynchronization than neutral verbs. In both time windows, the effect seems robust as it was supported by both permutation and FDR corrected Wilcoxon tests.

The effect of Space started mostly after object presentation, around 90 ms post-object presentation and ended around 680 ms post-object presentation. Permutation tests highlighted an effect of Space from 250 ms pre-object presentation until 15 ms post-object presentation. It suggests that objects induced a higher α rhythm desynchronization when presented in unreachable space compared to the reachable space. The effect of Space is probably not very robust as it was not supported by FDR corrected Wilcoxon tests.

The Space x Verb interaction over the posterior site (μ rhythm) is presented on **Figure 36**. Permutation tests highlighted a significant interaction in only one late time window from 590 to 810 ms following object presentation. In this time-window, α results highlighted a greater effect of space for neutral context compared to action context. The effect seems not highly reliable as it was only supported by permutation tests.

Mu (8-12 Hz) over centro-parietal sites



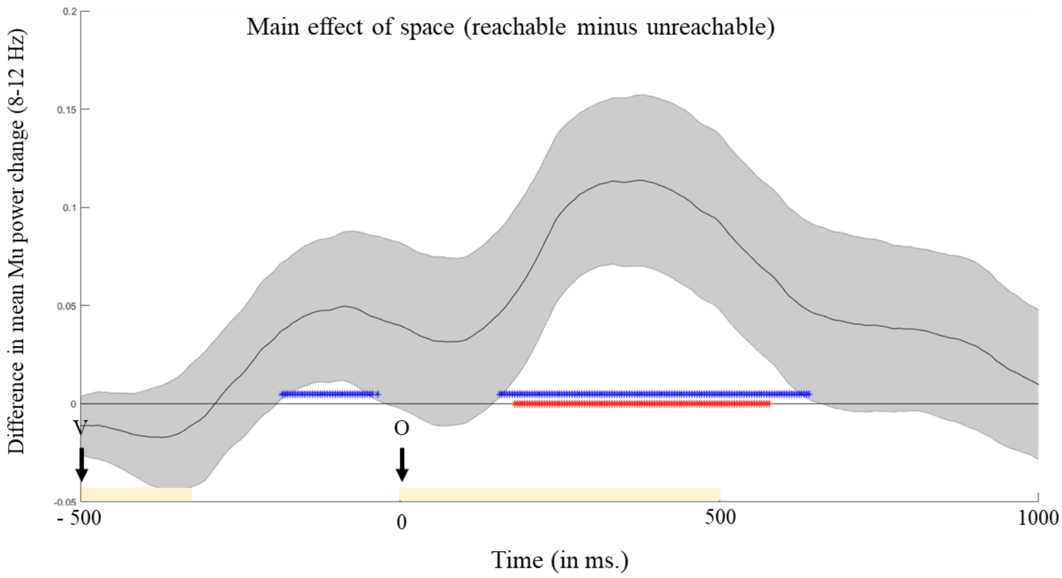


Figure 33. At each time point, the graphs show the difference in mean 8-12 Hz power change over centro-parietal electrodes (A1, A2, A3, B1, B2, D15, D16) between verbal contexts (**upper part:** neutral minus action) and between spaces (**lower part**: reachable minus unreachable). Shaded areas show 95% confidence intervals. The light-yellow bar on the x axis indicates respectively the time that the verb (i.e., -500 ms to -300 ms) and that the object (i.e., 0 ms to 500 ms) were on the screen. Blue marks (permutation test $p < .05$) and red marks (FDR-adjusted $p < .05$) indicate significant difference between conditions.

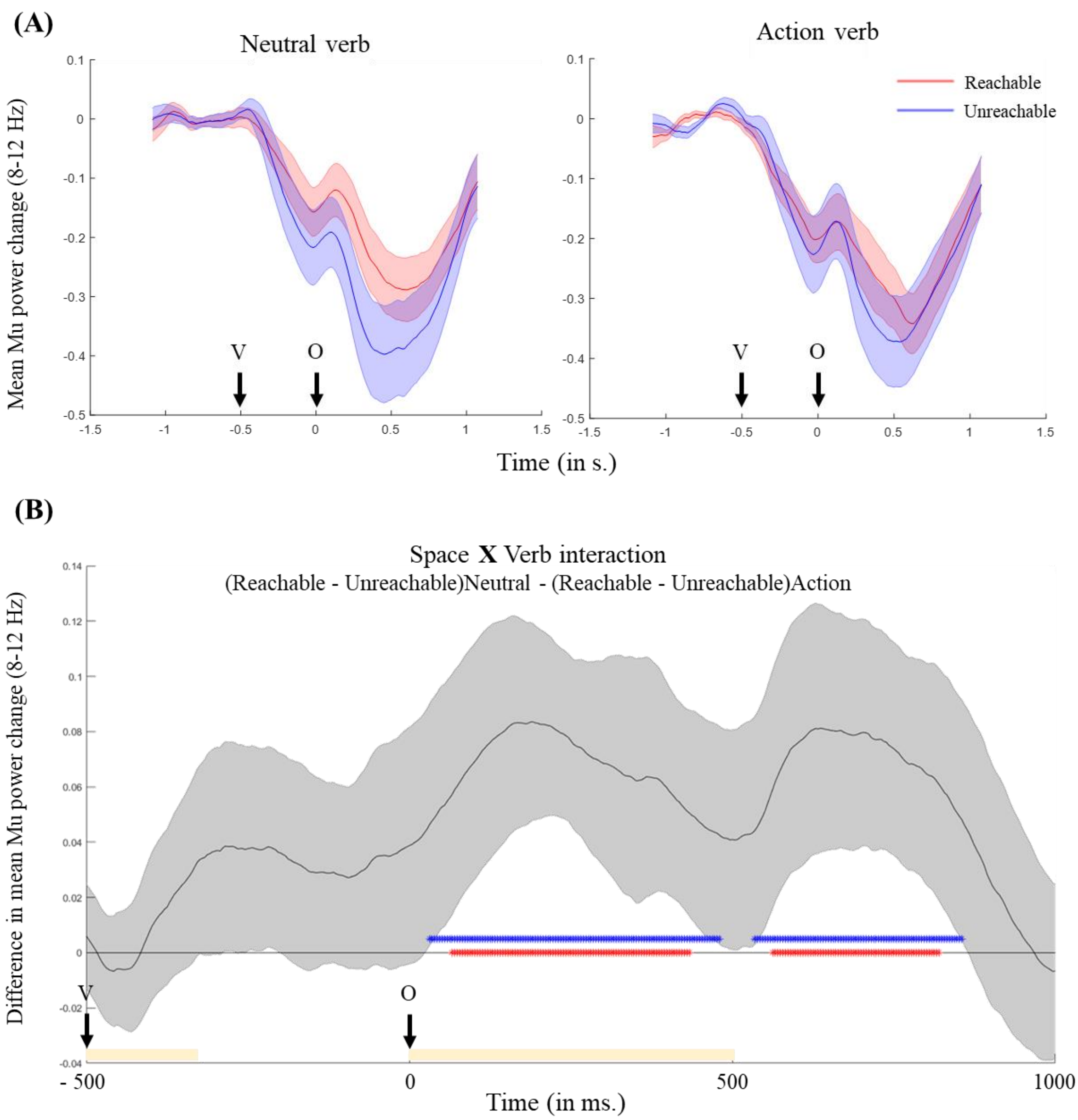


Figure 34. (A) At each time point, the graphs show mean 8-12 Hz power change over centro-parietal electrodes (A1, A2, A3, B1, B2, D15, D16) as a function of spaces for neutral verb (left) and action verb (right). **(B)** At each time point the graph shows the Space X Verb interaction effect on mean 8-12 Hz power change over centro-parietal electrodes (A1, A2, A3, B1, B2, D15, D16). Shaded areas show 95% confidence intervals. The light-yellow bar on the x axis indicates respectively the time that the verb (i.e., -500 ms to -300 ms) and that the object (i.e., 0 ms to 500 ms) were on the screen. Blue marks (permutation test $p < .05$) and red marks (FDR-adjusted $p < .05$) indicate significant difference between conditions.

Alpha (8-12 Hz) over posterior sites

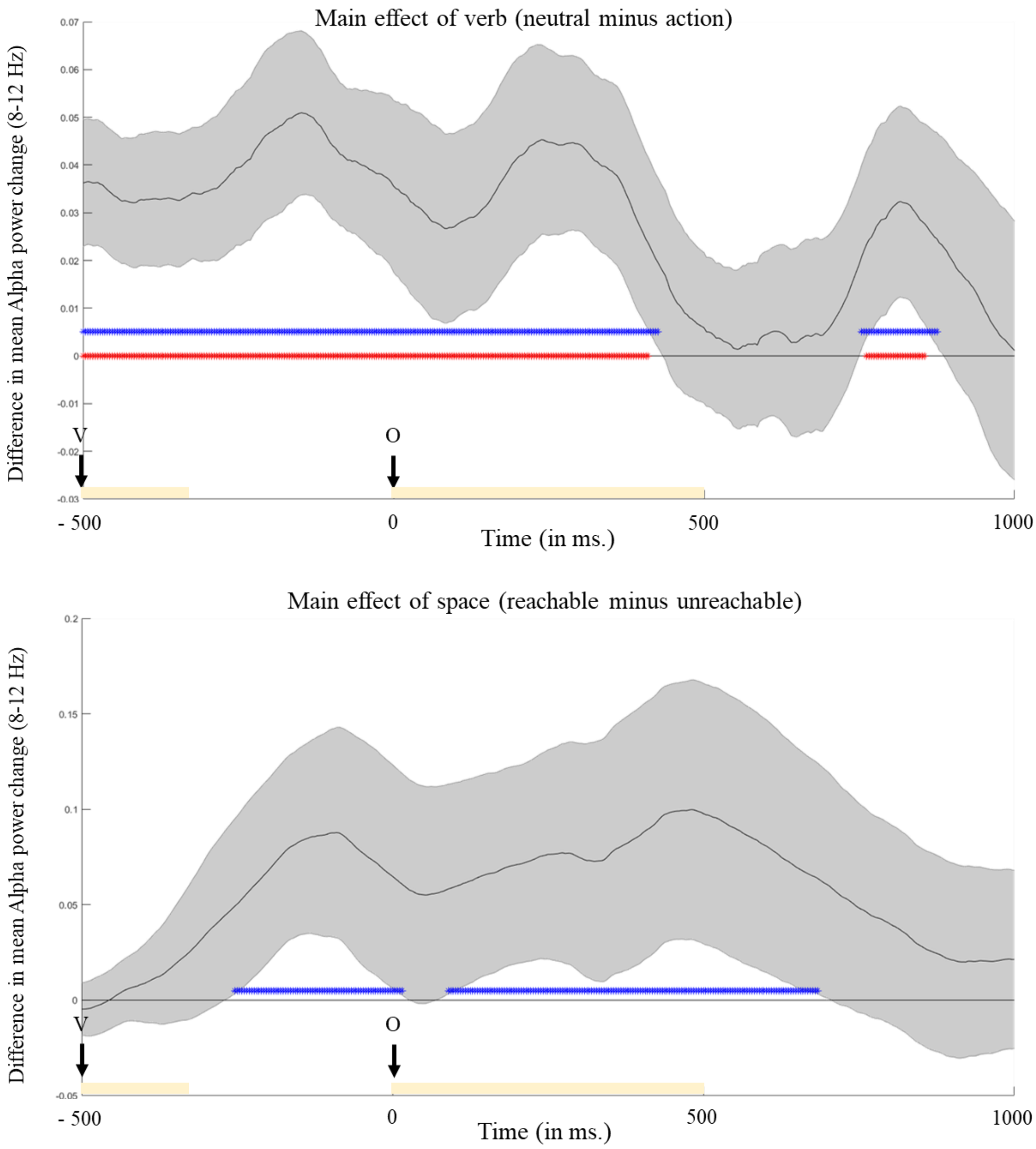


Figure 35. At each time point, the graphs show the difference in mean 8-12 Hz power change over posterior electrodes (A14, A15, A22, A23, A24, A27, A28) between verbal contexts (**upper part**: neutral minus action) and between spaces (**lower part**: reachable minus unreachable). Shaded areas show 95% confidence intervals. The light-yellow bar on the x axis indicates respectively the time that the verb (i.e., -500 ms to -300 ms) and that the object (i.e., 0 ms to 500 ms) were on the screen. Blue marks (permutation test $p < .05$) and red marks (FDR-adjusted $p < .05$) indicate significant differences between conditions.

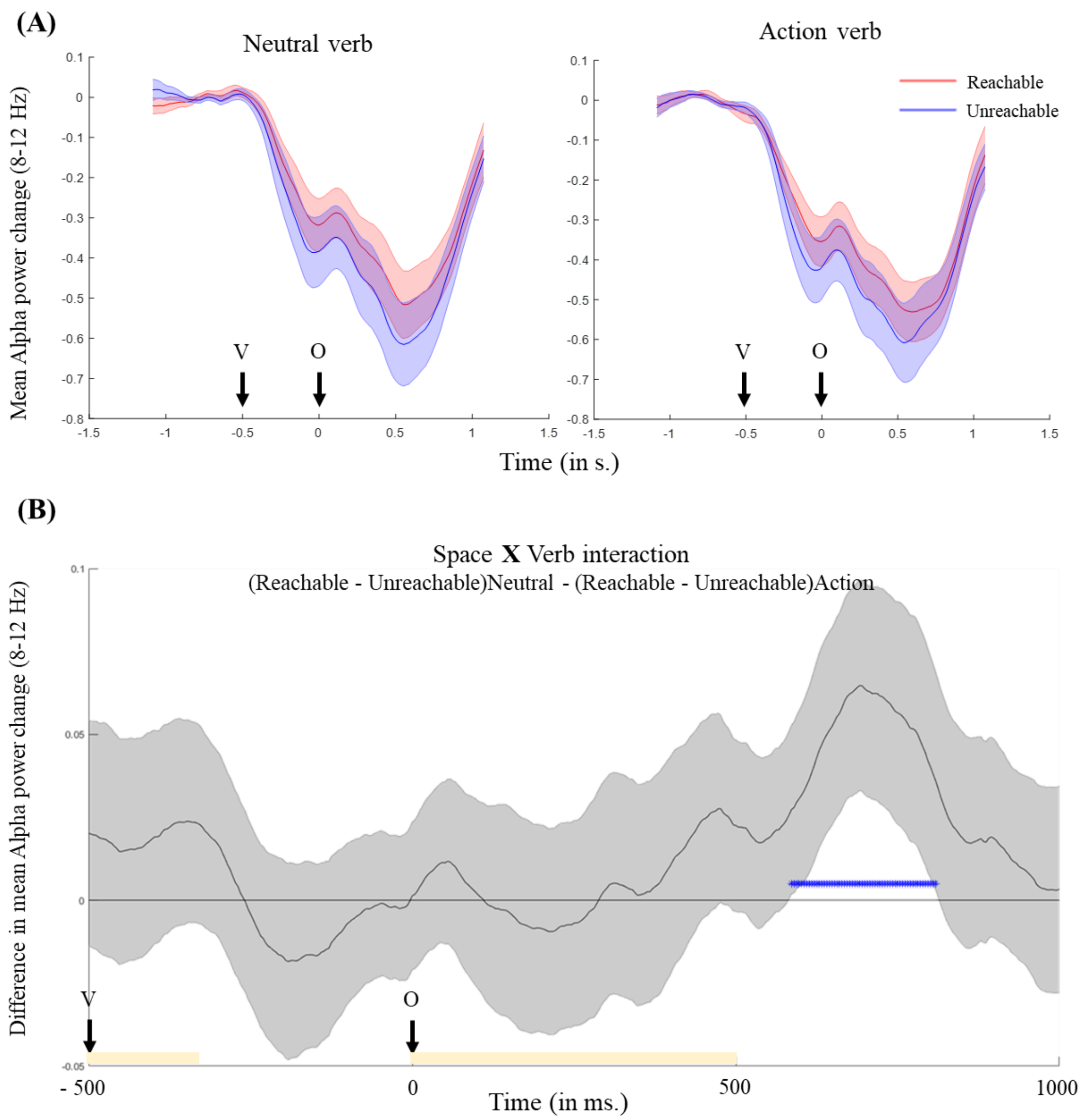


Figure 36. (A) At each time point, the graphs show mean 8-12 Hz power change over posterior electrodes (A14, A15, A22, A23, A24, A27, A28) as a function of spaces for neutrals verb (left) and action verb (right). **(B)** At each time point the graph shows the Space **X** Verb interaction effect on mean 8-12 Hz power change over posterior electrodes (A14, A15, A22, A23, A24, A27, A28) D15, D16). Shaded areas show 95% confidence intervals. The light-yellow bar on the x axis indicates respectively the time that the verb (i.e., -500 ms to -300 ms) and that the object (i.e., 0 ms to 500 ms) were on the screen. Blue marks (permutation test $p < .05$) and red marks (FDR-adjusted $p < .05$) indicate significant differences between conditions.

Discussion

The present electrophysiological study aimed at identifying the influence of the context on the competition between affordances during conflictual object perception. The reduction of the *μ* rhythm desynchronization when perceiving conflictual objects was assumed to reflect the impact of affordance competition on action selection processes (Wamain et al., 2018). As structural and functional affordances may be flexibly evoked depending on the context in which they are perceived (Kalénine et al., 2014), we expected a resolution of the competition between affordances when perceiving conflictual objects in verbal context triggering their typical using gesture. Twenty-five young adult participants took part in the study in order to assess the modulation of *μ* rhythm desynchronization during perceptual processing of conflictual objects - surrounded by action and neutral verbal contexts - in a 3D virtual environment (cf. Kalénine et al., 2016; Wamain et al., 2018).

First, we showed a Verbal effect on the *μ* desynchronization over centro-parietal electrodes that starts mostly after the onset of verb presentation (500 ms pre-object presentation) and extends until 100 ms post-object presentation. Globally, action verbs induced a higher *μ* rhythm desynchronization than neutral verbs. This result is in line with previous findings that showed specific association between verbal and motor information, especially when considering action verbs (Aravena et al., 2012, 2014; Boulenger et al., 2008; Hauk et al., 2004; Moreno et al., 2013; Pulvermüller, 1999; Pulvermüller et al., 2001; Tomasino et al., 2010; Vukovic et al., 2017). For instance, Moreno et al. (2013) reported that sentence containing action verbs induce specific *μ* and Bêta (β) desynchronization.

Another important result is the Space effect on the 8-12 Hz desynchronization over centro-parietal electrodes that starts mostly after the onset of object presentation (~ 160 to 640 ms). Globally, conflictual objects induced a higher *μ* rhythm desynchronization when presented in unreachable space compared to reachable space. This result replicates previous findings that showed that conflictual objects reduce the typical μ rhythm desynchronization compared to non-conflictual objects when presented in the peripersonal space (Wamain et al., 2018). Nonetheless, the presence of a possible Space effect before the onset of object target (from -180 to -30 ms) remains difficult to explain. Critically, the same Space effect is observed over the posterior electrodes before (-250 ms to -15 ms) and after (90 - 680 ms) object presentation, suggesting an involvement of attentional resources for processing space position of conflictual objects before and after object presentation. Both effects before object presentation reflect some sort of participant's anticipation of the space position of objects that raises multiple questions for which we have no clear answer yet. The best option to explore concerns task demands. Participants were asked to perform a reach-to-grasp judgement task and had to answer only when the object presentations ended on a question mark. The task itself (i.e., reach-to-grasp) might have directed attentional resources toward the reachable space of participants. For instance, it has been shown that task demands modulates the response amplitude of brain regions in charge of the processing of characteristics needed to complete the task (Harel et al., 2014). Such modulation has also been observed during perceptual processing of conflictual and non-conflictual objects (Wamain et al., 2018). For instance, Wamain et al. (2018) showed that processing of conflictual objects compared to non-conflictual objects induced a stronger μ rhythm desynchronization over posterior electrodes during a reach-to-grasp judgement task while the reverse pattern was observed during a semantic judgement task (i.e., "Is it a kitchen tool?"). However, the adjustment of attentional resources during the processing of the object location in space does not explain the existence of such an effect before the object was presented on the screen. Furthermore, real anticipation would reflect the existence of sequences of trials in the experiment, while trials were fully randomized and multiple verifications was conducted. Lastly, the effect was only supported by the permutation tests that seems to be less conservative in this study. Thus, we prefer not to give too much credit to this observation without additional support.

More importantly, results highlight a Space **X** Verb interaction on the 8-12 Hz desynchronization over the centro-parietal electrodes that starts quickly after the onset of object presentation (~ 30 ms). Results showed a greater effect of space for neutral context compared to action context. In the neutral context, the reduction of the μ rhythm desynchronization over centro-parietal electrodes for conflictual objects in the reachable space nicely mimics the same reduction previously observed when comparing conflictual and non-conflictual objects (Wamain et al., 2018). Thus, the neutral context constitutes a good baseline to study the influence of the action context on the processing of conflictual objects.

The results highlight that the reduction of the μ rhythm desynchronization when perceiving conflictual objects in reachable space compared to the unreachable space was less pronounced in the action context. The Space x Verb interaction on the μ rhythm desynchronization over the centro-parietal electrodes extends until 860 ms after object presentation with a short midway period in which the effect disappeared (between 480 and 820 ms). It is worth noting, however, that the same Space x Verb interaction on the 8-12 Hz power change (α rhythm) at the control posterior site starts later, and only overlaps with the second time period in which the interaction is significant for the μ desynchronization over the centro-parietal electrodes. Together, these results suggest that the effect observed over the centro-parietal electrodes from around 30 to 500 ms likely reflect motor processing (action selection processes, cf. Wamain et al., 2018), while the effect observed during the second time period (between 550 to 800 ms) would question the involvement of attentional resources. However, questioning the involvement of attentional resources in the μ rhythm desynchronization observed over centro-parietal electrodes in the second time period is speculative, because the effect on the α rhythm was only supported by the permutation tests, suggesting that the effect is less robust.

