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Discipline : Psychologie

Impulsivity is not just disinhibition: investigating the effects of impulsivity on the adaptation of cognitive control mechanisms

Impulsif ne veut pas dire désinhibé : étude de l'effet de l'impulsivité sur l'adaptation des mécanismes de contrôle cognitif

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Publications

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Abstract

Impulsivity is not just disinhibition: investigating the effects of impulsivity on the adaptation of cognitive control mechanisms

Impulsivity is a behavioral tendency frequently observed in the general population but at different degrees. Interestingly, higher impulsivity increases the probability to develop and to be diagnosed with a psychiatric disorder, such as substance use or personality disorders. To gain a better understanding on the emergence of such psychiatric disorders, my PhD project focused on the role of cognitive control in impulsive manifestations. Indeed, cognitive control is a set of basic executive functions ensuring adaptive behaviors to an ever-changing and complex environment. More particularly, during my PhD research, I investigated the flexible adaptation between reactive and proactive control mechanisms in impulsive individuals, mainly from the general population but also from an alcohol-dependent population.

The first three studies of my thesis revealed that high impulsivity was characterized by a less-proactive cognitive control system, and associated with a weaker adaptation of cognitive control mechanisms both to external demands and internal constraints. More specifically, I observed that high impulsive individuals less exert proactive control while it should be favored given contextual or individual characteristics. In the fourth study in which EEG signals were recorded, we were interested in the brain activity that is typically observed during errors (i.e., the ERN/Ne), which is thought to signal the need for control. A reduction in this brain activity was observed in high aggressive individuals, but not in high impulsive individuals. This finding suggests that the emergence of maladaptive behaviors may be explained, to a certain extent, by the reduced alarm signal. Finally, some preliminary results suggest a link between a peripheral index of physiological adaptation (i.e., HRV) and the capacity to adapt control mechanisms. These findings open new avenues for therapeutic interventions in the reduction in maladaptive behaviors.

Overall, findings from the current thesis suggest that impulsivity in the general population is associated with a less proactive and a less flexible cognitive control system, potentially leading to inappropriate behaviors when the control mechanisms at play are maladapted.

Keywords: Impulsivity ; Cognitive control ; EEG ; EMG ; Adaptation

Résumé

Impulsif ne veut pas dire désinhibé:
étude de l'effet de l'impulsivité sur l'adaptation des mécanismes de contrôle cognitif

L'impulsivité est une tendance comportementale fréquemment observée dans la population générale mais à des degrés différents. À ce propos, une forte impulsivité augmente les risques de développer un trouble psychiatrique, tel que les différentes formes d'addiction ou des troubles de la personnalité. Pour comprendre l'émergence de ces divers troubles comportementaux, mon projet de thèse s'est porté sur le rôle du contrôle cognitif dans les manifestations de l'impulsivité. Le contrôle cognitif est, en effet, un ensemble de fonctions cognitives nous permettant d'adapter nos comportements à un environnement changeant, et donc complexe. Durant ma thèse, je me suis plus particulièrement intéressée aux capacités d'adaptation des mécanismes de contrôle proactif et réactif chez des individus impulsifs, principalement dans la population générale mais également auprès de patients alcoolo-dépendants.

Les trois premières études de ma thèse ont montré qu'une forte impulsivité était caractérisée par une utilisation moindre des mécanismes proactifs associée à un défaut d'adaptation des mécanismes de contrôle aux demandes externes et aux contraintes internes. Les individus impulsifs exercent moins de contrôle proactif alors que celui-ci devrait être favorisé au vu des caractéristiques contextuelles ou individuelles. Dans une quatrième étude dans laquelle des enregistrements EEG ont été effectués, nous nous sommes intéressées à l'activité cérébrale typique observée au moment de l'exécution des erreurs, nommée ERN/Ne, et dont le rôle serait de signaler les besoins en contrôle. Une réduction de cette activité cérébrale a été observée chez les individus les plus agressifs, mais pas chez les individus les plus impulsifs. Ce résultat suggère que l'émergence de comportements inadaptés pourrait être en partie expliquée par cette réduction du signal d'alarme. Enfin, des résultats préliminaires suggèrent un lien entre un indice périphérique de l'adaptation physiologique (HRV) et les capacités d'adaptation des mécanismes de contrôle. Ce résultat ouvre la voie à de nouvelles interventions thérapeutiques pour la réduction des comportements inadaptés.

Dans l'ensemble, les résultats de cette thèse suggèrent que l'impulsivité en population générale est associée à un système de contrôle cognitif moins proactif et moins flexible, menant potentiellement à des comportements inappropriés quand les mécanismes de contrôle en jeu sont inadaptés.