Finally, these results are in line with the recent neurobiological model proposed by Cisek (2007; 2010) and developed earlier in the present thesis (see Chapter 3). When affordances are activated from the environment, they undergo biasing signals until the relevant affordance is selected. In the case of the present study, we highlighted that a verbal context can trigger such biasing signals. It is important to note that this effect highlights an influence of the verbal context on a mechanism at play in affordance competition (action selection processes, cf. Wamain et al., 2018), and not the consequences of affordance competition on a behavior (Kalénine et al. 2016, see also developmental study in Chapter 5). However, the present findings only support that the verbal context can induce a biasing signal when presented upstream of the object. We will go back to the discussion of these important nuances in the General Discussion. Further analysis on the μ rhythm desynchronization over centro-parietal electrodes in the trials where objects were followed by verb presentation (see experimental procedure) will provide precisions in the mechanisms at play in the resolution of affordance competition.

Global synthesis

The present electrophysiological study demonstrates that the competition elicited by the perception of distinct affordances during object processing is sensitive to verbal context. This finding extends previous results in adults showing an impact of affordance competition on action selection processes (i.e., μ rhythm desynchronization) and reinforce the relevance of considering contextual information for a better understanding of the action-perception relations during perceptual processing of object affordances. Critically, the reduction of μ rhythm desynchronization associated with the perceptual processing of conflictual objects increased in the presence of an action verbal context that triggers the typical use gesture associated with conflictual objects. The increase of μ rhythm desynchronization in this situation highlights an influence of the verbal context on the resolution of affordance competition during the processing of conflictual objects and suggests that functional affordances of conflictual objects have been selected and preferentially processed by the system. Overall, the present findings shed new lights on the influence of contextual information on the resolution of affordance competition that may help enriching recent theoretical views on affordances (Cisek, 2007; Cisek & Kalaska, 2010; Thill et al., 2013).

GENERAL DISCUSSION

Overall summary

Perception is an active phenomenon that guides actions and that is modulated by actions in the environment. At the neurophysiological level, both action and perception share several brain correlates and are therefore, two systems that show no clear distinctions. Grounded theorists usually account for such neurophysiological evidence by suggesting that perception and action would be constitutive parts of cognitive representations. Hence, when perceiving the environment, not only do we process the available visual information, but we also simulate the motor information associated with the visual elements present in the environment (see Chapter 1). In the domain of manipulable object perception, the simulation of motor information, also called affordances, have become a core research topic. However, how motor information of manipulable objects is represented at the cognitive level? What are the cerebral systems in charge of processing them? And to what extent they are automatically evoked? These are three current debates in the recent literature on manipulable object perception (see Chapter 2). One common assumption of recent approaches is that one object may evoke multiple types of motor information. Some motor information would be representations of action components based on current visual characteristics of objects (e.g., grasping actions). Other motor information would depend on deeper semantic representations of learned associations between visual characteristics of objects and specific action components (e.g., functional actions).

We also developed the discussion around the recent debates about the automaticity of affordance evocation (see Chapter 2). Initial investigations claim for an automatic evocation of affordances during manipulable object perception (Chao & Martin, 2000; Tucker & Ellis, 1998). However, recent accounts point toward significant individual (e.g., motor experience) and contextual (e.g., space location) modulations of affordance evocation (Chrysikou et al., 2017; Watson et al., 2013; Yee et al., 2013). Even though arguments for automatic and contextual modulations of affordance evocation are often presented in opposition, we do not consider them as such. Contextual modulations highlight that the consequences of affordance evocation on object processing are not automatic but it does not revoke that affordances were initially automatically activated. Finally, we highlighted that affordance perception is sometimes detrimental for manipulable object perception (see Chapter 3). In particular, distinct affordances may be in certain cases co-activated from a single object, having negative consequences on manipulable object processing. Specifically, structural and functional affordances associated with a single object compete with one another and this competition may be detrimental to the production of object-directed actions and object perceptual processing in adults. According to neurobiological models and recent neurophysiological evidence, we emphasized that the processing cost induced by affordance competition during action production and object perception must involve distinct neurocognitive mechanisms, namely *affordance specification* (i.e., activation of affordances from the environment) and *affordance selection* (i.e., competition and biasing toward relevant affordance).

In Study 1 presented in Chapter 4, we initially explored paradigms evaluating affordance evocation during manipulable object perception (i.e., *affordance specification*) with the aim at selecting the most suitable paradigm for assessing the mechanism of *affordance specification* in a subsequent study. Pilot investigations lead us to favor the action priming paradigm. We additionally reported that moderating factors, such as manipulable object category (i.e., manufactured or natural), could account for the weakness of action priming paradigm in demonstrating affordance effects. However, it indicated that our implementation of the action priming paradigm effectively assesses affordance evocation during visual object processing.

In Study 2 and Study 3 presented in Chapters 5 and 6, we evaluated the influence of developmental (Study 2) and contextual (Study 3) modulations on the cost induced by affordance competition during object perception. Consequently, we designed 3D pictures of manipulable objects evoking different grasping and using gestures (i.e., conflictual objects) and manipulable objects evoking similar gestures for both actions (i.e., non-conflictual objects). In line with previous investigations (Kalénine et al., 2016; Wamain et al., 2018), pictures were inserted in a 3D virtual environment at different distances in order to compare their perceptual processing in a context that triggers their motor information (i.e., reachable space) with a context that does not (i.e., unreachable space). As a reminder, when presented in peripersonal space conflictual objects are usually associated with a selective processing cost compared to non-conflictual objects.

In Study 2, five age groups from 8-year-olds to adult participants were included in the investigation. As we assumed that the affordance conflict cost may result from the joint contribution of *affordance specification* and *affordance selection* mechanisms, the two mechanisms were investigated as well. We found that selective cost for conflictual objects is present in children as young as 8 and follows a U-shape developmental trajectory between 8 and adulthood. We provided additional evidence that action priming effects targeting *affordance specification* shows a similar U-shape development, suggesting that the affordance conflict cost partially relies on *affordance specification*. However, results related to the *affordance selection* mechanism are less clear, as no developmental trajectory was observed in the Simon effects targeting this mechanism. In Study 3, we investigated the influence of a verbal context on the processing cost induced by affordance competition, based on an electroencephalographic marker (i.e., μ rhythm desynchronization). Conflictual objects were presented in neutral verbal contexts (i.e., observation verbs) and in action verbal contexts (i.e., action verbs that trigger the typical use gesture of objects). We reported that a verbal context can resolve affordance competition during the processing of conflictual objects.

In the following sections, we will discuss the present results in three parts. **In the first part**, we will discuss possible similarities and inconsistencies in the methodology and results from the different studies conducted. **In the second part**, we will discuss the contribution of the present thesis work to the actual models and theories about affordances and more generally, to the embodied cognition literature. We will also propose perspectives for future research on object affordances.

I. Similarities and inconsistencies in the present thesis results

During the present thesis work, we used similar experimental paradigms and/or methodology across studies. The results obtained with these experimental settings are often similar but we also found a few inconsistent results that deserve discussion.

1. The role of manipulable object category in action priming

In Chapter 4, we described a study conducted on young adults that reported the influence of moderating factors (i.e., manipulable object category) on action priming. We suggested that such moderating factors could account for the weakness of action priming paradigm in demonstrating affordance effects. In the developmental study described in Chapter 5, we used the same paradigm to assess the *affordance specification* mechanism in the different age groups tested. We did not find the expected modulation of action priming by category in this study, even in the adult group, and we therefore used the main effect of priming to examine the parallel between the development of *affordance specification* and affordance conflict cost. Note that the absence of moderation of action priming by object category was not mentioned in this chapter since we reported the submitted paper as such. Regardless, why do we observe such an inconsistency? We below furnish two possible answers.

One possibility is that we did not reach the statistical power needed for highlighting such effect. Indeed, as the modulation of action priming by object category had never been addressed before and that we expected action priming to be actually mostly present in manufactured objects, we decided to determine the sample size from a simple power analysis with an expected medium size effect for the critical priming x object category interaction. A sample size of about 25 participants was sufficient to ensure a statistical power of 0.80[14]. Perhaps, we should have expected a smaller size effect, resulting in the need of a larger sample. Nonetheless, we should notice that sample sizes largely varied across previous studies using similar action priming paradigms, ranging between 14 and 40 participants (e.g., Borghi et al., 2007, experiments 1 vs. 2), with most experiments involving 20-30 participants (Ni et al., 2018, experiments 1-4; e.g., Vainio et al., 2008, expriments 1-3). However, this answer is not convincing as we failed to replicate the modulation of manipulable object category over action priming in the developmental study, where the sample size was greater than our first investigation (i.e., 33 vs. 24). Thus, the failure to replicate this result may have another origin.

Another possibility is that the lack of moderation of action priming by manipulable object category in young adults in the developmental study might be explained by the experimental procedure. Participants were indeed asked to perform reachability and semantic judgement tasks in the 3D virtual environment paradigm in the first place, before being confronted to the action priming paradigm. The repetitive exposure to manipulable objects evoking affordances (i.e., conflictual and non-conflictual objects) might have induced greater engagement of the *affordance specification* mechanism in subsequent tasks. In this study, the action priming paradigm might have assessed more generally stable affordances (both functional and structural), and not only functional affordances. In this case, it would explain why we still retrieve a main effect of action priming. Finally, although the moderating effect of manipulable object category over action priming falls into the replication crisis (Maxwell et al., 2015), it does not call into question that our implementation of the action priming paradigm effectively assesses affordance evocation. We indeed observed action priming effects on young

[14] Sample size was determined using the power.t.test function of the pwr R package considering a medium effect size (d = 0.5) and a statistical power of 0.80 for the expected priming advantage for artefact versus natural objects.

adults in both assessments. Hence, action priming paradigm remains a suitable paradigm for assessing affordance evocation. Nonetheless, such inconsistency must nuance our first conclusion and moderate the weight accorded to manipulable object category in affordance evocation.

2. The role of object visual complexity in affordance conflict cost

In order to assess the consequences of affordance competition, we decided to investigate the perceptual processing of conflictual object perception using a 3D virtual environment paradigm from previous studies (Kalénine et al., 2016; Wamain et al., 2018). It should be reminded that, at the behavioral level, the perception of conflictual objects increases categorization judgement times compared to the perception of non-conflictual objects, but only when perceived in the peripersonal space (Kalénine et al., 2016). At the electrophysiological level, conflictual object perception reduces the typical μ rhythm desynchronization reported when perceiving non-conflictual objects within reach (Wamain et al., 2018). However, recent arguments suggest that the selective cost for conflictual objects might be caused by the involvement of confounded variables, especially visual complexity and number of parts (Bub et al., 2018). Conflictual objects would be composed with more parts and would be more complex visually, resulting in harder perceptual processing. In the present work, we provided indirect and direct arguments that discard these possible confounds.

In Chapter 5, we replicated previous study (Kalénine et al., 2016), showing an affordance conflict cost in young adults, using another set of stimuli. We also demonstrated an affordance conflict cost in young children (8-year-olds). As the difference between conflictual and non-conflictual objects was selective to peripersonal space, our findings combined with Kalénine et al. (2016) and Wamain et al. (2018) suggest that we can rule out most of the possible confounds related to potential differences between object types (e.g., number of parts of objects, object visual complexity). There is indeed no reason to assume that a difference in the perceptual processing of visual complexity (or other potential confounded factors) between conflictual and non-conflictual objects would occur only in peripersonal space. This seems very unlikely, especially when we know that manipulable objects benefit from an advantage of shape discrimination when presented in peripersonal space, even when controlling for object size, making far objects appear bigger than close ones (Blini et al., 2018). In addition, even if we consider that visual complexity of objects would have an influence only in peripersonal space, it is difficult to assume that differences in visual complexity would account for the U-shape development trajectory of the selective cost for conflictual objects. Assuming that visual complexity would have less and less influence on object processing with age, we should have observed a linear decrease trajectory of the selective cost for conflictual objects. Nonetheless, we conducted a complementary experiment to take into account the visual complexity of conflictual and non-conflictual objects (see. Chapter 5, complementary experiment). Visual complexity was assessed through two subjective judgements (i.e., the overall visual complexity and number of parts) and two algorithms providing a visual feature similarity index (i.e., FSIM) and an index of the activity of the inferotemporal cortex (i.e., HMAX). Data highlighted that conflictual and non-conflictual objects differ on subjective visual complexity judgements and number of parts. However, visual complexity does not account for the affordance conflict cost in young children and adults. These results support that interpretation that the affordance conflict cost assessed in the 3D virtual environment paradigm does not reflect a difference between object stimuli.

Finally, in study 3 (Chapter 6), we used a different baseline for investigating the perceptual processing of conflictual objects. With the addition of two verbal context modalities (i.e., action vs. neutral), the design was too complex to consider both conflictual and non-conflictual objects in the same experiment. Thus, we focused on conflictual objects that were presented in peripersonal space (where their affordances are supposed to be activated and compete with one another) and extrapersonal space (where there should be no activation and no competition), and we used the neutral context as a baseline against the action verbal context. As different categories of objects were not contrasted in Study 3, the question of potential confounded variables associated with different object stimuli cannot be raised in this study. Therefore, the EEG study reports direct investigation of the processing of motor information associated with the perception of conflictual objects. Any modulation of μ rhythm desynchronization in this study would effectively reflect modulation of affordance competition between structural and functional affordances of conflictual objects. Altogether, these findings should convince that the affordance conflict cost effectively reflects affordance competition and not a difference in confounded variables between conflictual and non-conflictual objects.

3. The role of contextual modulations in affordance evocation

In the present thesis, we investigated how inter- and intra-individual variabilities modulate the impact of affordance competition during manipulable object perception. To this end, we first conducted a developmental study and then, an EEG study in which we modulated the context surrounding object presentation. In the developmental study, we compared the processing of conflictual and non-conflictual objects in the peripersonal space with the same comparison in extrapersonal space. In the EEG study, we compared the processing of conflictual object preceded by action and neutral verbal contexts in peripersonal space with the same comparison in extrapersonal space. Importantly, we obtained converging evidence across studies. Results reported significant inter- and intra-individual modulations of the impact of affordance competition. More precisely, we highlighted two age periods with high sensitivity to affordance competition, that is in young children (8-year-olds) and in young adults. Between these two periods, individuals seemed less, if not at all, sensitive to affordance competition. In addition, we highlighted an influence of an action verbal context on the resolution of affordance competition during the processing of conflictual objects, suggesting that functional affordances of conflictual objects have been selected and preferentially processed by the system. Altogether these findings are consistent with recent accounts showing that affordance perception varies between individuals (Bellebaum et al., 2013; Chrysikou et al., 2017; Kiefer et al., 2007; Rüther et al., 2014; Watson et al., 2013; Yee et al., 2013), but also across individuals (Costantini et al., 2011; Ferri et al., 2011; Lee et al., 2012)..

Global synthesis

First, we consider that action priming paradigm is a suitable paradigm for assessing affordance evocation and more particularly evocation of stable affordances, although the role of object category is perhaps less robust than expected. Second, the present findings replicate previous results, showing that when they are co-activated from a single object, distinct affordances may have negative consequences on manipulable object processing. Nicely, the affordance conflict cost, used as an indicator of affordance competition (Kalénine et al., 2016; Wamain et al., 2018), does not seem to be the consequence of confounded variables. Furthermore, results as a whole demonstrate that affordance competition is modulated by inter- and intra-individual variabilities. We reported that affordance competition follows a non-linear developmental trajectory from 8 to young adults, with high periods of sensitivity in both extreme groups. Finally, we reported that affordance competition can be modulated and more precisely resolved by a verbal context. We will now discuss the contribution of the present findings to actual models and theories of affordance perception and action selection.

II. Consequences on theories and models of affordance perception and action selection.

Overall, our findings are in line with recent representational conceptions of affordances, and suggest that perceptual and conceptual processing of manipulable objects are affected by the evocation of the typical gestures and motor interactions associated with them. Furthermore, our findings are consistent with recent accounts that suggest noticeable inter- and intra-individual variabilities of affordance evocation. In the following sections, we will discuss the contribution of the present thesis work in the actual debate about the role of motor information in the perceptual processing of manipulable objects. Then, we will consider the actual debate about the automaticity of affordance evocation. We finally put forward a potential solution to ask more accurate questions about brain and cognitive functioning for the *specification* and *selection* of affordances.

1. How motor information of manipulable objects is represented at the cognitive level?

In the literature on manipulable object perception, there are important debates about how motor information of manipulable objects is represented at the cognitive level. For instance, authors question the nature of the representation of motor information evoked by manipulable objects (Borghi & Riggio, 2015; Buxbaum & Kalénine, 2010; Ellis & Tucker, 2000). Moreover, authors also question the functional contribution of motor information to the perceptual processing of manipulable objects (Mahon & Caramazza, 2008; Osiurak et al., 2017). This second debate refers - in the embodied cognition literature - to the relation that is maintained between action and perception in manipulable object representations (Gentsch et al., 2016; Weber & Vosgerau, 2016). In the following discussion, we will address these debates.

a. The nature of motor information associated with manipulable objects

Overall, our findings acknowledge that different natures of motor information are associated with manipulable objects. More particularly, our findings fall into the distinction between stable and variable affordances proposed by Borghi & Riggio (2015) and in the 2AS (two action system) theory proposed by Buxbaum & Kalénine (2010). For instance, Borghi and Riggio (2015) described stable affordances as motor information associated with invariant features of objects, such as object usual size. In contrast, variable affordances refer to motor information associated with temporary features of objects, such as object orientation. Similarly, Buxbaum and Kalénine (2010) distinguished structural from functional affordances. Structural affordances refer to motor information associated with the typical grasping gesture of objects. In contrast, functional affordances refer to motor information associated with the typical use gesture of objects, which is mostly the privilege of manufactured objects.

In Chapter 4, we reported a modulation of action priming by manipulable object category, with action priming being present only for manufactured objects. As objects were displayed in a standardized size, we suggested that manufactured objects evoked stable and more specifically functional affordances. Nonetheless, our failure to replicate the modulation of action priming effect by manipulable object category, in young adults of the developmental study, nuances our first interpretation. Our initial suggestion that in the action priming paradigm, manufactured objects evoked specifically functional affordances must be therefore considered with caution. Finally, the presence of action priming in both studies in young adults, without difference between natural and manufactured objects in the developmental study, supports that overall perceptual and conceptual processing of manipulable objects evoke stable affordances, at least in adults.

In Study 2 (Chapter 5), we reported an action priming effect in 8-year-olds. According to our interpretation of action priming paradigm, it indicates that children perceive stable affordances as early as 8-year-olds. We additionally reported that 8-year-old children exhibit an affordance conflict cost in the 3D virtual environment paradigm. However, the emergence of such effect in this paradigm requires the co-activation of both structural and functional affordances. Hence, our findings suggest that young children, as young as 8, already perceive both structural and functional affordances. We also reported that the action priming effect and the affordance conflict cost follow a non-linear developmental trajectory from 8-year-olds, suggesting a potential restructuration in the nature of motor representation associated with objects during childhood. Previous studies have for instance emphasized that affordance evocation may not be equivalent at all age periods (Collette et al., 2016; Kalénine et al., 2009). Noteworthy, when we observed an action priming effect, it evidenced evocation of motor information from visual objects **AND** use of this information in object processing. Conversely, when we did not observe an action priming effect, it suggests a lack of evocation of motor information (stable affordances) from visual objects **OR** a lack of use of this information in object processing. We already suggested (see Chapter 5) that affordance evocation during manipulable object perception may remain stable across age periods, but the relative contribution of these motor properties to object processing may change over time.

Finally, our last study demonstrated that the competition elicited by the perception of distinct affordances during object processing is sensitive to verbal contexts (see Chapter 6). Critically, the μ rhythm desynchronization associated with the perceptual processing of conflictual objects increased in the presence of an action verbal context that triggers the typical use gesture associated with conflictual objects. As a reminder, μ rhythm desynchronization is assumed to reflect the activity of the motor cerebral network and has been shown to be reduced by the competition between affordances when conflictual objects are presented within reach (Wamain et al., 2018). The release of μ rhythm desynchronization in the context of action verbs referring to object functional use highlights an influence of the verbal context on the resolution of affordance competition during the processing of conflictual objects. Moreover, it suggests that functional affordances of conflictual objects have been selected and preferentially processed by the system. The influence of a verbal information on the selection of the functional affordances associated with manipulable objects support that functional affordances share strong relationship with semantic/conceptual knowledge, as already suggested in the literature by Buxbaum and Kalénine (2010).

To conclude, our findings highlight that manipulable objects evoke stable affordances and - in more detail - distinct structural and functional affordances, as soon as 8-year-olds. As already suggested in the literature, findings from the EEG study support that functional affordances share strong relationship with semantic/conceptual knowledge (Buxbaum & Kalénine, 2010). Finally, the evocation of stable affordances in general would have no particular impact on the perceptual processing of manipulable object between 10- and 12-year-olds. This last finding questions the functional contribution of affordances to the perceptual processing of manipulable objects. We discuss this aspect below.

b. The functional contribution of affordance to perceptual processing of manipulable objects

In Chapter 1, we discussed about the types of empirical arguments that can be employed in support of the functional contribution of sensorimotor information in conceptual processing. Moseley et al. (2015) suggested three types of arguments. The first type of arguments concerns the temporal dynamics of sensorimotor activation during conceptual processing. The second type of arguments concerns the mutual influence of sensorimotor and conceptual processing. The third type of arguments concerns the influence of impaired sensorimotor processing on conceptual knowledge. In the present thesis, we brought some arguments toward a functional role of sensorimotor information in the perceptual processing of manipulable objects. More particularly, we provided evidence supporting the first and second types of arguments.

In Chapter 6, we highlighted that manipulable object perception induces a fast activation of sensorimotor information (cf. first type of arguments). Results reported higher μ rhythm desynchronization while processing conflictual objects in peripersonal space compared to the extrapersonal space, as early as 160 ms after the beginning of manipulable object presentation. Additional results reported that such effect of space was greater in neutral contexts compared to action contexts, as early as 30 ms after object presentation. These findings suggest that there is a fast implication of sensorimotor information in the perceptual processing of manipulable objects. The speed of the activation would suggest that no additional processing (e.g., conscious representation or epiphenomenon) could have occurred (Moseley et al., 2015). In the experimental contribution of the current thesis (cf. Chapters 4, 5 and 6), we highlighted mutual influence between sensorimotor and conceptual processing (cf. second type of arguments). The influence of sensorimotor information over conceptual processing was highlighted in Chapters 4 and 5 with the investigation of affordance evocation in the action priming paradigm. The influence of conceptual information over sensorimotor processing was highlighted in Chapter 6, with the investigation of the influence of a verbal context on the perceptual processing of manipulable objects.

Overall, most of our findings support the hypothesis that some sensorimotor information evoked by manipulable objects, along with other perceptual and non-perceptual features, contribute to object conceptual representations, in line with embodied and grounded views of concepts (e.g., Barsalou, 2008). However, the non-linear developmental trajectory observed in the developmental study suggests changes in the strength of the action-perception relations in manipulable object representation. Therefore, a more interesting question to ask is not whether action and perception are related but how. It will be discussed below in the light of Weber & Vosgerau (2016)'s conception of ability acquisition and constitution.

c. The relation between action and perception in manipulable object representations

When presenting grounded cognition accounts in the introduction, we acknowledged that Gentsch et al. (2016)'s framework was relevant for clarifying the multiple accounts in this domain. As a reminder, they suggested to classify grounded approaches by regarding how these theories conceive ability acquisition and constitution (Weber & Vosgerau, 2016). Considering

A and B as two abilities, the term "acquisition" applied to grounded cognition relates to the necessity of having ability A for acquiring ability B. While, the term "constitution" refers to how important is to maintain A for maintaining B. We emphasized that most grounded cognition accounts agree when they conceive ability acquisition but disagree about ability constitution. Weber and Vosgerau (2016) emphasized that three types of relations are associated with the existing grounded cognition accounts, what they called fully constitutive relations (i.e., if A is lost, B is lost as well), partially constitutive relations (i.e., if A is lost, B is partially impaired) and non-constitutive relations (i.e., if A is lost, B is conserved). We below discussed some findings of the present thesis in regard to Gentsch et al. (2016)'s framework.

In Chapter 5, we reported a non-linear developmental trajectory of the action priming effect and affordance competition. Hence, the influence of sensorimotor information over object conceptual and perceptual processing is not present at all age periods. These findings suggest that motor information and manipulable object representation do not share a fully constitutive relation. Moreover, we demonstrated that both action priming effect and affordance conflict follows a similar developmental trajectory. Affordances are sufficiently perceived to generate an action priming effect and a conflict cost at 8, but are not activated anymore at 10. In addition, in contrast to the other groups, 10-year-olds were the only children showing the expected positive relation between the amplitude of the conflict cost and the amplitude of the action priming effect. It suggests that the mechanism of *affordance specification* and affordance competition share fully constitutive relation (i.e., if A is lost, B is impaired). In other words, if the mechanism of *affordance specification* is impaired, affordance competition is too. Overall, the present findings fuel the debate about the constitution of the relation between action and perception in manipulable object representation.

2. Inter- and intra-individual modulations of affordance evocation during manipulable object perception

The findings of the present thesis fall within the recent debate about the automaticity of affordance evocation during manipulable object perception. In Chapter 2, we presented - in opposition - arguments toward automatic evocation of affordances and recent account for contextual modulations of affordance evocation. The initial claim about the automaticity of affordance evocation is based on behavioral (e.g., Ellis & Tucker, 2000; Tucker & Ellis, 1998) and neurophysiological (e.g., Gerlach et al., 2002; Proverbio, 2012) data showing a fast involvement of motor information in object perceptual and conceptual processing. In contrast, recent advances in affordance research have provided important nuances to the initial claim about the automaticity, showing important inter-individual (e.g., Chrysikou et al., 2017; Watson et al., 2013) and intra-individual modulations (e.g., Bub et al., 2008; Costantini et al., 2010) of affordance evocation. The contribution of the present work falls in the second class of evidence.

In Chapter 5, we presented important inter-individual modulations of *affordance specification* mechanism and of the consequences of affordance competition. Results showed that both follow a non-linear developmental trajectory. Altogether these findings suggest that affordance evocation is not automatic at all age periods (10- to 12-year-olds). However, we cannot completely agree with this interpretation as other assumptions can be made. First, we already suggested that the weight accorded to motor information in perceptual and semantic processing of manipulable objects could be considerably reduced in these age periods. In this case, manipulable objects could still evoke affordances but the consequence on manipulable object processing would not be visible. Another possibility is that manipulable objects still evoke affordances but the timing of their activation would not influence manipulable object processing. In other words, affordances would be evoked with a certain latency, resulting in the absence of behavioral consequences in our paradigms. Hence, findings from our developmental study demonstrated significant inter-individual variabilities but, they do not refute the initial claim about the automaticity of affordance evocation.

In Chapter 6, we presented intra-individual modulations of affordance competition. Results showed that the presence of a verbal context triggering the typical use gesture associated with conflictual objects can resolve affordance competition. These findings suggest that affordance evocation is sensitive to contextual information. Again, our results cannot rule out the initial claim about the automaticity of affordance evocation during manipulable object perception as two scenarios can be assumed (see **Figure 37**).

(1) If we assume that contextual modulations refute automatic activation of affordances (top panel of **Figure 37**), then when one processes the verb, the motor representation of the verb is activated (e.g., push). When the object is presented (e.g., camera), the motor representation of the verb - still activated - potentiates the typical use gesture associated with the object when presented within reach (e.g., vertical trigger). Thus, the manipulable object only evokes its functional affordance and no affordance competition is observed.

(2) If we assume that contextual modulations do not refute automatic activation of affordances (bottom panel of **Figure 37**), then when one processes the verb, the motor representation of the verb is activated (e.g., push). When the object is presented (e.g., camera), both structural (e.g., clench gesture) and functional (e.g., vertical trigger) affordances are automatically activated. The motor representation of the verb - still activated - thus triggers the typical use gesture of the object and inhibits its typical grasping gesture. Thus, only the functional affordance is processed and no affordance competition is observed.

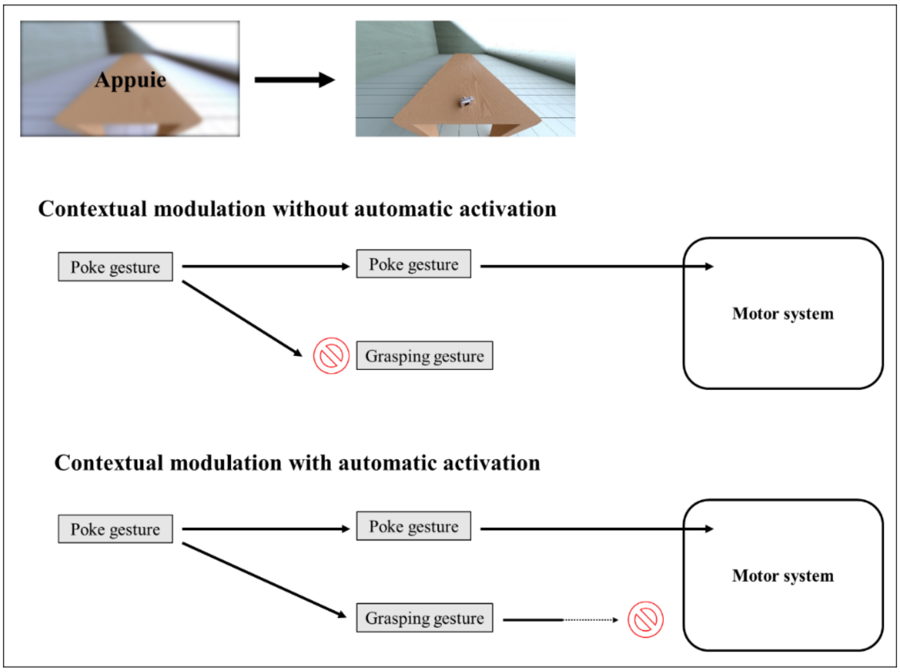


Figure 37. Schematic illustration of possible scenarios associated with contextual modulations of affordance evocation. In the first scenario, the verb acts as a triggering signal before object processing, resulting in the activation and processing of only one object-affordance (i.e., functional affordance). In the second scenario, the verb acts as a filter during object processing, resulting in the activation of both structural and functional affordances and the processing of only one of them (i.e., functional affordance).

Regarding Cisek (2007)'s model, the present EEG findings emphasized that contextual information presented previously to manipulable objects is able to modulate affordance evocation. However, we did not provide response elements about whether contextual information presented during manipulable object processing can modulate affordance evocation, as assumed in Cisek (2007)'s model. This question will be further addressed when we will analyze the data from the second part of the EEG study presented in Chapter 6. In this study, we actually presented verbal context 500 ms after the beginning of conflictual object presentation. If the verbal context modulates the processing of conflictual objects by reducing the consequence of affordance competition on the motor neural resonance (i.e., release of μ rhythm desynchronization), then we will be able to speculate that affordance evocation is automatically activated before being filtered by contextual information. Nonetheless, few questions will remain unresolved, as how and when modulating factors get involved in the resolution of affordance competition. The next and last section will put forward a potential solution to address these questions.

3. What computational modeling has to offer?

In the Chapter 3 of the Introduction, we presented models that address the question of multiple affordance perception (Caligiore et al., 2013, 2011; Caligiore & Borghi, 2010; Cisek, 2007; Cisek & Kalaska, 2010; Fagg & Arbib, 1998). After a short description of the models, we concluded that they detailed complementary aspects of affordance processing and control. Then, we made a clearer description of the influent neurobiological model developed by Cisek (Cisek, 2007; Cisek & Kalaska, 2010) to address recent behavioral and neurophysiological evidence on the topic. Nonetheless, we did not advertise that computational modeling as a major advantage over classical box model proposed in the cognitive literature. That is, when box models describe the cognitive functioning based on acquired evidence, computational modeling allows one to ask specific questions, to test the model and to generate new evidence. I below describe a potential solution that brings together current cognitive and neurobiological knowledge to answer how and when modulating factors get involved in the resolution of affordance competition during manipulable object perception.

The description of the solution and the neurocomputational model that will be described below are the product of the collaboration with Serge Thill during my 3 months Indoc at the Donders institute for artificial intelligence at Nijmegen

a. The Neural engineering framework (NEF)

In his book, Eliasmith (2013) described what he called the neural architecture for biological cognition. It is after a short description of how cognitive theories became what they currently are, that he proposed to unify the theories of cognition to answer the following questions: **(1)** *"How is semantic capture in the system?* **(2)** *How is syntactic structure encoded and manipulated by the system?* **(3)** *How is the flow of information flexibly controlled in response to task demands?* and **(4)** *How are memory and learning employed in the system?".* We will not directly address these questions and their issues. However, Eliasmith (2007, 2013) argued that these questions cannot be addressed properly if we do not consider the cognitive (i.e., what does the brain do?) and the brain (i.e., how does the brain do?) functioning as two sides of the same answer. The Neural Engineering Framework (NEF) has been though for this purpose. It is a method that can be used to build realistic brain models of large-scale neural network, that gives equal weight to cognitive and brain functioning (Eliasmith, 2007).

The NEF provide not only a theoretical solution but also a technical one: NENGO (https://www.nengo.ai/). NENGO is an open-access Python package that helps to deployed brain neural networks. NENGO offers solutions to create semantic pointer architecture (SPA), to transform, structure and bind the semantic pointers, to generate and apply control signals (i.e., selection and routing) to modulate neural flux and to implement learning and memory functioning. Semantic pointers can be described at three levels. They are high-dimensional vector in space (i.e., mathematic level), activity in biological neural network (i.e., physical level) and compressed semantic representation (i.e., function level). Transformation, structuration and binding of semantic pointers are realized by means of circular convolution – a mathematical tool - that allows to create structured representations. The control and routing of information is mainly represented by an implemented simulation of the basal ganglia, but other possibilities exist. Learning is implemented based on multiple neuronal knowledge. NENGO has been used to build SPAUN (Semantic Pointer Architecture Unified Network, Bekolay et al., 2014; Eliasmith, 2013), a model that is able to perform eight different tasks (e.g., object recognition, learning, syntactic induction, motor control, …). However, NENGO is becoming popular in other domains. For instance, a model of PID controller[15] has been built using NENGO in the domain of miniature aerial vehicles (Levy, 2019). Therefore, the NEF provides a robust theoretical and powerful technical solution to address cognitive/brain functioning questions.

b. Computational model of affordance competition mechanisms: the beginning of a solution

The model that will be described in this part is still under conception (see **Figure 38**) and we will only provide first observations (see **Figure 39**). The model is directly in line with one problematic of the present thesis work, as it concerns the intra-individual modulations of affordance competition. More particularly, it aims at assessing how and when modulating factors get involved in the resolution of affordance competition during manipulable object perception. The model was built according to the distinction between functional and structural affordances (Buxbaum & Kalénine, 2010), for cognitive details, and based on the neurobiological model of Cisek (2007), for cerebral details.

We below make a short description of the model conceived during my 3 months Indoc in Nijmegen. Manipulable objects (i.e., conflictual and non-conflictual objects) are presented to the model. They are processed by the system and their visual characteristics are extracted to trigger their typical associated gestures (e.g., calculator → clench for the grasping gesture and poke for the using gesture). These characteristics are processed and integrated as semantic pointers. Then, biasing signals coming from the task[16] and the distance of the object are implemented to modulate the weight accorded to each activated gesture. Gesture representations are then driven to a single module representing the motor system (cf. “motor”

[15] PID (proportional, integral, derivative) controllers are used to regulate the performance of a system in a closed loop.
[16] At the moment of the conception of the model, we still though that task would act as a biasing signal. We know now that it is not. A biasing signal for verbal information will be implemented instead.

box in both **Figure 38** and **Figure 39**). The first objective of the model is to reproduce consequences of affordance competition. The second objective of the model is to provide initial answers to when and how modulating factors get involved in the resolution of affordance competition during manipulable object perception.

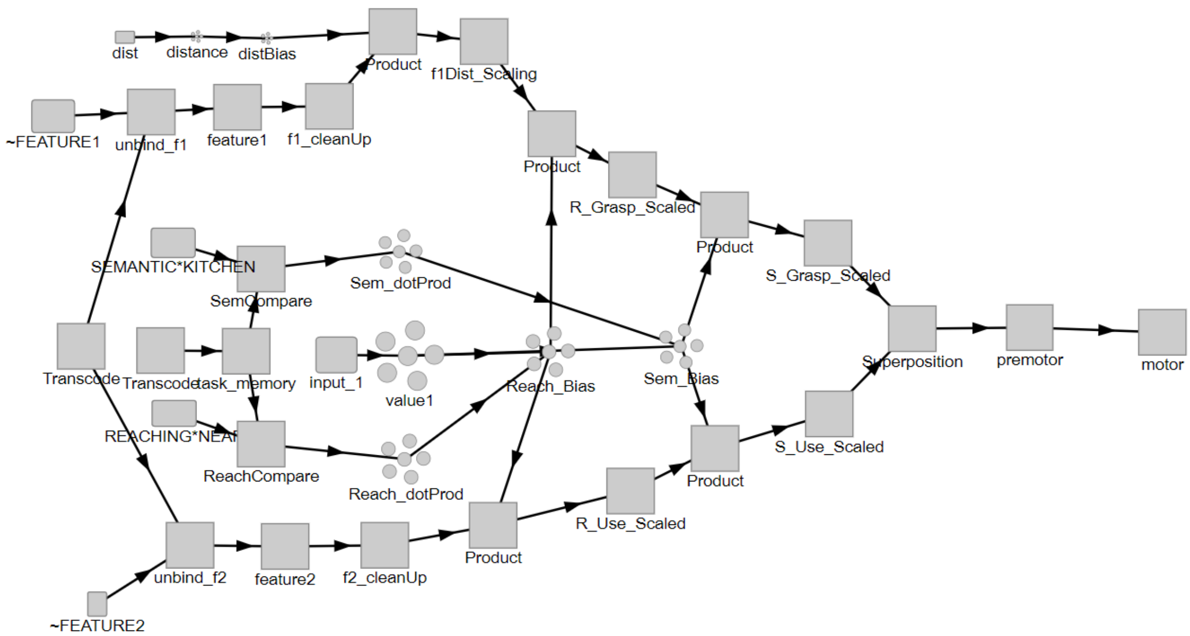


Figure 38. Schematic illustration of the NENGO model built to reproduce neural competition between structural and functional affordances and to investigate when and how modulating factors get involved in the resolution of affordance competition during manipulable object perception. The name of the different boxes must not be considered, as the schematic illustration is still an initial draft of the model.

Initial observation tends to support that the model is able to select among object-associated gestures depending on space location of the observer and task demands (see **Figure 39** for an example). We below present a schematic illustration of the model in operation. In the example, a gas lighter is presented at the model at a reasonable distance (cf. reachable or peripersonal space) and in a context that primes the using gesture of objects. After a certain delay, the model represents the typical use gesture of a gas lighter (i.e., horizontal trigger) in the motor system (cf. "motor" box). Additional verifications must be conducted, but it seems that we have successfully address our first objective.

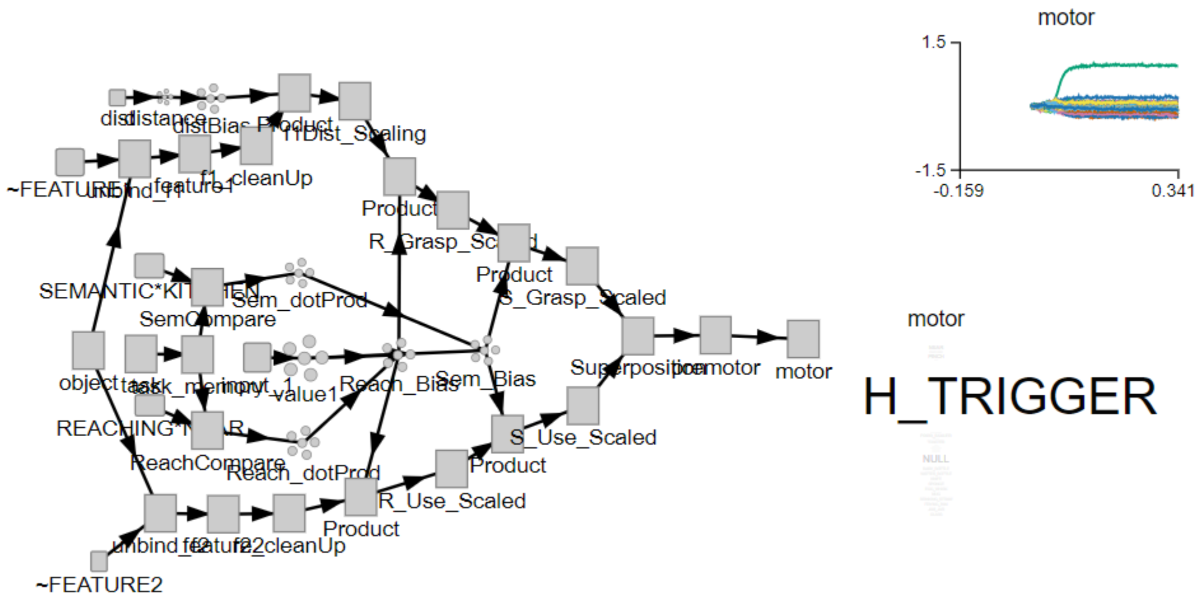


Figure 39. Schematic illustration of the NENGO model processing characteristics associated with a gas lighter. The gas lighter was presented at reasonable distance (cf. reachable or peripersonal space) and in a context that primes the functional gesture of objects. The top right plot shows the timing of spikes produced by the population of neurons in the box called "motor" (for motor system). The bottom right text refers to semantic pointer that are the "most" represented by the population of neurons in the box called "motor".

III. Global conclusion

Recent approaches have contributed in considering perception as an active phenomenon that guides actions and that is modulated by actions in the environment. Overall, theoretical conceptions agree for saying that action and perception are closely interconnected at the cerebral and cognitive levels. As action-perception relations become a converging theme in literature, the simulation of motor information grown to be a major topic in manipulable object perception. It is now strongly assumed that when perceiving manipulable objects, motor information emerging from the relation between the observer and the objects are activated (i.e., affordance evocation). Hence, various experimental paradigms have been designed in order to assess affordance evocation. In the **first experimental contribution** presented in this manuscript, we tried to select one of them in order to assess affordance evocation as purely as possible for further investigations.

Besides this issue, initial investigations of affordances claimed for a fast and automatic evocation of affordances during manipulable object perception, while latter investigations nuance the claim, showing noticeable inter-individual and intra-individual variabilities. Additional evidence showed that manipulable objects seem to evoke distinct affordances depending on the context. Furthermore, it seems that when they are co-activated from a single object, distinct affordances may have negative consequences on manipulable object processing. Specifically, distinct affordances associated with a single object compete with one another and this competition may be detrimental to production of object-directed actions and object perceptual processing. In the **second experimental contribution** of the present thesis, we have investigated how intra- and inter-individual variabilities modulate the impact of affordance competition on manipulable object perception. The overall objective was guided by a recent neurobiological model of *affordance specification* and *affordance selection* (Cisek, 2007). In his model, Cisek (2007) accounts for the processing and factors at play in *affordance* *specification* and *affordance selection* for action. Altogether, our findings are consistent with recent accounts concerning the role of the individual development and context in affordance evocation of manipulable objects and contribute to theoretical models of action selection. Now that we have demonstrated that individual and contextual factors modulate the mechanisms at play during affordance *specification* and *selection* during affordance competition, questions remain unresolved. Especially it is not clear how and when these factors get involved in the resolution of affordance competition. In the end, if we have to ask "what have we actually accomplished in the last 50 years of affordance thinking and research", I would stand by the side of Eliasmith (2013) and answer that we can now ask more accurate questions.

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APPENDICES

Appendix 1. Ethical protocol (Experimental contribution, Chapter 4 and 5)

Appendix 2. Ethical protocol (Experimental contribution, Chapter 6)

Appendix 3. Stimuli used in the implementation of the delayed-handle response compatibility paradigm

Appendix 4. Full list of manufactured objects used in the implementation of the action priming paradigm

Appendix 5. Full list of natural objects used in the implementation of the action priming paradigm

Appendix 6. Instruction given for assessments of manipulability and variability of manipulation in the action priming paradigm. English translation below each frame.

Appendix 7. Full list of non-conflictual objects used in the implementation of the 3D virtual paradigm and their conflict index.

Appendix 8. Full list of conflictual objects used in the implementation of the 3D virtual paradigm and their conflict index.

Appendix 9. Full list of conflictual object and verb association used in the implementation of the 3D virtual paradigm of the EEG study.

Appendix 1. Ethical protocol (Experimental contribution, Chapter 4 and 5)

Université de Lille

Comité d'éthique en sciences comportementales

Président :
Yvonne DELEVOYE-TURRELL

Président adjoint :
Céline DOUILLIEZ

Personne ressource (dossier administratif) :
Aurélie DUCROQUET
Tél : 03.20.41.67.92 -
E-mail : aurelie.ducroquet@univ-lille3.fr

Villeneuve d'Ascq le 31/01/2018

Références comité d'éthique :	2017-5-S56
Sigle :	MoDEV-MP
Numéro de version et date :	Version 1 du 30/10/2017
Promoteur :	Lille 3
Porteur projet :	S.Kalenine, Y.Wamain, M.Godard, MA.Lecerf

Date de la soumission : 31/10/2017

Date de la réunion du comité d'éthique : 14/11/2017

Avis du comité d'éthique : AVIS FAVORABLE

Le protocole est accepté en état. Si pour une quelconque raison, vous souhaitez modifier le protocole (en terme de calendrier, inclusion d'un nouveau groupe...), vous êtes tenu d'informer le comité d'éthique par l'envoi d'un avenant expliquant les motivations mais également les modifications apportées au protocole initial.

Cet avenant sera réévalué par le comité d'éthique.

Pr Yvonne DELEVOYE-TURRELL
Présidente du comité d'éthique

Y. Delevoye

Appendix 2. Ethical protocol (Experimental contribution, Chapter 6)

Université de Lille

Comité d'éthique en sciences comportementales

<u>Présidente :</u>
Yvonne DELEVOYE-TURRELL

<u>Président adjoint :</u>
Cédric PATIN

<u>Gestionnaire administrative :</u>
Stella BOUAMRIRENE
Tel : 03 -62- 26- 80- 82
E-mail : Stella.Bouamrirene@univ-Lille.fr

Villeneuve d'Ascq le 07/01/2020

Références comité d'éthique :	2019-385-S77
Sigle :	CV-O-ES
Numéro de version et date :	Version 2 du 20/12/2019
Promoteur :	ULille SHS-ALL
Responsable Scientifique du projet : Solène KALENINE	

Date de la soumission :

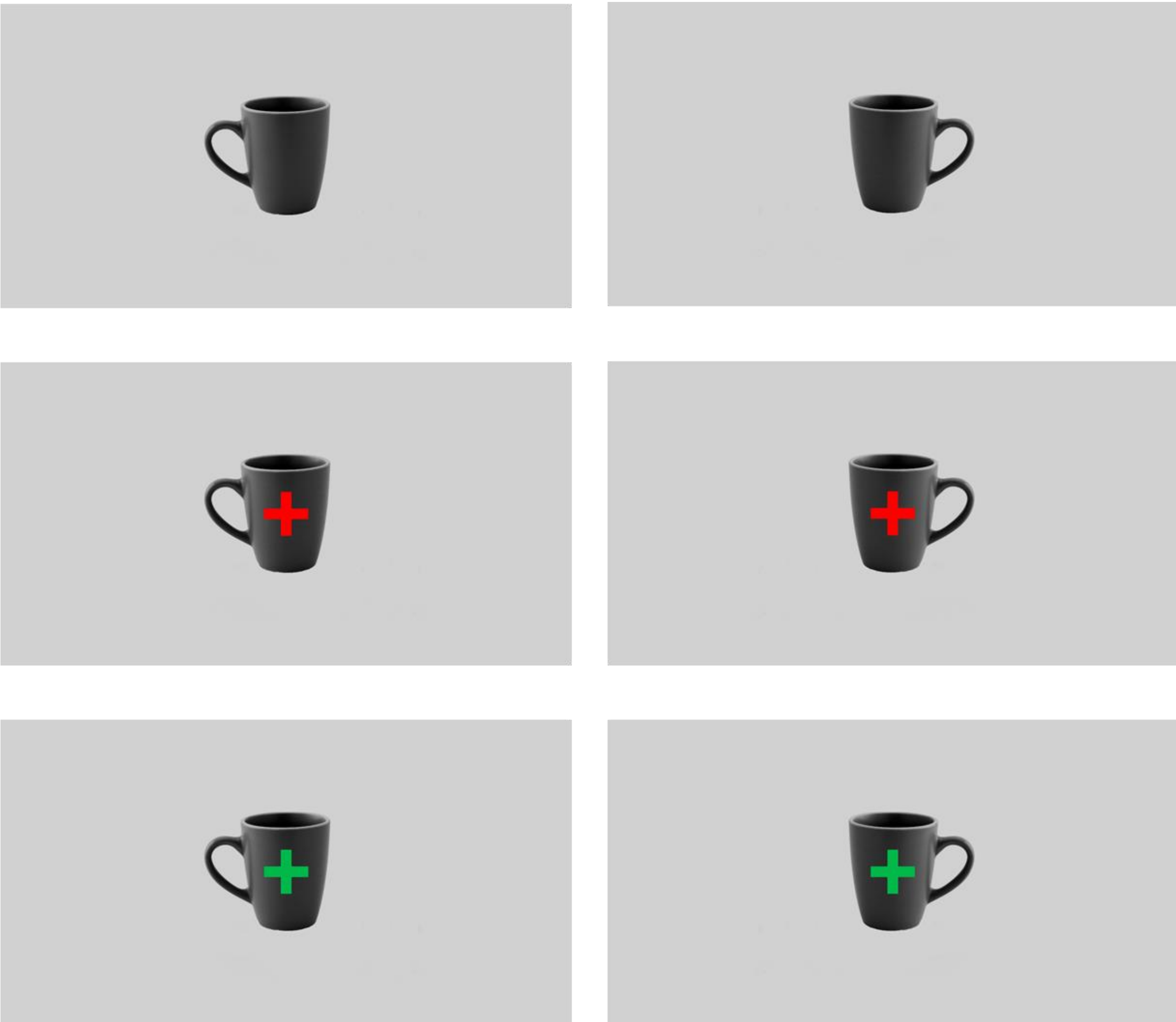
Avis du Comité d'Ethique : Avis favorable.

Le protocole est accepté en état. Si pour une quelconque raison, vous souhaitez modifier le protocole (en terme de calendrier, inclusion d'un nouveau groupe…), vous êtes tenu d'informer le comité d'éthique par l'envoi d'un avenant expliquant les motivations mais également les modifications apportées au protocole initial. Cet avenant sera réévalué par le comité d'éthique.

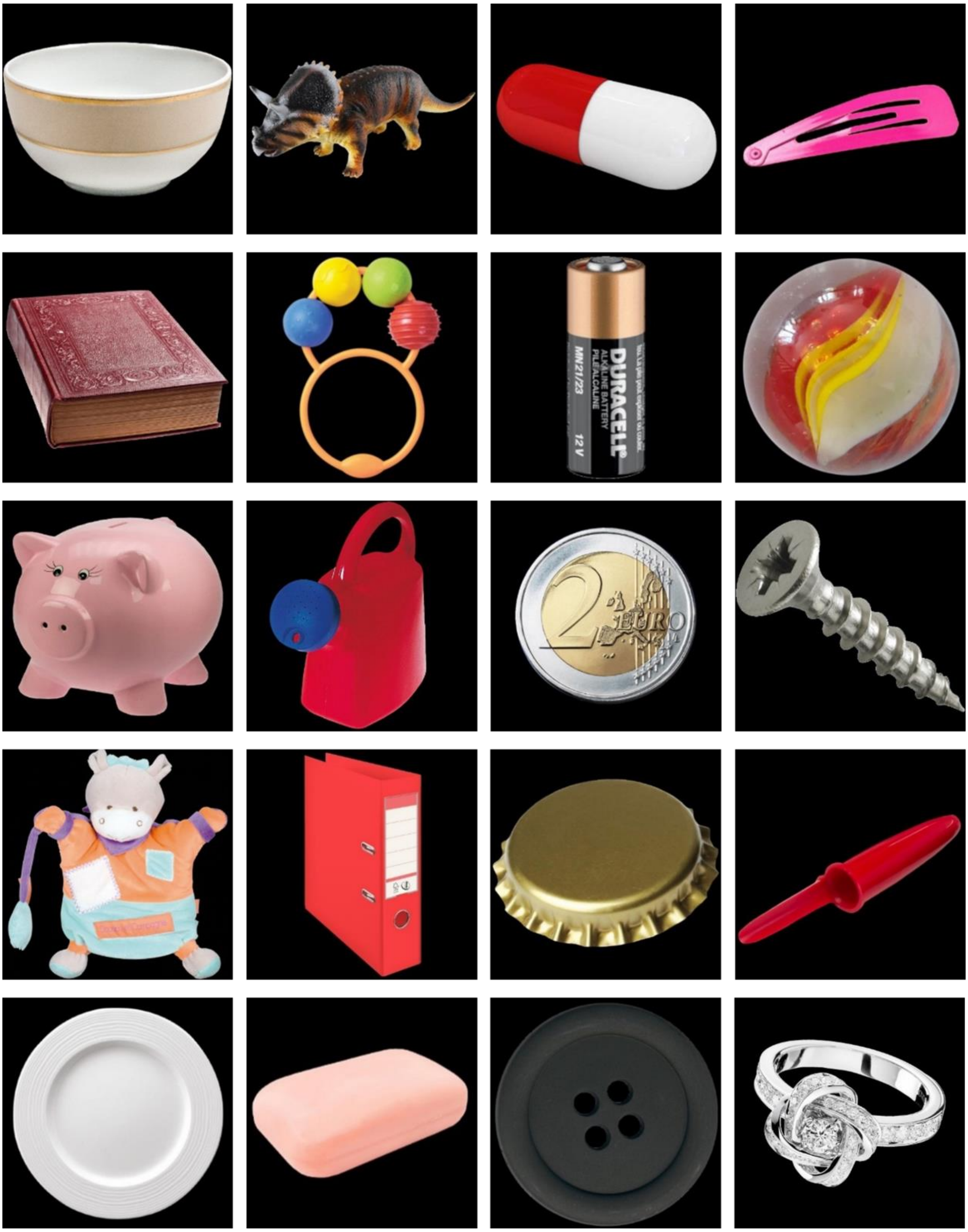
L'avis du CER-Lille n'exonère pas des formalités réglementaires. A cet égard, il vous appartient notamment, si vous traitez des données se rapportant à un individu directement ou indirectement identifiable, de vous conformer au règlement européen sur la protection des données (RGPD) en vigueur depuis 2018. Pour cela, vous pouvez solliciter les conseils du Correspondant informatique et libertés (DPO) ou du service juridique de votre université ou de votre organisme de recherche.

Pr Yvonne DELEVOYE-TURRELL
Présidente du comité d'éthique
Y. Delevoye

Appendix 3. Stimuli used in the implementation of the delayed-handle response compatibility paradigm



Appendix 4. Full list of manufactured objects used in the implementation of the action priming paradigm



Appendix 5. Full list of natural objects used in the implementation of the action priming paradigm

Appendix 6. Instruction given for assessments of manipulability and variability of manipulation in the action priming paradigm. English translation below each frame.

1. Jugez sur l'échelle de 1 à 5, la manipulabilité de l'objet en fonction de la facilité avec laquelle vous pouvez le saisir et l'utiliser avec une main (1 : pas du tout, 5 : beaucoup).

   Exemples :

   - Rhinocéros = 1, car pas manipulable.

1	2	3	4	5
☑	☐	☐	☐	☐

   - Cuillère = 5, car manipulable.

1	2	3	4	5
☐	☐	☐	☐	☑

Translation: Judge on the scale from 1 to 5, the manipulability of the object in function of your facility to grasp and use it with on hand (1: not at all, 5: very).

<u>Examples</u>: Rhinoceros = 1, because it is not manipulable; Spoon = 5, because it is manipulable.

2. Jugez sur l'échelle de 1 à 5, dans quelle mesure la manière dont vous manipulez cet objet peut varier à chaque manipulation (1 : ne varie pas, 5 : varie beaucoup).

   Exemples :

   - Balle = 1, peu variable.

1	2	3	4	5
☑	☐	☐	☐	☐

   - Chiffon = 5, variable.

1	2	3	4	5
☐	☐	☐	☐	☑

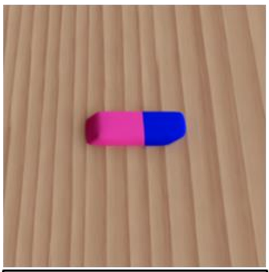
Translation: Judge on the scale from 1 to 5, to what extent the way you manipulate this object can vary for each manipulation (1: don't vary, 5: vary a lot).

<u>Examples</u>: Ball = 1, low variable, Rag = 5, variable.

Appendix 7. Full list of non-conflictual objects used in the implementation of the 3D virtual paradigm and their conflict index.


Conflict index: 0


Conflict index: 0


Conflict index: 25


Conflict index: 0


Conflict index: 16.67


Conflict index: 0


Conflict index: 0


Conflict index: 25


Conflict index: 0


Conflict index: 16.67


Conflict index: 8.33


Conflict index: 16.67


Conflict index: 0


Conflict index: 0


Conflict index: 0


Conflict index: 25


Conflict index: 0


Conflict index: 0


Conflict index: 8.33


Conflict index: 0

Appendix 8. Full list of conflictual objects used in the implementation of the 3D virtual paradigm and their conflict index.


Conflict index: 100


Conflict index: 100


Conflict index: 91.67


Conflict index: 100


Conflict index: 100


Conflict index: 83.33


Conflict index: 83.33


Conflict index: 100


Conflict index: 75


Conflict index: 100


Conflict index: 91.67


Conflict index: 100


Conflict index: 66.67


Conflict index: 50


Conflict index: 100


Conflict index: 100


Conflict index: 100


Conflict index: 58.33


Conflict index: 91.67


Conflict index: 91.67

Appendix 9. Full list of conflictual object and verb association used in the implementation of the 3D virtual paradigm of the EEG study.

Objects	Action verbs	Neutral verbs
Gas lighter	Brûler (to burn)	Observer (to observe)
Camera	Appuyer (to press)	Inspecter (to inspect)
Kitchen scale	Peser (to weight)	Contempler (to contemplate)
Tin can	Ouvrir (to open)	Observer (to observe)
Music box	Tourner (to turn)	Observer (to observe)
Spray can	Vaporiser (to spray)	Inspecter (to inspect)
Calculator	Compter (to count)	Regarder (to look at)
Game die	Lancer (to throw)	Admirer (to admire)
Soap distributor	Appuyer (to press)	Admirer (to admire)
Toaster	Toaster (to toast)	Examiner (to examine)
Desk lamp	Eclairer (to light)	Evaluer (to evaluate)
Timer	Programmer (to program)	Contempler (to contemplate)
Pepper mill	Assaisonner (to season)	Regarder (to look at)
Perfume	Vaporiser (to spray)	Observer (to observe)
Cheese grater	Mouliner (to mill)	Constater (to see)
Alarm clock	Stopper (to stop)	Scruter (to scrutinize)
Salt shaker	Assaisonner (to season)	Inspecter (to inspect)
Sugar bowl	Servir (to serve)	Evaluer (to evaluate)
Corkscrew	Ouvrir (to open)	Scruter (to scrutinize)
Spinning top	Tourner (to turn)	Evaluer (to evaluate)

CURRICULUM VITAE

MARC GODARD

Doctorant en psychologie cognitive

27 ans, célibataire
439 rue de Cambrai, 59500 Douai
06 98 17 46 35
marc.godard.62@gmail.com
www.linkedin.com/in/marc-godard-07961013b

Curieux
Autodidacte
Flexible
Rigoureux

DIPLÔMES & FORMATIONS

2017 - 2020

Formation doctorale

(ED SHS, Ecole doctorale Sciences de l'Homme et de la Société Lille)

- Emplois, métiers et carrières après un doctorat en SHS,
- Veille et stratégie de recherche documentaire
- Workshop TRACE (Transdisciplinary research association on cognition and embodiement)
- Challenge doc 2020 (Résolution d'une problématique d'entreprise),
- Atelier d'anglais (Apprendre la communication scientifiques écrite et orale)

MOOC (Massive Open Online Courses)

- **FunMooc**: Apprendre à coder avec Python;
- **Datacamp**: "Introduction to R", "Intermediate R";
- **Datacamp**: "Introduction to Python", "Intermediate Python";
- **Datacamp**: "Fundamentals of Bayesian Analysis in R", "Bayesian Regression Modeling with rstanarm", "Bayesian Modeling with RJAGS";
- **Openclassroom** : "Présentez des diaporamas avec Powerpoint", "Améliorez l'impact de vos presentations", "La mise en page avec Adobe InDesign";
- **Nengo Brain Maker** (*python package*): Tutoriels Nengo GUI;

2016 - 2017

Master 2 PPNSA

(Psychologie des processus neurocognitifs et sciences affectives)

Thème du mémoire de recherche : Implication des processus attentionnels dans la perception.
Technique : Enregistrement des mouvements oculaires (oculomètre)

2015 - 2016

Master 1 de Psychologie

Thème du mémoire de recherche : Implication des facteurs de personnalité dans la perception.
Technique : Echelle de mesure de la personnalité, analyses de données comportementales

EXPERIENCES PROFESSIONNELLES

2020 - …	**Chercheur en sciences humaines et sociales** (MOHA, My Own Health Activity) **Poste**: Responsable de la qualité scientifique du travail de l'entreprise MOHA. Conception, évaluation et valorisation des méthodologies d'analyse du bien-être dans l'entreprise.
2019 - 2020	**Doctorant consultant pour entreprises** (MOHA, My Own Health Activity) **Problématique**: Mise en place d'un outil d'évaluation des attentes et des effets des interventions de l'entreprise MOHA sur la qualité de vie et le bien-être au travail.
2017 - 2020	**Doctorant contractuel en psychologie** (SCALab, Laboratoire de sciences cognitives et affectives) **Thèse**: Modification développementales et contextuelles des représentations motrices impliquées dans la perception des objets • *Directrice*: Solène Kalénine (chercheuse CNRS) • *Co-directeur*: Yannick Wamain (maître de conférences) ***Techniques***: Analyses comportementales, Analyses électroencéphalographiques, Affichage 3D en réalité virtuelle **Activités complémentaires:** Enseignements en psychologie cognitive (178h), Organisation d'événements pour diffuser le savoir scientifique, Coreprésentant des doctorants, Supervision des stagiaires,
	Stage en modélisation computationnelle (Département d'intelligence artificielle, Institut Donders, Pays-Bas) **Thématique**: Modélisation des processus neuronaux de la compétition entre représentations motrices lors de la perception des objets. • *Encadrant*: Serge Thill (professeur associé, Institut Donders) ***Technique***: Modélisation neuronale (Python, package NENGO)
2016 - 2017	**Stage de recherche** (SCALab, Laboratoire de sciences cognitives et affectives) **Thématique**: Analyse des marqueurs neuronaux de la perception des contingences dans l'environnement • *Encadrant*: Jérémie Jozefowiez (maître de conférences) ***Technique***: Electroencéphalographie, tâche comportementale
2015 - 2016	**Stage clinique en CAMPS** (Centre d'accueil médico-social précoce, Creil) **Activité**: Prise en charge neuropsychologique (bilan et rééducation) d'enfants de 0 à 6 ans.

PUBLICATIONS

Godard, M, Wamain, Y, Delepoulle, S, & Kalénine, S (**submitted**). How competition between affordances affects object perception during development. Cognition.

Godard, M, Wamain, Y, Ott, L & Kalénine, S. (**in prep.**). Disentangling affordance from spatial compatibility effects during object perception. Acta Psychologica,

Godard, M, Wamain, Y & Kalénine, S. (2019). Do manufactured and natural object evoke similar motor information: the case of action priming. Quarterly journal of experimental psychology. doi: 10.1177/1747021819862210.

COMMUNICAITONS

Godard, M., Wamain, Y., Delepoulle, S., & Kalénine, S. (2019). The development of the processing cost entailed by conflicting affordances during object perception. 21st conference of the European Society for Cognitive Psychology, Tenerife, Spain, Oral Communication.

Godard, M., Wamain, Y., Delepoulle, S., & Kalénine, S. (2019). Predicting object visual processing from motor affordance sensitivity and conflict monitoring abilities: a developmental study. 3rd Biennial International Convention of Psychological Science, Paris, France, Poster.

Godard, M., Wamain, Y., & Kalénine, S. (2018). Distinguer les effets d'affordances de l'effet Simon lors de la perception d'objet. 59ème Congrès de la Société Française de Psychologie, Reims, France, Communication Orale.

Godard, M., Wamain, Y., & Kalénine, S. (2018). Do manufactured and natural objects evoke similar motor information? Evidence from action priming. 5th Workshop TRACE, Transdisciplinary Research Association on Cognition and Embodiement, Brusells, Belgium, Oral Communication.

Godard, M., & Sparrow, L. (2017). Influence de la charge attentionnelle et des mouvements oculaires sur la perception du temps. 12ème Journée Scientifique des Jeunes Chercheurs en Psychologie, Lille, France, Communication Orale.

COMPETENCES

Informatique	**Programmation** : Python, R, Matlab, Eprime **Bureautique** : Word, Excel, Powerpoint **Logiciel d'analyses statistiques** : Statistica, JASP **Infographie** : Photoshop, Lightroom
Langues	**Français** : langue maternelle **Anglais :** lu, écrit et parlé

AFTERWORD

Guide du doctorant heureux dans sa chemise blanche café

Regardez les doctorants autour de vous, surprenez-vous leur donnant un costume : lui est un bon programmeur, elle est bonne oratrice, il se défini par sa créativité, elle deviendra une grande chercheuse… Ces costumes prennent et prendront d'innombrables formes au cours de votre thèse, mais aussi de votre vie. Vous en donnerez tous les jours et vous en revêtirez tous les jours. Sources d'énergie et de motivation un temps, fardeaux ils seront le suivant. Ils nous permettent d'affronter la réalité, aussi d'en prendre conscience. Que serions-nous sans ces costumes ? Et pourtant, quand la violence de la réalité est telle que ces costumes deviennent lourds à porter, nous réalisons qu'ils collent à notre peau, puis des pensées nous assaillent.

Je ne suis pas un bon programmeur, je ne suis pas un bon orateur, je ne suis pas créatif, je ne serai pas un grand chercheur. Oui, c'est un fait de poser une étiquette, s'en est un autre de se rendre compte qu'elle n'est pas posée sur nous. Au diable ces costumes ! Abandonnez-les ! Vous êtes extraordinaires ! Sans costume vous pouvez tout traverser. Avec, vous devez tout affronter.

Ainsi, je décrirais la thèse comme une épreuve à la fois traumatisante et libératrice. Habillé d'un beau costume à l'arrivée pour affronter ce travail qui vous attend, vous traverserez ce travail en chemise blanche café et souriant. Mais à chaque histoire, ses leçons. Cette histoire est la mienne et celle de l'aboutissement de cette thèse. Je vous laisse le plaisir de construire vos propres enseignements.

Je souhaitais terminer ce guide par une citation qui me tient à cœur et qui représente le costume que je souhaite endosser à l'avenir.

TU SERAS UN HOMME MON FILS

Si tu peux voir détruit l'ouvrage de ta vie
Et sans dire un seul mot te mettre à rebâtir,
Ou perdre en un seul coup le gain de cent parties
Sans un geste et sans un soupir ;

Si tu peux être amant sans être fou d'amour,
Si tu peux être fort sans cesser d'être tendre,
Et, te sentant haï, sans haïr à ton tour,
Pourtant lutter et te défendre ;

Si tu peux supporter d'entendre tes paroles
Travesties par des gueux pour exciter des sots,
Et d'entendre mentir sur toi leurs bouches folles
Sans mentir toi-même d'un mot ;

Si tu peux rester digne en étant populaire,
Si tu peux rester peuple en conseillant les rois,
Et si tu peux aimer tous tes amis en frère,
Sans qu'aucun d'eux soit tout pour toi ;

Si tu sais méditer, observer et connaître,
Sans jamais devenir sceptique ou destructeur,
Rêver, mais sans laisser ton rêve être ton maître,
Penser sans n'être qu'un penseur ;

Si tu peux être dur sans jamais être en rage,
Si tu peux être brave et jamais imprudent,
Si tu sais être bon, si tu sais être sage,
Sans être moral ni pédant ;

Si tu peux rencontrer Triomphe après Défaite
Et recevoir ces deux menteurs d'un même front,
Si tu peux conserver ton courage et ta tête
Quand tous les autres les perdront,

Alors les Rois, les Dieux, la Chance et la Victoire
Seront à tous jamais tes esclaves soumis,
Et, ce qui vaut mieux que les Rois et la Gloire
Tu seras un homme, mon fils.

Rudyard Kipling

VERSION SYNTHETIQUE EN FRANÇAIS

La perception et l'action sont deux processus dynamiques et interconnectés. Ils partagent de nombreux corrélats cérébraux et font partie intégrante des représentations cognitives. Dans ce projet de thèse, nous nous sommes concentrés sur les conceptions représentationnelles des liens perception-action pour les objets manipulables. Les conceptions les plus récentes s'accordent pour dire que la perception d'objets manipulables induit une réactivation de leurs informations motrices, ce qui est habituellement appelé « affordances ». Bien qu'un nombre important de preuves expérimentales suggèrent que l'évocation d'affordances lors de la perception d'objets soit automatique, plusieurs arguments expérimentaux montrent une variabilité inter-individuelle et intra-individuelle notable. L'expérience motrice individuelle et le contexte, tout particulièrement, modulent l'activation des affordances d'objet. Enfin, l'évocation d'affordances peut parfois être préjudiciable. Quand un unique objet évoque plusieurs affordances distinctes (objet « conflictuel »), ces affordances entrent en compétition. Cette compétition induit un coût de traitement, ralentissant les jugements perceptifs et supprimant la résonance motrice neurale (désynchronisation du rythme Mu). L'objectif de la thèse est d'évaluer comment le coût de la compétition peut être affecté par des facteurs individuels et contextuels. Dans une première série d'expériences, nous avons cherché à préciser les propriétés motrices d'objets évaluées avec les paradigmes classiquement utilisés pour mettre en lumière les effets d'affordance. Les résultats suggèrent qu'il est possible d'évaluer l'activation d'affordances fonctionnelles d'objets manipulables à l'aide d'un paradigme d'amorçage par l'action, en s'affranchissant de l'influence de la compatibilité spatiale dans l'évaluation des effets d'affordance. Dans une seconde étude, nous avons réalisé une vaste expérimentation sur le développement du coût de la compétition entre affordances auprès de participants âgés de 8 ans à l'âge adulte. Les résultats démontrent que le développement du coût de la compétition entre affordances et celui de l'évocation d'affordances lors de la catégorisation d'objets suivent des trajectoires non linéaires semblables. Dans une troisième étude, nous avons évalué l'influence du contexte visuel sur le coût de la compétition entre affordances à l'aide de l'électroencéphalographie. Les objets conflictuels étaient amorcés par des verbes écrits. Nous avons observé une réduction de la désynchronisation du rythme Mu quand les objets atteignables étaient précédés par un contexte verbal évoquant une action congruente avec l'utilisation fonctionnelle de l'objet. Cela suggère que le contexte verbal a biaisé le traitement de l'objet vers une affordance spécifique, réduisant le coût de la compétition. Dans l'ensemble, les données rapportées ici sont en accord avec les propositions récentes concernant le rôle du contexte et des caractéristiques individuelles dans l'activation des affordances d'objets. Ces résultats aideront à affiner et étendre les modèles neurobiologiques de la sélection d'action.

CHAPITRE 1. LA PERCEPTION AU SERVICE DE L'ACTION

Les conceptions théoriques récentes argumentent en faveur d'une contribution fonctionnelle de la perception pour guider l'action dans l'environnement. Ces conceptions s'accordent pour dire que la perception est une fonction adaptative qui permet à un individu de recueillir des informations dans l'environnement pour agir et survivre. Les chercheurs ont, par exemple, étudié la perception pour son rôle dans la discrimination des propriétés nécessaires à identifier ou se représenter les actions associées aux objets, pour interagir avec ces objets ou même se représenter les actions d'autrui. Ils ont également étudié l'intégration – dans les représentations cognitives - des variations partagées entre les actions menées dans l'environnement et les conséquences de ces actions sur les propriétés perceptives de l'environnement. Par exemple, les chercheurs ont étudié l'intégration des contraintes d'action dans la perception de l'espace ou l'intégration des informations sensorimotrices au sein des connaissances conceptuelles à long-terme. Les interconnexions entre la perception et l'action sont soutenues par de nombreux cadres théoriques et preuves expérimentales. Parmi ces cadres théoriques, on retrouve plusieurs débats, mais aucun d'eux n'interroge directement les interconnexions entre la perception et l'action. Dans cette première partie de résumé, nous tenterons de convaincre le lecteur que la perception et l'action sont dynamiquement interconnectées, en se focalisant sur la perception visuelle. L'objectif sera de fournir au lecteur des informations pertinentes pour discuter de la perception des objets manipulables pour la suite de la lecture. Tout d'abord, nous résumerons brièvement l'approche écologique de la perception (Gibson, 1986), puis nous discuterons des découvertes neurophysiologiques récentes et nous terminerons par les approches cognitives actuelles, dans lesquelles s'inscrit le présent travail de thèse.

I. L’approche écologique de la perception visuelle

Dans la seconde moitié du 20ème siècle, Gibson a proposé une approche écologique de la perception visuelle (Gibson, 1979, 1986). Dans son approche écologique de la perception, Gibson a fait l’hypothèse d’une perception directe des informations de l’environnement (Gibson, 1986), ce qui signifierait que l’information est contenue dans l’environnement lui-même, présente dans le pattern de stimulations sensorielles (aussi appelées propriétés invariantes) provenant de l’environnement et par conséquent il réfute le concept de représentation mentale (Baggs & Chemero, 2018). Gibson (1986) souligne le rôle adaptatif des relations perception-action, assumant un rôle adaptatif fonctionnel de ces relations dans la survie d’un individu face aux contraintes environnementales. En ce sens, la perception serait unique à chaque individu et inséparable de ses actions. Gibson (1986) va encore plus loin en suggérant que la perception n’est pas seulement au service de l’action mais serait un phénomène actif qui émerge de l’action et de l’exploration de l’environnement. L’élément central de l’approche de Gibson (Gibson, 1979, 1986) est le terme d’affordance qu’il a créé pour définir les informations fournies à un organisme par son environnement. Les affordances font références aux possibilités d’action qu’un organisme possède dans son environnement en fonction de ses contraintes d’action. Tout comme la perception, les affordances seraient uniques à chaque individu. Elles seraient à la juste limite entre l’objectivité et la subjectivité, parce qu’elles existent indépendamment de la perception mais dépendent des capacités individuelles d’action. Selon Gibson, les affordances seraient donc des actions possibles évoquées par l’environnement. Pour terminer, bien que l’approche écologique de la perception soit une théorie controversée, notamment concernant l’absence de considération de représentations mentales, la théorie a fortement contribué à considérer que la perception, compte tenu de ses fortes interconnexions avec l’action, se situe à l’interface entre l’humain et l’environnement.

II. Les approches neurophysiologiques

D'un point de vue neurophysiologique, il a été récemment souligné que la perception et l'action sont deux systèmes qui ne montrent pas de distinction claire. Nous résumerons d'abord la découverte du système visuel à double voies puis nous résumerons la découverte des neurones visuomoteurs.

1. Le système visuel à double voies

Au début des années 1980, la découverte de deux systèmes visuels distincts chez le singe a fourni des preuves concrètes de l'existence d'un traitement perceptif spécifique à l'action (Mishkin et al., 1983). C'est en étudiant le système visuel des singes qu'un groupe de chercheurs a mis en évidence l'existence de deux systèmes visuels - fonctionnellement et neuroanatomiquement distincts (Mishkin & Ungerleider, 1982; Van Essen et al., 1992; Young, 1992) - dédiés à la perception des objets (i.e., « quoi ») et de l'espace (i.e., « où ») respectivement (Mishkin et al., 1983). Le premier système est connu sous le nom de voie ventrale et connecte les cortex occipital et temporal (i.e., perception des objets). Le second système est connu sous le nom de voie dorsale et connecte les cortex occipital et pariétal (i.e., perception de l'espace). Plus tardivement, la voie dorsale a été associée au traitement de tout type d'activités visuomotrices (Goodale, 1993 ; Goodale et al., 1991, 1992 ; Milner & Goodale, 1993) et hérita du nom de « how system » (ou le système du « comment » agir). Chez l'être humain, les rôles fonctionnels des voies ventrale et dorsale ont été mis en évidence par des preuves provenant d'études neuropsychologiques (Goodale, 1993 ; Goodale et al., 1991, 1992 ; Jeannerod et al., 1994 ; Milner & Goodale, 1993), d'études en neuroimagerie (Culham et al., 2003 ; Gallivan et al., 2009 ; Malach et al., 1995, 2002) et d'études comportementales (Aglioti et al., 1995 ; Króliczak et al., 2006). Face à une telle accumulation de preuves, il est largement accepté que le traitement visuel des objets chez le primate est réalisé par au moins deux systèmes visuels différents (Milner & Goodale, 2006) : un système sous-tendant le traitement des caractéristiques visuelles pour accéder à l'identité des objets (i.e., le système du « quoi » ou voie ventrale) et un système sous-tendant le traitement des actions associées aux objets (i.e., le système du « comment » agir ou voie dorsale). Il est important de noter que le système visuel des primates semble posséder un traitement perceptif spécifique au service de l'action (i.e., la voie dorsale), soutenant l'idée que la perception et l'action sont deux systèmes étroitement connectés.

2. Les neurones visuomoteurs (neurones canoniques et miroirs)

Quelques années après la découverte du système visuel à double voies (Mishkin et al., 1983), des chercheurs ont montré que l'équivalent du cortex prémoteur humain chez le singe contenait des neurones visuomoteurs réagissant lorsque le singe réalisait une action mais aussi lorsque le singe percevait certains stimuli visuels. Plus tardivement, la même équipe de chercheurs a souligné l'existence de deux classes de neurones visuomoteurs (Rizzolatti & Fadiga, 1998), en fonction des stimuli visuels auxquels ils réagissaient. Premièrement, les neurones miroirs qui réagissent lorsque le singe réalisait une action et lorsque le singe percevait un autre individu réaliser la même action. Deuxièmement, les neurones canoniques qui réagissent lorsque le singe réalisait une action dirigée vers un objet et lorsque le singe percevait ce même objet sans action. Plus généralement, Rizzolatti and Fadiga (1998) ont suggéré que les deux classes de neurones visuomoteurs soient impliquées dans la représentation des actions, ou ce qu'ils ont appelé « ideas on how to act » (p. 89, « représentation de la manière d'agir »). L'existence des neurones visuomoteurs chez le singe a été démontré à l'aide d'une méthodologie d'enregistrement unicellulaire via des électrodes directement implantées dans le cerveau (Rizzolatti et al., 1988). Cette technique est relativement invasive et, par conséquent, est rarement utilisée chez l'humain. Chez l'humain, l'existence de neurones visuomoteurs est soutenue par des preuves majoritairement indirectes qui utilisent des techniques enregistrant l'activité de populations de neurones (i.e., EEG, MEG, fMRI, PET). Il existe, néanmoins, une récente étude en enregistrement unicellulaire apportant des preuves directes de l'existence de neurones miroirs chez l'humain (Keysers & Gazzola, 2010 ; Mukamel et al., 2010). En dépit des critiques récentes sur l'existence de neurones visuomoteurs chez l'humain, les nombreuses études neurophysiologiques dans le domaine ont contribué à développer les connaissances sur les corrélats cérébraux associés au traitement perceptif des actions d'autrui et des attributs moteurs des objets. Il est important de noter que le système moteur des primates semble posséder des neurones ou populations de neurones impliqués à la fois dans le traitement des informations perceptives et dans le traitement des informations motrices, soutenant l'idée que la perception et l'action sont deux systèmes étroitement connectés.

Synthèse des approches neurophysiologiques

Globalement, les approches neurophysiologiques suggèrent que les traitements cérébraux de la perception et de l'action sont parfois difficiles à distinguer. Les preuves provenant de la littérature sur le système visuel à double voies et des neurones visuomoteurs montrent que la perception et l'action partagent de nombreux corrélats cérébraux. En un sens, les preuves chez le singe et leur généralisation chez l'humain suggèrent que nous sommes phylogénétiquement et biologiquement organisés pour traiter la perception et l'action d'une manière similaire. De plus, nous pouvons considérer les deux approches neurophysiologiques comme deux approches complémentaires. Alors que le cadre théorique du système visuel à double voies décrit le fonctionnement cérébral qui transforme les informations visuelles en informations motrices au niveau de réseaux de neurones, le cadre théorique des neurones visuomoteurs décrit une fonction similaire au niveau du neurone.

III. Les approches ancrées de la cognition

Les approches ancrées de la cognition font l'hypothèse que la perception et l'action sont étroitement interconnectées avec la cognition. Ces approches englobent un nombre considérable de conceptions théoriques qui divergent toutes - partiellement - entre elles. Ces divergences trouvent leur source dans la différence de fonction cognitive spécifiquement décrite par chaque approche. Tout d'abord, nous présenterons un cadre théorique permettant de classifier ces différentes approches, sans être exhaustif, puis nous illustrerons deux approches représentationnelles fortement liées au présent travail de thèse.

1. Les multiples approches ancrées de la cognition

Les multiples approches ancrées de la cognition portent différentes appellations parce qu'elles privilégient certains aspects de l'interconnexion entre la perception, l'action et la cognition, comme le rôle du corps ou des simulations cognitives internes (Barsalou, 2008). Barsalou (2008) réunit toutes ces approches sous l'appellation « Grounded Cognition » (ou cognition ancrée). Globalement, les approches ancrées de la cognition font l'hypothèse d'interconnexions systématiques entre la perception, l'action et la cognition (Barsalou, 2020 ; Gentsch et al., 2016). Par conséquence, la cognition est conceptualisée comme étant enracinée dans l'action et la perception. Cela signifie que les représentations cognitives internes s'appuient sur les processus sensorimoteurs qui ont lieu durant les expériences vécues. Néanmoins, les divergences entre les multiples conceptions peuvent perturber la compréhension de l'approche théorique globale (Gentsch et al., 2016). C'est pourquoi pour clarifier les différentes conceptions, Gentsch et al. (2016) ont proposé un cadre pertinent pour les aborder. Ils ont suggéré de classer les différentes conceptions selon la fonction (i.e., contrôle moteur, représentation, perception) pour laquelle elles ont été développées dans un premier temps, ainsi que de regarder la manière dont les conceptions décrivent l'acquisition et la constitution de nouvelles capacités (Weber & Vosgerau, 2016). Lorsqu'on s'intéresse à la question de l'acquisition et la constitution des capacités, la question cruciale a posé n'est pas « est-ce que l'action et la perception sont liées » mais « comment ? ». Le terme acquisition décrit la nécessité de posséder une première capacité pour en développer une seconde. Le terme constitution décrit la nécessité de posséder une première capacité pour en développer une seconde mais surtout il décrit la nécessité de conserver la première capacité pour préserver la seconde. Ainsi, Gentsch et al. (2016) ont identifié trois grandes conceptions théoriques : (1) les théories du codage commun, (2) les théories des modèles internes et (3) les théories de la simulation, qui divergent souvent sur la conceptualisation du lien constitutif entre les capacités. Bien que ce manque de cohérence dans les approches ancrées de la cognition mène à d'importantes critiques de la théorie (Goldinger et al., 2016 ; Ostarek & Huettig, 2019), il n'est pas souvent discuté. Une des raisons pourrait être que les chercheurs étudient des aspects spécifiques de l'ancrage qui n'abordent pas directement de plus larges aspects théoriques. Dans le cadre de ce travail de thèse, nous nous concentrerons sur un aspect spécifique de l'ancrage (i.e., les représentations d'action dans la perception des objets manipulables), nous n'adresserons pas de réponse directe concernant les aspects théoriques plus large des approches ancrées de la cognition.

2. Deux illustrations des approches ancrées de la cognition

Dans le cadre du présent travail de thèse, nous allons utiliser des concepts provenant des approches ancrées de la cognition qui furent développer principalement pour étudier la perception. Plus particulièrement, le présent travail de thèse prend racines dans les approches ancrées de la perception de l'espace et de la simulation de propriétés d'objets. En ce sens, il est important d'illustrer les approches qui ont mis l'accent sur le rôle des représentations sensorimotrices dans la perception de l'espace (Previc, 1990, 1998) et sur le rôle des mécanismes de simulation dans les connaissances conceptuelles (Barsalou, 1999, 2008).

a. La perception ancrée de l'espace

Parmi les approches ancrées de la cognition, les chercheurs se sont particulièrement intéressés à la manière dont nous percevons l'espace autour de nous. L'accumulation de preuves expérimentales a mené les chercheurs à affirmer l'existence de deux parties fonctionnellement distinctes de l'espace perçu : l'espace péripersonnel et l'espace extrapersonnel (Previc, 1990, 1998). La distinction fonctionnelle entre ces espaces a été mis en évidence, dans un premier temps, chez le singe au travers d'études neurophysiologiques (Rizzolatti et al., 1981) puis a été étendue chez l'humain au travers d'études chez les patients cérébrolésés (Cowey et al., 1994 ; Halligan & Marshall, 1991). Globalement, l'espace péripersonnel est décrit comme l'espace autour de l'observateur qui intègre ses possibilités directes d'action, alors que l'espace extrapersonnel est décrit comme l'espace au-delà de cette limite. Plus spécifiquement, la représentation de l'espace péripersonnel serait déterminée par la représentation que les gens ont de leur corps, la représentation des contraintes physiologiques auxquelles l'organisme doit faire attention et la représentation des actions simulées que l'individu peut réaliser sur des objets atteignables (Morgado & Palluel-Germain, 2015). La représentation de l'espace extrapersonnel serait moins influencée par toutes ces contraintes. Les mécanismes d'ancrage sous-tendant la perception de l'espace sont encore largement étudiés. Un des paradigmes utilisés pour étudier la perception de l'espace est le paradigme d'atteignabilité. Ce paradigme profite de la distinction fonctionnelle entre les deux espaces pour évaluer l'implication des représentations d'action dans le traitement de différentes catégories de stimuli. Par exemple, les chercheurs ont étudié l'implication des représentations d'action lors de la perception d'objets manipulables (Costantini et al., 2010, 2011 ; Ferri et al., 2011), en comparant le traitement de ces stimuli lorsqu'ils étaient présentés dans l'espace péripersonnel vs. dans l'espace extrapersonnel. Dans le cadre de ce travail de thèse, nous tirerons profit de la distinction fonctionnelle entre les deux espaces pour étudier les propriétés motrices associés aux objets manipulables.

b. Les connaissances conceptuelles ancrées

Dans les années 1990, Barsalou (1999) a proposé une nouvelle approche du stockage des connaissances conceptuelles au niveau cérébral en opposition aux approches amodales de l'époque. Dans son approche appelée « The Perceptual Symbol System (PSS) », Barsalou suppose que les connaissances conceptuelles soient ancrées dans les expériences perceptuelles et motrices. De ce fait, Barsalou propose une approche modale de la cognition qui souligne le rôle des informations sensorimotrices dans les représentations cognitives. En ce sens, la perception, l'action et la cognition partageraient le même système représentationnel. De nombreux appuis empiriques peuvent être cités pour étayer la théorie de Barsalou. Par exemple, il existe une littérature largement documentée montrant l'implication de régions cérébrales habituellement dédiées à des processus sensoriels et moteurs dans le traitement des connaissances conceptuelles (Fernandino et al., 2015 ; Goldberg et al., 2006). Aujourd'hui, l'implication et le rôle fonctionnel des informations sensorimotrices dans l'émergence des états perceptifs et dans la représentation des connaissances conceptuelles sont largement acceptés. Dans les approches ancrées de la cognition, il est admis que les connaissances conceptuelles sont représentées par les expériences perceptives et motrices qui ont eu lieux lorsque l'individu a interagit avec l'élément auquel le concept fait référence. Lorsqu'un élément est rencontré une nouvelle fois, des mécanismes de simulation feraient des inférences sur les propriétés associées à cet élément en se basant sur sa représentation.

Synthèse des approches ancrées de la cognition

Dans un premier temps, nous avons dressé un tableau non-exhaustif des multiples approches ancrées de la cognition. L'existence de multiple approches ancrées de la cognition est principalement dû à la diversité des fonctions cognitives sur lesquelles elles mettent l'accent (e.g., la perception de l'espace, les connaissances conceptuelles). Les multiples approches ne sont pas toujours cohérentes lorsqu'elles décrivent la relation entre les capacités perceptives et motrices, mais globalement, elles supposent que les deux sont étroitement connectées et font partie des représentations cognitives. Par conséquent, elles soutiennent une conception modale de la cognition qui met l'accent sur le rôle des informations sensorimotrice dans les représentations cognitives.

Dans un second temps, nous avons illustré les approches ancrées de la cognition en nous centrant sur le rôle des représentations sensorimotrices dans (1) la perception de l'espace et (2) le rôle des mécanismes de simulation dans les connaissances conceptuelles. Nous avons mis en évidence que la perception de l'espace peut être divisée en deux régions fonctionnellement distinctes de l'espace autour d'un individu en fonction de ses contraintes d'action (i.e., l'espace péripersonnel et l'espace extrapersonnel). Nous avons soutenu que cette distinction fonctionnelle entre les deux espaces constitue une excellente opportunité, dont nous pouvons tirer avantage, pour étudier les interconnexions entre la perception et l'action, en comparant le traitement de catégories de stimuli dans chacun des espaces. D'un point de vue plus théorique, nous avons expliqué comment les connaissances conceptuelles sont ancrées dans les expériences perceptives et motrices.

Synthèse globale

Globalement, les récentes approches de la perception supposent que la perception est étroitement interconnectée avec l'action. La perception est vue comme un phénomène actif qui guide l'action et qui est modulé par l'action dans l'environnement. Les organismes percevraient l'environnement en fonction des actions potentielles qu'il offre (i.e. affordances). De plus, il a été montré que l'action et la perception partagent de nombreux corrélats cérébraux et sont donc deux systèmes neurophysiologiques qui ne montrent pas de distinction claire. Cela suggère que nous sommes phylogénétiquement et biologiquement organisés pour traiter la perception et l'action de la même manière. Les théoriciens de approches ancrées de la cognition utilisent habituellement ces découvertes neurophysiologiques pour appuyer l'idée que la perception et l'action feraient partie des représentations cognitives. Par conséquent, ils soutiennent une conception modale de la cognition qui met l'accent sur le rôle des informations sensorimotrices dans les représentations cognitives. Ainsi, la perception, l'action et la cognition partageraient le même système représentationnel. Par exemple, les chercheurs supposent que les représentations de l'espace et des connaissances conceptuelles soient ancrées dans les expériences sensorimotrices. La perception de l'espace serait divisée en deux régions fonctionnellement distinctes de l'espace autour d'un individu en fonction de ses contraintes d'action (i.e., l'espace péripersonnel et l'espace extrapersonnel). Les connaissances conceptuelles seraient façonnées par l'information sensorimotrices qui est survenue lors de l'expérience perceptive qui a produit la connaissance. Le présent travail de thèse s'inscrit dans ces conceptions du couplage perception-action, et principalement dans les approches ancrées de la cognition, en supposant que la perception et l'action sont étroitement interconnectées et jouent un rôle important dans la cognition. Dans le prochain chapitre, nous évoquerons le rôle des informations motrices lors de la perception des objets manipulables.

CHAPITRE 2. ACTIVATION D'INFORMATIONS MOTRICES LORS DE LA PERCEPTION D'OBJETS MANIPULABLES

Dans le premier chapitre, nous avons souligné les interconnexions entre la perception et l'action. Conformément à Gibson (1986), nous avons supposé que la perception joue un rôle fondamental dans l'action et que la perception est un phénomène actif qui émerge de l'action et de l'exploration de l'environnement. Nous avons ensuite postulé que les traitements de la perception et de l'action partagent de nombreux corrélats cérébraux chez le singe et chez l'humain, suggérant une organisation phylogénétique et biologique similaire des deux processus. Les chercheurs ont donc été amené à considérer l'existence d'étroites interconnexions entre la perception et l'action au niveau cérébral. En accord avec les approches ancrées de la cognition (Barsalou, 2008, 2020), nous sommes allés plus loin en suggérant que la perception et l'action sont étroitement reliées et font partie des représentations cognitives. Par conséquent, nous soutenons une conceptualisation modale de la cognition, et soulignons le rôle des informations sensorimotrices dans les représentations. Toujours dans le domaine des approches ancrées de la cognition, les auteurs ont emprunté le terme « affordance » à Gibson (1979), et ont modifié sa définition initiale pour y inclure des aspects représentationnels cérébraux et cognitifs. Dans ce chapitre, nous passerons en revue cette littérature.

I. Automaticité, représentations et traitement cérébral

Selon Gibson (1979), le terme « affordance » fait référence aux possibilités d'action qu'un organisme possède dans son environnement en fonction de ses contraintes d'action. Les affordances sont donc considérées comme de propriétés environnementales. Cependant, depuis que Gibson a défini le terme « affordance », le terme a été utilisé de nombreuses manières différentes. A titre d'exemple, des conceptions plus restrictives se sont concentrées sur l'activation d'affordance lors de la perception d'objets manipulables au lieu de considérer tous les éléments dans l'environnement. Ces conceptions sont souvent en accord avec les approches ancrées de la cognition (Barsalou, 2008) et considèrent que les affordances ne sont pas des propriétés de l'environnement. Au contraire, les affordances consisteraient en des représentations mentales des propriétés sensorimotrices et sémantiques des informations motrices associées aux objets manipulables. De plus, les affordances possèderaient leurs propres corrélats cérébraux. En ce sens, les auteurs rejettent la vision des affordances de Gibson, proposant un point de vue plus représentationnel. Les approches représentationnelles actuelles des affordances constituent le cadre du présent travail de thèse. Dans ce travail de thèse, nous limiterons donc notre intérêt aux approches cognitives et neuroscientifiques qui se concentrent sur les objets manipulables (Borghi & Riggio, 2015; Buxbaum & Kalénine, 2010; Ellis & Tucker, 2000; Osiurak et al., 2017). Parmi les approches représentationnelles des affordances, de nombreuses positions théoriques ont émergé pour décrire les propriétés motrices associées aux objets manipulable (voir Osiurak et al., 2017, pour une revue de littérature récente). Les différentes théories ont organisé leur débat autour de trois aspects : l'automaticité de l'activation des affordances, la nature des représentations des affordances et les réseaux cérébraux impliqués dans la perception des affordances. L'automaticité de l'activation des affordances est discutée dans la **Box 1. Automaticité**. La nature des représentations des affordances et les réseaux cérébraux impliqués dans la perception des affordances sont évoqués ci-dessous dans la description des conceptions représentationnelles des affordances. Il faut noter que la majorité des conceptions supposent l'existence de plusieurs types d'affordances, impliquant des degrés d'automaticité, des natures de représentation et des corrélats cérébraux variés. Globalement, les conceptions considèrent la perception d'affordances comme une activation des représentations d'éléments d'action lors de la perception d'objets (tel que les gestes d'atteinte, de saisie ou les interaction typiques associées aux objets). Dans la section suivante, nous résumerons les approches les plus pertinentes au regard du présent travail de thèse : les micro-affordances (Ellis

& Tucker, 2000; Tucker & Ellis, 1998), la distinction entre affordances structurelles et fonctionnelles (Buxbaum & Kalénine, 2010) et la distinction entre affordances stables et variables.

Box 1. Automaticité

Parmi les propriétés d'affordance en questionnement dans la littérature, l'automaticité de l'activation des affordances n'est pas simple à traiter. Certains auteurs suggèrent que les affordances sont automatiquement activées (Ellis & Tucker, 2000), alors que d'autres suggèrent que non (Borghi & Riggio, 2015; Buxbaum & Kalénine, 2010).

Le problème majeur dans la définition de l'automaticité de l'activation des affordances ne concerne pas les désaccords dans la littérature, mais plutôt le fait que les auteurs utilisent des arguments différents contre l'automaticité. Les arguments principaux sont l'influence des modulations du contexte (Borghi & Riggio, 2015) et la modulation par l'intention (Buxbaum & Kalénine, 2010).

- Pour Borghi & Riggio (2015), les modulations contextuelles - incluant l'espace, le contexte verbal, le contexte visuel, etc. - sont souvent utilisées. Cela sera également le cas dans le présent travail de thèse.

- Pour Buxbaum & Kalénine (2010), les modulations d'intention - incluant les demandes de la tâche, la production d'action, l'entraînement moteur, etc. - sont souvent utilisés. L'intention ne sera pas directement évoquée dans ce travail de thèse, sauf en considérant les demandes de la tâche.

En se basant sur ces observations, les auteurs suggèrent que les affordances ne sont pas toujours activées ou dépendent des intentions d'action et ils réfutent la propriété d'automaticité d'activation des affordances.

Dans le présent travail de thèse, nous considérerons que ni les modulations contextuelles, ni les modulations d'intention constituent un argument clair pour réfuter la propriété d'automaticité. Selon notre avis, une confusion est présente dans l'utilisation du terme « automaticité ». Le terme devrait faire références aux conséquences de l'activation d'affordances et non l'activation elle-même. Les arguments susmentionnés démontrent clairement que les conséquences de l'activation des affordances ne sont pas automatiques. Par conséquent, nous ne prendrons pas d'avis tranché sur la propriété d'automaticité des affordances.

1. Micro-affordances

Au début des années 1990, un groupe de chercheurs s'est intéressé à l'implication des composants d'action dans la représentation des objets manipulables (Tucker & Ellis, 1998). Ils ont redéfini le terme d'affordance et ont proposé le terme de « micro-affordances » (Ellis & Tucker, 2000). Les micro-affordances font références à des informations motrices automatiquement et temporairement activées lors de la perception d'objets manipulables (Ellis & Tucker, 2000; Tucker & Ellis, 2001). Plus tard, ces mêmes chercheurs ont proposé de faire la distinction entre les micro-affordances extrinsèques et intrinsèques (Derbyshire et al., 2006; Tucker & Ellis, 2004). Les micro-affordances extrinsèques correspondraient aux possibilités d'action liées aux caractéristiques visuelles des objets qui doivent être traitées en direct à cause de leur imprévisibilités (e.g., la localisation ou l'orientation d'un objet dans l'espace). Les micro-affordances extrinsèques seraient traitées par la voie visuelle dorsale (cf. Chapitre 1). Les micro-affordances intrinsèques correspondraient aux possibilités d'action liées aux représentations des caractéristiques visuelles des objets (e.g., leur taille, leur forme) acquises au travers d'interactions visuomotrices. Les micro-affordances extrinsèques seraient traitées en direct et ne seraient pas représentées alors que les micro-affordances intrinsèques seraient représentés au niveau sensorimoteur.

2. Affordances structurelles et fonctionnelles

Buxbaum & Kalénine (2010) ont proposé de faire la distinction entre les affordances structurelles et les affordances fonctionnelles. Les affordances structurelles font références à l'activation de gestes associés à la saisie typique des objets en considérant leurs caractéristiques volumétriques et seraient représentées à un niveau sensorimoteur. Elles seraient automatiquement et temporairement activées. Les affordances fonctionnelles font références à l'activation de gestes associés à l'utilisation typique des objets en considérant leur représentation conceptuelle et seraient représentées à un niveau sémantique. Elles seraient activées en fonction du contexte et seraient plus persistantes dans le temps. De récentes découvertes concernant le modèle visuel à double voies (voir le Chapter 1 pour une description, Goodale et al., 1992) ont proposé de diviser la voie visuelle dorsale en deux sous-systèmes (Rizzolatti & Matelli, 2003) : le système dorso-dorsal et le système ventro-dorsal. Au regard des caractéristiques de ces systèmes, Buxbaum & Kalénine (2010) ont supposé que les affordances structurelles seraient traitées par le système dorso-dorsal et les affordances fonctionnelles par le système ventro-dorsal.

3. Affordances variables et stables

Borghi and Riggio (2009, 2015) ont proposé de faire la distinction entre les affordances variables et les affordances stables. Initialement appelée affordances temporaires (Borghi & Riggio, 2009), les affordances variables font références aux composants d'action activés par les caractéristiques visuelles imprédictibles des objets (e.g., leur orientation). Elles sont décrites comme étant dépendantes du contexte et nécessiteraient un traitement direct. Au contraire, les affordances stables font références aux composants d'action activés par les caractéristiques visuelles des objets qui ne sont pas dépendantes du contexte. Elles seraient traitées par le biais de représentation formées par des associations répétitives entre les caractéristiques visuelles des objets et les actions typiques que nous réalisons avec les objets. De récentes découvertes en lien avec les travaux sur les neurones visuomoteurs (Raos et al., 2006; Rizzolatti et al., 1988; Rizzolatti & Fadiga, 1998) ont proposé de diviser la voie ventro-dorsale (Rizzolatti & Matelli, 2003) en deux sous-systèmes (voir Orban & Caruana, 2014 pour des explications plus détaillées) : un système plus dorsale que l'autre. Les affordances variables seraient traitées par le système le plus dorsal et les affordances stables par le système le plus ventral.

Synthèse intermédiaire

Les principales conceptions de la perception des affordances soutiennent fortement l'idée que les affordances émergent de la relation entre celui qui perçoit et l'environnement. Bien que la plupart des conceptions se focalisent sur les perceptions des affordances d'objets manipulables, elles rejoignent plusieurs aspects de l'approche écologique de Gibson, en considérant que la perception des affordances est flexible et peut être mise à jour au travers de nouvelles expériences motrices. En revanche, elles ne s'accordent pas avec l'approche de Gibson en considérant l'implication de représentations neuronales. Selon ces approches représentationnelles, certaines affordances correspondraient à une activation de représentations sensorimotrices des composants d'action lors de la perception de caractéristiques visuelles d'objets (i.e., les micro-affordances extrinsèques, les affordances structurales et variables). D'autres affordances correspondraient à une activation de représentations plus sémantiques apprises via de multiples associations entre les caractéristiques visuelles des objets et des actions spécifiques réalisées avec eux (i.e., les affordances fonctionnelles). Une hypothèse commune aux trois approches présentées dans cette section concerne le fait qu'un objet peut activer plusieurs affordances différentes, comme ces gestes de saisie et d'utilisation.

II. Activation d'affordance lors de la perception d'objets manipulables

L'activation d'affordance lors de la perception d'objets manipulables a été largement étudiée dans la littérature. Les premières études comportementales et neurophysiologiques ont souligné une implication rapide et automatique des informations motrices lors du traitement perceptif et conceptuel des objets. Cependant, des découvertes plus récentes ont nuancé l'hypothèse initiale d'une automaticité de l'activation des affordances lors de la perception d'objets. La littérature a au contraire montré des modulations contextuelles notables de l'activation d'affordance. Les chercheurs se sont aussi interrogés sur le type de propriétés motrices activées et le moment auquel ces propriétés s'activent lors de la perception d'objets. Nous résumerons brièvement les preuves expérimentales en faveur de l'hypothèse d'une automaticité de l'activation des affordances. Nous résumerons ensuite les preuves en faveur de modulations contextuelles de l'activation des affordances. Pour finir, nous évoquerons des études sur l'activation flexible d'affordances.

1. Hypothèse initiale d'une automaticité d'activation des affordances

Au niveau comportemental, l'automaticité d'activation des affordances est classiquement soutenue en montrant que des jugements sur les caractéristiques générales d'un objet sont facilités par ses propriétés visuelles, telle que sa taille (Borghi et al., 2007; Ellis et al., 2007; Ellis & Tucker, 2000) ou son orientation spatiale (Dekker & Mareschal, 2014; Fischer & Dahl, 2007; Pavese & Laurel, 2002; Pellicano et al., 2010; Tucker & Ellis, 1998), qui sont compatibles avec des composants d'action non pertinents pour la tâche de jugement. Parmi ces paradigmes, on retrouve le paradigme de compatibilité anse-réponse (Fischer & Dahl, 2007; Pellicano et al., 2010; Tucker & Ellis, 1998) ou le paradigme d'amorçage (Borghi et al., 2007; Collette et al., 2016). Cependant, ces paradigmes sont confrontés à de nombreuses critiques (Borghi et al., 2007; Buxbaum & Kalénine, 2010; Riggio et al., 2008; Symes et al., 2005; Yang & Beilock, 2011). Nous évoquerons ces critiques dans le premier chapitre expérimental de ce travail de thèse. Additionnellement, des études neurophysiologiques sont souvent utilisées comme argument pour soutenir l'hypothèse d'une automaticité de l'activation d'affordances. Il existe de nombreuses études en neuroimagerie qui suggèrent que la perception ou l'identification d'objets manipulables induit une activation des aires motrices cérébrales recouvrant les réseaux neuronaux impliqués dans les actions dirigées vers les objets (Chao & Martin, 2000; Creem-Regehr & Lee, 2005; Gerlach et al., 2002; Grafton et al., 1997; Grèzes et al., 2003; Johnson-frey et al., 2005; Muthukumaraswamy & Johnson, 2004). Des études en électroencéphalographie (EEG) ont également montré une implication rapide des régions motrices pendant le traitement des objets manipulables (e.g., Goslin, 2012; Kiefer et al., 2011; Proverbio, 2012; Proverbio et al., 2011, 2013; Vainio et al., 2014; Wamain et al., 2016, 2018). Ensemble, ces études montrent que la perception et l'identification d'objets manipulables induisent une activation rapide et automatique des régions motrices cérébrales impliquées dans le traitement des actions dirigées vers les objets.

2. Impact du contexte sur l'activation des affordances d'objets

Des découvertes récentes dans la recherche sur les affordances ont fortement nuancé l'hypothèse initiale d'une automaticité de leur activation lors de la perception d'objets manipulables. Plus particulièrement, il a été proposé que la perception des affordances puisse être sensible au contexte de perception de l'objet. Il a notamment été montré que la perception des affordances varient entre les individus selon leur niveau d'expériences motrices (Bellebaum et al., 2013; Chrysikou et al., 2017; Kiefer et al., 2007; Rüther et al., 2014; Watson et al., 2013; Yee et al., 2013), questionnant le rôle de l'augmentation du nombre d'expériences motrices au cours du développement d'un individu. La perception des affordances semble également sensible à des variables environnementales, telle que la position de l'objet dans l'espace (Costantini et al., 2010, 2011; Ferri et al., 2011; Kalénine et al., 2016; Wamain et al., 2016, 2018). Ces études ont globalement montré que les objets manipulables activent préférentiellement leurs affordances dans l'espace péripersonnel. Additionnellement, des études électrophysiologiques ont montré une modulation de l'activation du système moteur cérébral, en réponse à la perception d'affordance (Cardellicchio et al., 2011; Wamain et al., 2016), similaire au pattern comportemental préalablement observé (Costantini et al., 2010, 2011; Ferri et al., 2011; Kalénine et al., 2016; Wamain et al., 2016, 2018). Ensemble, ces études ont mis en évidence que le système moteur est préférentiellement activé quand les objets manipulables sont présentés dans l'espace péripersonnel.

En plus des modulations contextuelles de l'activation d'affordance, il n'est pas évident de déterminer quelle propriété d'action associée aux objets manipulables est activée et quand elle est activée, un seul objet pouvant évoquer plusieurs affordances en fonction des différentes interactions que nous avons avec lui (Borghi & Riggio, 2015; Buxbaum & Kalénine, 2010; Tucker & Ellis, 2004). L'activation d'affordances étant modulée par le contexte, les chercheurs se sont donc demandés si plusieurs affordances associées à un même objet pouvaient être activées différemment selon le contexte (Costantini et al., 2011; Kalénine et al., 2014). Costantini et al. (2011) ont montré que lorsqu'ils sont présentés dans l'espace péripersonnel, les objets manipulables activent leurs affordances structurelle et fonctionnelle (Buxbaum & Kalénine, 2010). Kalénine et al. (2014) ont montré que les affordances structurelle et fonctionnelle étaient activées différemment en fonction de la scène visuelle dans laquelle ils sont présentées. (Kalénine et al., 2014). Pour finir, des études récentes ont montré des dynamiques temporelles différentes dans l'activation des affordances structurelles et fonctionnelle (Lee et al., 2012, 2018). Ils ont observé une activation plus tardive mais plus persistante des affordances fonctionnelles comparativement aux affordances structurelles.

Synthèse intermédiaire

Lorsqu'on considère l'accumulation de preuves, il est évident d'accepter que la perception d'objets manipulables évoque la représentation des actions typiques que nous réalisons avec eux (i.e., affordances). Les études initiales ont fortement suggéré que percevoir un objet manipulable induisait une activation automatique de leurs affordances. Plusieurs paradigmes ont été construit avec cet objectif. Cependant, ces paradigmes font face à des problématiques méthodologiques et/ou théoriques majeures. De même, les études en neuroimageries citées habituellement pour argumenter en faveur d'une automaticité de l'activation des affordances sont critiquées. Ces critiques ont nuancé la conclusion habituelle des études sur l'automaticité de l'activation des affordances. Comme nous le mentionnons dans la **Box 1. Automaticité**, l'automaticité de l'activation des affordances est fortement débattue. Nous avons expliqué un des arguments contre l'hypothèse initiale d'automaticité, qui est les modulations contextuelles. Nous avons souligné que l'activation d'affordance est modulée par l'expériences motrices des individus, la position dans l'espace de l'objet en rapport avec l'observateur, et que plusieurs affordances associées à un même objet pouvaient être activées différemment en fonction du contexte dans lequel l'objet manipulable est perçu. Bien que nous ayons présenté ces arguments en opposition, nous ne considérons pas les deux arguments comme étant pleinement contradictoire.

Synthèse générale

Globalement, les conceptions représentationnelles récentes se focalisent sur l'activation d'affordance associée à la perception des objets manipulables. Les affordances sont habituellement décrites comme des informations motrices qui émergent de la relation entre l'observateur et l'objet perçu. Elles s'accordent avec la description initiale de Gibson en considérant que la perception d'affordance est un phénomène flexible et qui peut être actualisé aux travers de nouvelles expériences motrices mais elles ne s'accordent pas avec Gibson lorsqu'elles considèrent l'implication de représentations cognitives et neuronales. L'automaticité de l'activation des affordances, la nature des représentations cognitives et les systèmes cérébraux impliquées dans leur perception sont trois sujets de débat. Plusieurs auteurs suggèrent l'existence de plusieurs types d'affordances ayant différents degrés d'automaticité, différents niveaux de représentations et différents corrélats cérébraux. Conformément à l'objectif du présent travail de thèse, nous avons orienté la discussion autour du débat de l'automaticité. Nous avons examiné les preuves comportementales et neurophysiologiques cohérentes avec l'hypothèse initiale d'une automaticité de l'activation d'affordance. Cependant, nous avons souligné l'existence de critiques méthodologiques et/ou théoriques de ces études initiales. Nous avons ensuite souligné l'existence de preuves empiriques montrant des modulations individuelles et contextuelles de l'activation d'affordance. De plus, nous avons souligné que différentes affordances pouvaient être évoquées par différents contexte. Pour conclure, bien que nous ayons présenté les arguments d'automaticité et de modulation contextuelle de l'activation d'affordance en opposition, nous ne tirons pas une conclusion tranchée sur le débat de l'automaticité. Néanmoins, nous insistons sur l'importance de considérer que l'influence de l'activation d'affordance sur le traitement des objets manipulables se fait de manière flexible suivant des modulations inter-individuelles et intra-individuelles notables.

CHAPTER 3. CONSEQUENCES DE LA CO-ACTIVATION D'AFFORDANCES

Dans le Chapitre 1, nous avons souligné l'existence de connections étroites entre l'action et la perception visuelle. Nous avons mis en évidence que la perception et l'action partagent de nombreux corrélats cérébraux et font partie des représentations cognitives. Dans le Chapitre 2, nous avons soutenu que dans le cadre de la perception d'objets manipulables, la plupart des conceptions représentationnelles considèrent maintenant que percevoir un objet manipulable peut induire une activation des actions habituellement réalisées avec ces objets (i.e., affordances). Nous avons présenté des preuves empiriques en faveur d'une automaticité de l'activation d'affordance. Nous avons contesté l'hypothèse initiale d'une automaticité sans prendre de conclusion définitive, en contrastant cette hypothèse avec les preuves empiriques mettant en évidence l'existence de modulations contextuelles de l'activation d'affordance. De plus, nous avons souligné que les objets manipulables peuvent évoquer différentes affordances en fonction du contexte. Dans le Chapitre 3, nous allons soutenir l'hypothèse que la perception d'affordance puisse parfois être préjudiciable pour le traitement perceptif des objets manipulables. Plus particulièrement, différentes affordances peuvent dans certains cas être co-activées par un même objet, ayant des conséquences négatives sur le traitement perceptif de cet objet.

I. L'hypothèse de la compétition entre affordances

Nous avons déjà déterminé que percevoir un objet manipulable active les actions habituellement réalisées avec cet objet (i.e., affordances). Nous avons également souligné que les objets manipulables sont associés à différentes affordances qui peuvent être activées en fonction du contexte (Kalénine et al., 2014; Lee et al., 2012). En outre, nous pouvons facilement noter que l'environnement est rempli d'objets manipulables. Si tous ces objets évoquent leurs affordances en une seule fois ou si un objet évoque plusieurs affordances, comment le système fait pour gérer toutes ces activations et choisir correctement parmi elles ? Cette question a été traité par de nombreux modèles (voir Thill et al., 2013 pour revue) et tous suggèrent que les affordances rivalisent pour être sélectionnées (Caligiore & Borghi, 2010; Cisek, 2007; Cisek & Kalaska, 2010; Fagg & Arbib, 1998). Tous les modèles supposent que lorsque plusieurs affordances sont activées par la perception d'un objet manipulable, elles rivalisent entre elles pour accéder aux processus de traitement suivant et cette compétition subit des signaux permettant de sélectionner l'affordance pertinente. Par exemple, l'influent modèle neurobiologique de Cisek (Cisek, 2007; Cisek & Kalaska, 2010) propose que l'activation d'affordances de l'environnement (i.e., spécification des affordances) et la compétition et la sélection vers l'affordance pertinente (i.e., sélection des affordances) sont deux processus parallèles. Plus précisément, ce modèle suppose que quand le système est confronté à l'activation de plusieurs affordances, deux processus sont impliqués afin de spécifier et sélectionner les affordances pertinentes. Les paramètres de chaque affordance seraient spécifiés le long du cortex pariétal. Diverses sources d'information sont utilisées pour spécifier et sélectionner les paramètres des affordances pertinentes. Quand le système résout la compétition, l'affordance sélectionnée est transmise au cortex prémoteur pour agir. Nous ferons une description brève des différentes études conçues pour étudier l'impact de la co-activation d'affordances sur la perception des objets manipulables.

Box 2. Définitions des objets conflictuels and non-conflictuels

Les conséquences de la co-activation d'affordances ont été étudiées à l'aide d'objets associés à plusieurs affordances. Bien souvent, les objets sont associés à des gestes de saisie (i.e., affordance structurelle) et d'utilisation (i.e., affordance fonctionnelle) différents (e.g., une calculatrice).

Dans la majorité des études présentées (Bub et al., 2018; Jax & Buxbaum, 2010, 2013; Kalénine et al., 2016; Lee et al., 2018; Wamain et al., 2018), les objets associés à des affordances structurelle et fonctionnelle différentes sont appelés objets « conflictuels » et sont comparés au traitement d'objets « non-conflictuels » (i.e., des objets associés à des gestes de saisie et d'utilisation similaire, e.g., un verre). Le terme « conflictuel » a été proposé par Jax et Buxbaum (2010, 2013) qui ont souligné que ces objets sont associés à des actions conflictuelles.

Une seule étude mentionnée ci-dessous n'utilise par le terme « conflictuel » (Schubotz et al., 2014). Dans cette étude, les chercheurs se sont plutôt intéressés aux différentes actions d'utilisation que nous pouvons réaliser avec une paire d'objets. Par exemple, un couteau et une pomme sont associés à l'action de couper la pomme ou d'éplucher la pomme.

Dans le présent travail de thèse, nous utiliserons les termes d'objets « conflictuels » et « non-conflictuels » suivant la définition de Kalénine et al. (Kalénine et al., 2016; Wamain et al., 2018). Un objet conflictuel est associé à différentes affordances structurelle et fonctionnelle. Un objet non-conflictuel est associé à des affordances structurelle et fonctionnelle similaires.

II. Evaluation comportementale de la co-activation d'affordances

Classiquement, dans les études évaluant l'impact de la co-activation de différentes affordances sur la production d'action (Bub et al., 2018; Jax & Buxbaum, 2010, 2013), les participants doivent produire des actions dirigées vers les objets et placer leur main dominante sur l'objets comme s'ils allaient le saisir ou l'utiliser. Les deux actions sont réalisées de manière alternative pour déterminer l'influence de la pré-activation d'une affordance sur le traitement de la seconde lors de la planification de l'action. Les chercheurs enregistrent souvent le temps d'initiation de l'action (i.e., le moment entre la présentation du stimulus et le début de l'action) afin de pouvoir étudier directement le processus cognitif et non des différences de cinématique de mouvement entre les actions de saisie et d'utilisation. Généralement, les chercheurs mettent en évidence un coût de traitement. Ce coût de traitement se caractérise par des temps d'initiation d'action plus long pour les objets conflictuels comparativement aux objets non-conflictuels (Bub et al., 2018; Jax & Buxbaum, 2010, 2013). Ces études montrent un impact négatif de la co-activation d'affordances sur la planification d'action dirigée vers des objets manipulables.

Des études récentes ont étudié l'impact de la co-activation d'affordances sur la simple perception d'objets manipulables (Kalénine et al., 2016; Wamain et al., 2018). Dans ces études, des images 3D d'objets conflictuels et non-conflictuels étaient présentés à différentes distances du participant. Les participants devaient catégoriser les objets selon deux types de jugements : « l'objet est-il atteignable et saisissable ? » et « l'objet est-il un objet de la cuisine ? ». Indépendamment de la tâche, les résultats ont montré des temps de catégorisation plus long pour les objets conflictuels comparativement aux objets non-conflictuels mais uniquement dans l'espace péripersonnel des participants (Kalénine et al., 2016). Cette étude montre que la co-activation de différentes affordances induit une compétition. Cette compétition entre différentes affordances crée un coût de traitement perceptif qui dépend de la possibilité d'action de l'individu.

Synthèse intermédiaire

Globalement, ces études fournissent des preuves comportementales soutenant l'hypothèse selon laquelle différentes affordances structurelle et fonctionnelle associées à un même objet peuvent rivaliser l'une contre l'autre et cette compétition peut être préjudiciable pour la production d'action et le traitement perceptif des objets chez l'adulte. Cependant, bien qu'elles constituent des preuves importantes montrant les conséquences de la co-activation d'affordances sur la perception des objets, ces études ne nous informent pas sur les mécanismes à l'œuvre dans ce coût de traitement. Ce coût de traitement observé lors de la production d'action et la perception d'objets pourraient être la conséquence de mécanismes complémentaires.

III. Evaluation neurophysiologique de la co-activation d'affordances

Des dissociations entre les régions cérébrales impliquées dans la spécification des affordances par opposition à la sélection d'affordance lors de la perception et la réalisation d'actions dirigées vers des objets ont été récemment fournies (Schubotz et al., 2014; Watson & Buxbaum, 2016). Watson & Buxbaum (2016) ont demandé à des patients cérébrolésés de réaliser des pantomimes de gestes d'utilisation sur des objets conflictuels et non-conflictuels. Leurs résultats ont montré que des aires cérébrales plus postérieures (e.g., circonvolution temporale moyenne postérieure et le cortex antérieur intra-pariétal) sont impliquées dans le traitement des affordances en général, alors que des aires plus antérieures (e.g., aires motrices supplémentaires et la circonvolution frontale inférieure) sont impliquées dans la gestion de la compétition entre plusieurs actions possibles. L'étude en neuroimagerie de Schubotz et al. (2014) montrent des résultats similaires qui suggèrent que les aires cérébrales postérieures sont impliquées dans le processus de spécification des affordances, alors que les aires plus antérieures sont impliquées dans le processus de sélection des informations pertinentes pour résoudre la compétition.

L'implication du système dorsal fronto-pariétal dans la résolution de la compétition entre affordances a aussi été étudié à l'aide de l'électroencéphalographie (Wamain et al., 2018). Dans cette étude, les chercheurs se sont intéressés à la désynchronisation du rythme Mu (μ) au-dessus des régions centro-pariétales. Le rythme μ correspond à une gamme de fréquence de 8 à 12 Hz qui est habituellement associée à l'activité du système moteur (Pineda, 2005). Sa désynchronisation représenterait la résonance motrice associées au traitement de l'information motrice de l'environnement. A la suite des travaux de Kalénine et al. (2016), l'étude de Wamain et al. (2018) a été réalisée afin d'évaluer l'impact de la co-activation de différentes affordances structurelle et fonctionnelle sur la désynchronisation du rythme µ. Wamain et al. (2018) ont observé une réduction et même une suppression de la désynchronisation du rythme µ lors de la perception d'objets conflictuels comparativement aux objets non-conflictuels mais seulement dans l'espace péripersonnel. Ces résultats suggèrent que la compétition entre différentes affordances structurelle et fonctionnelle affecte la résonance motrice associée avec le système moteur. Plus précisément, ils montrent que la résonance motrice du système moteur lors de la perception d'objets manipulable ne reflète pas la perception d'affordance dans sa globalité mais plutôt des mécanismes de sélection d'affordance. Par conséquent, la désynchronisation du rythme µ constitue un marqueur électrophysiologique pertinent pour étudier les processus de sélection lors de la compétition entre affordances.

Synthèse générale

Dans ce chapitre, nous avons décrit les récents modèles neurobiologiques qui expliquent la perception de plusieurs affordances. Nous avons discuté de la manière dont les paramètres d'action sont perçus dans l'environnement, de la manière dont ils sont sélectionnés et des informations utilisées pour résoudre la compétition entre ces paramètres. Nous avons discuté des quelques preuves expérimentales démontrant les conséquences de la co-activation de différentes affordances sur le traitement des objets. Plus particulièrement, nous avons souligné que les affordances structurelle et fonctionnelle associée à un même objet pouvait rivaliser entre elles et être préjudiciable pour la perception et la production d'action chez l'adulte. Puis, nous avons déterminé que le coût de traitement observé implique certainement des mécanismes neurocognitifs distincts, à savoir la spécification et la sélection des affordances. Enfin, nous avons suggéré que l'étude de la résonance motrice neuronale (i.e., µ rythme) en utilisant l'électroencéphalographie est une méthodologie appropriée pour évaluer l'impact de la co-activation de différentes affordances sur la perception des objets. Dans la dernière partie de ce chapitre, nous allons fixer les objectifs du présent travail de thèse conformément à ce domaine de recherche en pleine expansion.

OBJECTIFS DU PROJET DE THESE

Le présent travail de thèse est directement en lien avec les études précédentes évaluant l'impact de la co-activation de plusieurs affordances sur le traitement perceptif des objets (Kalénine et al., 2016; Wamain et al., 2018) lorsque l'individu perçoit un seul objet manipulable. Le projet a pour objectif d'évaluer comment des variabilités intra-individuelles et interindividuelles modulent l'impact de la compétition entre affordance lors de la perception d'objets, au travers d'indicateurs comportementaux (i.e., temps de réponse) et électrophysiologiques (i.e., désynchronisation du rythme µ). Au regard de la variabilité interindividuelle, nous avons cherché à identifier les périodes d'âge où l'individu est le plus sensible à la compétition entre affordances. De plus, nous avons exploré l'implication respective des mécanismes de spécification et de sélection des affordances dans les changements de sensibilité à la compétition entre affordance, au travers de mesures indépendantes. Au regard de la variabilité intra-individuelle, nous avons cherché à déterminer si les informations contextuelles peuvent moduler la compétition entre affordance et contribuer à résoudre la compétition lors du traitement perceptif des objets.

Le projet sera divisé en trois chapitres expérimentaux. Le premier chapitre présentera des investigations préalables qui ont pour objectif de préciser les propriétés d'actions qui sont réellement évaluées avec différents paradigmes conçus pour mesurer la perception des affordances. Le second chapitre évaluera comment l'impact de la co-activation de plusieurs affordances sur le traitement perceptif des objets évolue au cours du développement, et évaluera l'implication des mécanismes de spécification et de sélection des affordances dans la compétition entre affordances. Pour finir, le troisième chapitre rapportera une étude réalisée à l'aide de l'électroencéphalographie qui explore l'influence d'un contexte verbal sur la résolution de la compétition entre affordances en se concentrant sur la résonance motrice neuronale (i.e., désynchronisation du rythme μ).

Le deuxième chapitre concernera l'identification de la trajectoire développementale des conséquences de la co-activation de plusieurs affordances sur le traitement perceptif des objets manipulables. Au regard des modèles d'affordance récent (Cisek, 2007; Cisek & Kalaska, 2010), nous avons supposé que l'impact négatif de la compétition entre affordances sur le traitement perceptif des objets pouvait résulter de la contribution conjointe de deux mécanismes, la spécification et la sélection d'affordances (Schubotz et al., 2014; Watson & Buxbaum, 2016), et pouvait montré une trajectoire développementale non-linéaire. Cinq groupes d'âge de 8 ans à l'âge adulte ont participé (N = 131). De la même manière que dans les études précédentes (Kalénine et al., 2016; Wamain et al., 2018), les participants ont réalisé des jugements perceptifs sur différents objets présentés en 3D dans un environnement virtuel afin d'évaluer le coût perceptif de la compétition entre affordances. Les participants ont réalisé deux tâches complémentaires, une tâche d'amorçage par l'action et une tâche de Simon pour mesurer les mécanismes de spécification et de sélection d'affordances respectivement.

Le troisième chapitre concernera l'influence du contexte verbal sur la résolution de la compétition entre affordances. Il existe de nombreuses preuves que l'activation d'affordance est sensible à plusieurs facteurs contextuels (voir Chapitre 2). Les affordances sont majoritairement activées lorsque les objets sont perçus dans l'espace péripersonnel (Wamain et al., 2016). Cet effet est amplifié en présence d'un contexte verbal congruent (Costantini et al., 2011). Au niveau neurophysiologique, le coût sélectif pour les objets conflictuels se reflète par une réduction de la désynchronisation du rythme μ, suggérant que la compétition entre affordances modifie la résonance motrice lors de la perception d'objets manipulables (Wamain et al., 2018). En utilisant l'enregistrement électroencéphalographique, nous avons testé si un verbe d'action congruent pouvait aider à résoudre la compétition entre affordances et libérer la désynchronisation du rythme µ. L'étude a été réalisée sur 25 participants (recrutements interrompus par le COVID-19). Les participants ont réalisé des jugements perceptifs sur des objets conflictuels en 3D dans un environnement virtuel et présentés à différentes distances. Les objets étaient précédés par un verbe d'action congruent avec leur geste d'utilisation type et un verbe d'action neutre.

CHAPITRE 4. PLUSIEURS PARADIGMES EVALUANT LES AFFORDANCES : LEQUEL CHOISIR ?

Ce premier chapitre concerne l'évaluation de l'activation d'affordance. En effet, il existe un nombre considérable de preuves que la présentation visuelle d'objets manipulables active des informations motrices, appuyant l'existence d'effets d'affordance lors de la perception d'objets. Cependant, la plupart des arguments proviennent de paradigmes de compatibilité stimulus-réponse. Ces paradigmes ont été fortement critiqués dans la littérature. Certains chercheurs soutiennent une probable contamination des effets par de la compatibilité spatiale et d'autres remettent en question l'automaticité des effets d'affordance mesurés. De nombreux paradigmes expérimentaux ont été conçus dans l'objectif de mesurer les effets d'affordance plus proprement. Des preuves indirectes suggèrent que certaines versions du paradigme de compatibilité stimulus-réponse, comme lorsqu'on ajoute un délai entre la présentation du stimulus et de la réponse, peuvent surmonter les critiques habituelles. De plus, on estime que les paradigmes d'amorçage par l'action peuvent surmonter la problématique de la contamination par la compatibilité spatiale, mais ils montrent des résultats moins fiables, peut-être parce que les effets d'affordance sont modérés par des facteurs supplémentaires. Dans ce chapitre, nous reporterons brièvement des investigations pilotes menées afin de choisir le paradigme approprié pour explorer l'implication du mécanisme de spécification des affordances dans la compétition entre affordances (voir Chapitre 5). Ensuite, nous reporterons une étude publiée qui évaluait plus précisément le paradigme d'amorçage par l'action. Plus particulièrement, nous avons testé si des facteurs modérateurs supplémentaires, tel que la catégorie d'objets manipulables (i.e., fabriqués vs. naturel), pouvait expliquer la faiblesse du paradigme d'amorçage par l'action de démontrer des effets d'affordances.

Section 1. Etude pilote pour choisir un paradigme évaluant l'activation d'affordance

Dans le Chapitre 2, nous avons mentionné que les études princeps sur les effets d'affordances utilisaient des paradigmes de compatibilité stimulus-réponse (Fischer & Dahl, 2007; Pellicano et al., 2010; Tucker & Ellis, 1998, 2001). Dans ces études, les résultats de compatibilité sont souvent interprétés comme une activation automatique de composants d'action associés aux objets lors de leur traitement perceptif. Cependant, nous avons noté que ces interprétations font face à plusieurs problématiques méthodologiques et théoriques. Plusieurs paradigmes ont été conçus pour répondre à ces problématiques (Borghi et al., 2007; Dekker & Mareschal, 2014; Godard et al., 2019; Ni et al., 2018; Phillips & Ward, 2002; Vainio et al., 2008). Globalement, deux grands paradigmes ont été conçu pour étudier les effets d'affordance plus proprement : le paradigme de compatibilité stimulus-réponse avec délai et le paradigme d'amorçage par l'action. Nous avons décidé de mener des investigations pilotes pour choisir le paradigme le plus approprié pour mesurer les mécanismes de spécification d'affordance. Curieusement, lors de la conception du paradigme de compatibilité stimulus-réponse avec délai, nous avons rencontré de nombreuses problématiques méthodologiques (e.g., persistance rétinienne) et les résultats obtenus montraient peu de preuve de l'existence d'effet de compatibilité, contrairement à ce qui avait été rapporté dans la littérature (Dekker & Mareschal, 2014). Nous avons donc choisi le paradigme d'amorçage par l'action pour étudier les mécanismes de spécification d'affordance dans le Chapitre 5.

Section 2. Est-ce que les objets fabriqués et naturels évoquent les mêmes informations motrices ? Le cas du paradigme d'amorçage par l'action.

Il existe de nombreuses preuves expérimentales qui montrent que percevoir un objet manipulable active des informations motrices, appuyant l'existence d'effets d'affordance lors de la perception d'objets. Cependant, la plupart des arguments proviennent des paradigmes de compatibilité stimulus-réponse, soulevant la problématique de l'automaticité de l'activation d'affordances. Les paradigmes d'amorçage par l'action dépassent cette problématique mais montrent des résultats moins fiables, peut-être parce que les effets d'affordance sont modérés par des facteurs supplémentaires. Cette étude a pour objectif de déterminer si les effets d'affordances observés dans les paradigmes d'amorçage par l'action peuvent être affecté par la catégorie d'objet (fabriqué ou naturel). Vingt-quatre jeunes adultes ont réalisé une tâche de catégorisation sémantique sur des objets cibles naturels ou fabriqués présentés après des amorces neutre (posture de main sans préhension) et des amorces d'action (postures de préhension). Les résultats ont montré une modulation des effets d'amorçage par l'action en fonction de la catégorie d'objets. La catégorisation sémantique était plus rapide après une amorce d'action qu'une amorce neutre, mais seulement pour les objets fabriqués. Ces résultats suggèrent que les objets naturels et fabriqués évoquent différents types d'affordances et que les paradigmes d'amorçage par l'action favorisent l'activation d'affordances fonctionnelle lors de la catégorisation sémantique.

Synthèse générale

Un des objectifs principaux du présent travail de thèse est de déterminer comment la variabilité interindividuelle module la compétition entre affordance lors de la perception d'objets manipulable (voir Chapitre 5). Plus particulièrement, nous voulons explorer l'implication respective des mécanismes de spécification et de sélection des affordances lors de la compétition, au travers de mesures indépendantes. Dans ce chapitre, nous avons exploré les paradigmes évaluant l'activation d'affordances lors de la perception d'objets manipulables (i.e., spécification) avec l'objectif de choisir le paradigme le plus approprié pour évaluer les mécanismes de spécification d'affordance depuis l'enfance dans le Chapitre 5. Nous avons choisi de concevoir et tester deux paradigmes expérimentaux qui ont été classiquement utilisés dans ce but : le paradigme d'amorçage par l'action (Borghi et al., 2007) et le paradigme de compatibilité stimulus-réponse (ou anse-réponse) avec délai (Dekker & Mareschal, 2014). Ce chapitre a été divisé en deux sections. Dans la première section, nous avons décrit des résultats expérimentaux obtenus lors de la conception des deux paradigmes. Dans la seconde section, nous avons décrit une étude publiée qui suggère que les résultats des paradigmes par l'action puissent être modulés par la catégorie des objets manipulables présentés (i.e., fabriqué vs. naturel). Lors de la conception des deux paradigmes, nous avons rencontré plusieurs problématiques lors de l'implémentation du paradigme de compatibilité stimulus-réponse avec délai. Par conséquent, nous avons privilégié le paradigme d'amorçage par l'action pour évaluer l'activation d'affordance dans le Chapitre 5.

CHAPTER 5. MODULATIONS DEVELOPPEMENTALES DE LA COMPETITION ENTRE AFFORDANCES LORS DE LA PERCEPTION D'OBJET

Dans la première section de ce chapitre, nous allons étudier comment la variabilité interindividuelle module l'impact de la compétition entre affordance sur la perception d'objet. Plus particulièrement, nous allons évaluer la trajectoire développement des conséquences de la co-activation de plusieurs affordances sur le traitement perceptif des objets. Nous faisons l'hypothèse que l'impact négative de la compétition entre affordances sur le traitement perceptif des objets puisse résulter de la contribution conjointe de deux mécanismes, la spécification et la sélection d'affordance, et pourrait montrer une trajectoire développementale non-linéaire. Les participants réaliseront des jugements perceptifs sur différents objets présentés en 3D dans un environnement virtuel afin d'évaluer le coût sélectif de traitement associé aux objets conflictuels. Les participants réaliseront également deux tâches complémentaires dans deux paradigmes supplémentaires : un paradigme d'amorçage par l'action et un paradigme de Simon pour mesurer, respectivement, les mécanismes de spécification et de sélection des affordances. Dans la seconde section, nous présenterons brièvement une étude complémentaire qui a été menées sur des participants adultes afin d'évaluer l'implication de potentielles variables confondues (i.e., la complexité visuelle) sur l'émergence du coût de traitement associé aux objets conflictuels.

Section 1. Comment la compétition entre affordances affecte la perception des objets au cours du développement

Des preuves récentes indiquent que, chez l'adulte, le traitement perceptif des objets est affecté par la compétition entre affordances. En l'absence de planification motrice spécifique, les objets présentés dans l'espace péripersonnel et évoquant différentes affordances structurelle et fonctionnelle provoque des temps de jugement plus long que les objets évoquant des affordances similaires. L'objectif de cette étude était d'identifier le développement de coût de la compétition entre affordance. A la lumière des récent modèles sur les affordances, nous avons fait l'hypothèse selon laquelle le coût de la compétition sera le résultat de la contribution conjointe de deux mécanismes, la spécification et la sélection des affordances, et pourrait suivre une trajectoire développementale non-linéaire. Cinq groupes d'âge allant de 8 ans à l'âge adulte ont participé (N = 131). Comme dans les études précédentes, les participants ont réalisé des jugements perceptifs sur différents objets 3D présentés dans un environnement virtuel afin d'évaluer le coût de la compétition. Ils ont également réalisé deux tâches complémentaires, une tâche d'amorçage par l'action et une tâche de Simon pour mesurer, respectivement, les mécanismes de spécification et de sélection des affordances. Les principaux résultats démontrent que le coût de la compétition est présent chez les enfants dès 8 ans et suit une trajectoire développementale en forme de « U » entre 8 ans et l'âge adulte. Les résultats obtenus aux tâches complémentaires montrent une trajectoire développementale similaire pour l'effet d'amorçage par l'action, suggérant que le coût de la compétition dépend des mécanismes de spécification des affordances, et témoignant d'importants changement au début de l'adolescence. Le rôle des capacités de monitoring dans la sélection des affordances et dans l'émergence du coût de la compétition est moins clair et requière d'autres investigations.

Cette étude développementale démontre que la compétition provoquée par la perception de différentes affordances lors du traitement perceptif d'objets manipulables induit un coût chez l'enfant dès 8 ans. Cette découverte étend les résultats précédents chez l'adulte montrant un impact similaire de la compétition entre affordances sur des jugements perceptifs et renforce la pertinence de considérer les relations perception-action pour une meilleure compréhension du développement de la perception des objets manipulables. Surtout, le développement du coût de la compétition montre une trajectoire développementale en forme de « U » entre 8 ans et l'adulte, avec une disparition de l'effet négatif entre 10 et 14 ans. La trajectoire non-linéaire souligne des périodes différentes de haute sensibilité à la compétition entre affordances et suggère des changements complexes dans les mécanismes de spécification et de sélection des affordances pendant l'adolescence. Des résultats préliminaires sur la contribution des mécanismes de spécification et de sélection des affordances dans le coût de la compétition, indiquent que les mécanismes de spécification, montrant une trajectoire non-linéaire similaire, sont susceptibles de subir des changements critiques dès le début de l'adolescence et participent probablement aux modifications du coût de la compétition. Le rôle des capacités de monitoring dans le cadre des mécanismes de sélection d'affordance requière de plus amples investigations. Globalement, ces découvertes fournissent de nouvelles connaissances dans le domaine du développement de la compétition entre affordances qui pourront aider à enrichir les points de vue théoriques récents sur les affordances (Cisek, 2007; Thill et al., 2013).

Section 2. Expérience complémentaire. Est-ce que la complexité visuelle explique le coût de la compétition ?

Ce travail avait pour objectif d'identifier l'implication de la complexité visuelle dans l'émergence du coût de la compétition dans le paradigme de perception 3D utilisé dans cette thèse. Des chercheurs ont proposé que la complexité visuelle pouvait expliquer la différence de temps de jugement entre les objets conflictuels et non-conflictuels (Bub et al., 2018). Les objets conflictuals serait plus complexes visuellement et posséderaient plus de parties (i.e., d'éléments) que les objets non-conflictuels, ils auraient besoin de processus de traitement plus profond, ce qui impliquerait des décisions de catégorisation plus difficiles. La complexité visuelle a été évaluée au travers de mesures subjectives (i.e., la complexité visuelle globale, nombre de parties). Deux indices objectifs supplémentaires ont été calculé à l'aide d'algorithmes (i.e., FSIM and HMAX). Nous avons comparé les objets conflictuels et non-conflictuels sur la base de ces différentes mesures de complexité visuelle. Puis, nous avons évalué l'influence de la complexité visuelle des objets sur l'émergence du coût de la compétition chez les enfants de 8 ans et les jeunes adultes, ayant montré un coût de compétition dans l'étude précédente. Nos premiers résultats ont montré une différence de complexité visuelle entre les objets conflictuels et non-conflictuels, mais seulement pour les mesures subjectives de complexité visuelle globale et de nombre de parties. Par conséquent, les objets conflictuels étaient jugés plus complexe visuellement que les objets non-conflictuels. Aucune différence entre les objets n'a été observée pour les indicateurs FSIM et HMAX. Bien que le travail ait été réalisé sur des versions d'images 3D différentes, nos résultats soutiennent partiellement ce que Bub et al. (2018) ont souligné concernant les résultats de Kalénine et al. (2016), que – globalement – les objets conflictuels sont plus complexe visuellement et possèdent plus de parties que les objets non-conflictuels.

De manière plus importante, les résultats ont montré que, même après avoir contrôlé la complexité visuelle, le coût de la compétition est toujours présent à 8 ans et chez l'adulte. Par conséquent, nos résultats ne soutiennent pas l'idée que le coût de la compétition soit explicable par la complexité visuelle des objets (Bub et al., 2018). Ces découvertes sont un argument pour dire que la différence de vitesse de réponses entre les objets conflictuels et non-conflictuels est un bon indicateur de compétition entre affordances. La présence d'une trajectoire développementale non-linéaire est un second argument qui va à l'encontre de l'influence de la complexité visuelle sur l'émergence du coût de la compétition. Il n'y a aucune raison de croire que la sensibilité à la complexité visuelle suivrait une trajectoire développementale non-linéaire à partir de l'âge de 8 ans.

Synthèse générale

Globalement, ce chapitre fournie une démonstration de la manière dont la variabilité interindividuelle module l'impact de la compétition entre affordances lors de la perception d'objets manipulables. Nous avons identifié deux périodes d'âge où les individus sont plus sensibles à la compétition entre affordance, qui sont chez le jeune enfant (8 ans) et le jeune adulte (réplication des résultats de Kalénine et al., 2016). L'implication des mécanismes de spécification des affordances dans la compétition est plus claire que l'implication des mécanismes de sélection. Une étude complémentaire a démontré une différence de complexité visuelle entre les objets conflictuels et non-conflictuels, bien que cela ne soit pas visible sur toutes les mesures de complexité visuelle utilisées. De plus, nous avons souligné que le coût de la compétition chez les enfants de 8 ans et chez le jeune adulte reste présent même après avoir contrôlé la complexité visuelle des stimuli. Globalement, les découvertes fournissent des preuves supplémentaires pour interpréter le coût de la compétition dans l'espace péripersonnel comme un indicateur de compétition entre affordances. Dans le prochain chapitre, nous étudierons comment la variabilité intra-individuelle module l'impact de la compétition entre affordance lors de la perception d'objets manipulables. Plus particulièrement, nous essaierons de déterminer si une information contextuelle peut moduler la compétition entre affordances et contribuer à résoudre la compétition lors du traitement perceptif de objets manipulables.

CHAPTER 6. MODULATIONS CONTEXTUELLES DES MECANISMES NEURONAUX SOUS-TENDANT LA COMPETITION ENTRE AFFORDANCES LORS DE LA PERCEPTION DES OBJETS

Dans ce chapitre, nous avons étudié comment la variabilité intra-individuelle module l'impact de la compétition entre affordances lors de la perception d'objets manipulables. Dans cette étude en électroencéphalographie, nous avions pour objectif d'identifier l'influence d'un contexte sur la compétition entre affordances lors de la perception d'objets. On a supposé que la réduction de la désynchronisation du rythme µ lors de la perception d'objets conflictuels reflétait l'impact de la compétition entre affordances sur les processus de sélection d'action (Wamain et al., 2018). Comme les affordances structurelle et fonctionnelle peuvent être flexiblement activées en fonction du contexte dans lequel l'objet est perçu (Kalénine et al., 2014), nous nous attendions à une résolution de la compétition entre affordances lors de la perception d'objets conflictuels dans un contexte verbal évoquant le geste d'utilisation typique de l'objet. Vingt-cinq participants ont participé à l'étude. Dans cette étude, nous avons évalué les modulations de la désynchronisation du rythme µ lors de la perception d'objets conflictuels entourés par des contextes verbaux d'action et neutre.

Nous avons démontré que la compétition provoquée par la perception de différentes affordances lors du traitement perceptif d'objets manipulables est sensible au contexte verbal. Cette découverte élargit des résultats obtenus préalablement chez l'adulte en montrant un impact de la compétition entre affordance sur les processus de sélection d'action (i.e., désynchronisation du rythme µ). Cela consolide la pertinence de considérer l'information contextuelle pour mieux comprendre les relations perception-action lors du traitement perceptif des affordances associées aux objets manipulables. Surtout, la réduction de la désynchronisation du rythme µ associée au traitement perceptif des objets conflictuels est diminuée en présence d'un contexte verbal d'action qui évoque le geste d'utilisation typique de l'objet. L'augmentation de la désynchronisation du rythme μ dans cette situation souligne l'influence du contexte verbal sur la résolution de la compétition entre affordances lors du traitement perceptif des objets conflictuels et suggère que les affordances fonctionnelles des objets conflictuels ont été choisi et ont subi un traitement préférentiel par le système. Globalement, ces découvertes mettent en lumière l'influence des informations contextuelles sur la résolution de la compétition entre affordances, ce qui peut enrichir les points de vue théoriques récents sur les affordances (Cisek, 2007; Cisek & Kalaska, 2010; Thill et al., 2013).

DISCUSSION GENERALE

La perception est un phénomène actif qui guide les actions et qui est modulée par les actions réalisées dans l'environnement. Au niveau neurophysiologique, l'action et la perception partage de nombreux corrélats cérébraux et sont donc deux systèmes qui ne montrent pas de distinction claire. Les théoriciens des approches ancrées de la cognition utilisent généralement ces preuves neurophysiologiques pour suggérer que la perception et l'action font partie des représentations cognitives. Par conséquent, quand nous percevons l'environnement, non seulement nous traitons les informations visuelles disponibles, mais nous simulons également les informations motrices associées aux éléments visuels présents dans l'environnement (voir Chapitre 1). Dans le domaine de la perception d'objets manipulables, la simulation des informations motrices, aussi appelée affordances, est devenu un sujet de recherche central. Cependant, « comment les informations motrices des objets manipulables sont représentées au niveau cognitif ? quels sont les systèmes cérébraux responsables de leur traitement ? et dans quelle mesure les affordances sont activées automatiquement ? » sont trois débats actuels dans cette littérature (voir Chapitre 2). Une hypothèse commune à toutes ces approches récentes concerne le fait qu'un objet peut évoquer plusieurs types d'informations motrices.

Nous avons également développé la discussion autour des débats récents sur l'automaticité de l'activation des affordances (voir Chapitre 2). Les investigations initiales ont supposé que l'activation des affordances lors de la perception d'objets manipulables était automatique (Chao & Martin, 2000; Tucker & Ellis, 1998). Cependant, des résultats récents ont mis en évidence l'influence de modulations individuelles (e.g., l'expérience motrice) et contextuelles (e.g., la position dans l'espace) dans l'activation des affordances (Chrysikou et al., 2017; Watson et al., 2013; Yee et al., 2013). Bien que nous ayons opposés les arguments en faveur de l'automaticité et ceux en faveur de modulations contextuelles, nous n'avons pas pris de décision tranchée sur ce débat. Finalement, nous avons mis en évidence que la perception des affordances est parfois préjudiciable pour le traitement perceptif des objets manipulables (voir Chapitre 3). En effet, différentes affordances peuvent être, dans certains cas, co-activées par un même objet, ce qui a des conséquences négatives sur son traitement perceptif. Plus spécifiquement, les affordances structurelle et fonctionnelle associées à un même objet rivalisent entre elles et cette compétition peut être préjudiciable pour la production d'action dirigée vers ces objets ou le traitement perceptif de ces objets chez l'adulte. Au regard des modèles neurobiologiques et des preuves neurophysiologiques récentes, nous avons supposé que le coût induit par la compétition entre affordances puisse impliquer des mécanismes neurocognitifs différents, à savoir la spécification des affordances (i.e., l'activation des affordances) et la sélection des affordances (i.e., la compétition et le choix des affordances pertinentes pour l'action).

Dans la première étude présentée dans le Chapitre 4, nous avons exploré les paradigmes évaluant l'activation des affordances lors de la perception d'objets manipulable (i.e., la spécification des affordances) avec pour objectif de choisir le paradigme le plus approprié pour étudier les mécanismes de spécification des affordances dans l'étude suivante. Une investigation pilote nous a permis de favoriser le paradigme d'amorçage par l'action. De plus, nous avons rapporté que des facteurs modérateurs, comme la catégorie d'objets manipulable (i.e., fabriqué vs. naturel), puissent être responsables de la faiblesse des paradigmes d'amorçage par l'action dans la démonstration des effets d'affordance. Cependant, ces résultats indiquent que notre implémentation du paradigme d'amorçage par l'action évalue l'activation d'affordances lors de la perception d'objets manipulables.

Dans l'étude 2 et l'étude 3 présentées aux Chapitre 5 et 6, nous avons évalué l'influence des modulations développementales (étude 2) et du contextuelles (étude 3) sur le coût de la compétition entre affordances. Par conséquent, nous avons conçu des images 3D d'objets manipulables évoquant différents gestes de saisie et d'utilisation (i.e., objets conflictuels) et d'objets manipulables évoquant un geste similaire pour les deux actions (i.e., objets non-conflictuels). De la même manière que dans les études précédentes (Kalénine et al., 2016; Wamain et al., 2018), les images ont été insérées dans un environnement virtuel en 3D, à différentes distances afin de comparer le traitement perceptif des objets dans un contexte qui induit une activation des informations motrices (i.e., espace péripersonnel) avec un contexte qui n'induit pas d'activation des informations motrices (i.e., espace extrapersonnel). Pour rappel, quand les objets conflictuels sont présentés dans l'espace péripersonnel, ils sont habituellement associés à un coût de traitement spécifique comparativement aux objets non-conflictuels.

Dans l'étude 2, cinq groupes de participants allant de 8 ans à l'âge adulte ont été recrutés. Comme nous avions fait l'hypothèse que le coût de la compétition pouvait résulter de la contribution conjointe des mécanismes de spécification et de sélection des affordances, les deux mécanismes ont été étudiés. Nous avons montré un coût de la compétition dès 8 ans. Ce coût de la compétition suit une trajectoire développementale non-linéaire en forme de « U » à partir de 8 ans et jusqu'à l'âge adulte. Nous avons fourni des preuves supplémentaires montrant que l'effet d'amorçage par l'action, ciblant les mécanismes de spécification des affordances, suit une trajectoire non-linéaire similaire au coût de la compétition. Néanmoins, les résultats associés aux mécanismes de sélection des affordances sont moins clairs, puisque nous n'avons trouver aucune trajectoire développementale de l'effet Simon, utiliser pour définir ce mécanisme. Dans l'étude 3, nous avons étudié l'influence d'un contexte verbal sur le coût de la compétition, en utilisant un marqueur électroencéphalographique (i.e., la désynchronisation du rythme μ). Les objets conflictuels étaient présentés dans un contexte verbal neutre (i.e., verbe d'observation) et dans un contexte verbal d'action (i.e., verbe d'action évoquant le geste d'utilisation typique des objets). Nous avons montré qu'un contexte verbal d'action pouvait résoudre la compétition entre affordances lors de la perception d'objets conflictuels.