Mots-clés: Impulsivité ; Contrôle cognitif ; EEG ; EMG ; Adaptation

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Abbreviations

— **ACC**: anterior cingulate cortex
— **AUD**: alcohol use disorder
— **AD**: alcohol-dependent
— **ADHD**: attention-deficit hyperactivity disorder
— **AX-CPT**: AX variant of the Continuous Performance Test
— **BP**: bipolar disorder
— **BPD**: borderline personality disorder
— **CR**: correction ratio
— **CRN/Nc**: correct(-related) negativity
— **CT**: correction time
— **DLPFC**: dorsolateral prefrontal cortex
— **DMC**: dual mechanisms of control
— **DSM**: diagnostic and statistical manual of mental disorders
— **ECG**: electrocardiography
— **EEG**: electroencephalography
— **EMG**: electromyography
— **ERN/Ne**: error(-related) negativity
— **ERP**: event-related potential
— **HC**: healthy controls
— **HRV**: heart rate variability
— **ICD**: impulse-control disorders
— **OCD**: obsessive-compulsive disorder
— **PBI**: proactive behavioral index
— **Pe**: error positivity
— **PES**: post-error slowing
— **PFC**: prefrontal cortex
— **RT**: reaction time
— **SD**: standard deviations
— **SMA**: supplementary motor area
— **SZ**: schizophrenia

Part I

Foreword

Impulsivity is derived from the latin word *impellere* which means "to goad to", "to incite to". Simply put, acting impulsively is reacting without control, to an external or internal impulse (e.g., a sound, an emotion). As humans, we all act on impulses by reacting to stimulation arising from the environment; impulsivity can be observed at different degrees, within a continuum from normal to pathological populations.

Impulsivity can have beneficial outcomes. It can lead to seize opportunities by taking risks, or it can lead to gain valuable new experiences (Winstanley, 2011). However, in the literature, and in its common use, the term "impulsivity" is mostly associated with negative outcomes (i.e., incompatible with long-time goals). When smelling a chocolate croissant as you walk by a bakery makes you buy it whereas you already had something to eat, you have acted on an impulse. Eating that croissant was not your goal at the moment and yet, the odor made you act. Every once in a while, we act impulsively, but undoubtedly, in the general population, we do not buy croissants every time we smell one. We are most of the time able to control our impulses to achieve our goals. Moreover, the outcomes of daily impulsive behaviors are not critical for the individual or his/her entourage (e.g., eating a chocolate croissant, or buying an expensive pair of shoes on the spur of the moment). However, for some individuals, these behaviors can be more frequent and lead to more severe negative outcomes (e.g. debt, addiction) and impulsivity can in such cases lead to pathological behaviors.

Impulsivity is a great source of interest in the psychopathological fields of research for two clinical aspects. On the one hand, impulsivity is a diagnostic feature in several psychiatric disorders. In the DSM-IV (Diagnostic and Statistical Manual of mental disorders, American Psychiatric Association, 1994), the "impulsivity" criterion appears in eight categories of mental disorders: attention-deficit hyperactivity disorder (ADHD), Tourette's disorder, substance-related disorder, obsessive-compulsive disorder (OCD), mania, personality disorders and in particular the cluster B (i.e., antisocial, borderline and histrionic personality disorders). Behaviors related to an impulse control disorder (ICD) represents an entire category of mental disorders in the DSM-IV including the not elsewhere classified disorders such as kleptomania, pyromania, trichotillomania, gambling disorder and intermittent explosive disorder. In the DSM-IV, impulsivity is the second most evoked diagnostic criterion after subjective distress (Whiteside & Lynam, 2001; Billieux, Rochat, & Linden, 2014). In the most recent DSM-V (American Psychiatric Association, 2013), impulsivity is still largely represented in the diagnostic features of these disorders. On the other hand, impulsivity is associated with the severity of a disorder and poor treatment outcomes (e.g., Moody, Franck, Hatz, & Bickel, 2016; Verdejo-García, Bechara, Recknor, & Pérez-García, 2007; Day, Metrik, Spillane, & Kahler, 2013; Loree, Lundahl, & Ledgerwood, 2015; Reyes-Huerta, dos Santos, & Martínez, 2018). Impulsivity is therefore a relevant research topic to improve the care of psychiatric disorders.

More importantly, impulsivity in the general population increases the risk of being later diagnosed with a psychiatric disorder. Higher impulsivity is indeed a vulnerability factor (i.e., a characteristic that increases the probability of the emergence of a disorder) for the above-mentioned psychiatric disorders (Moffitt et al., 2011; Beauchaine, Zisner, & Sauder, 2017; Martel, Levinson, Lee, & Smith, 2017). Multiple studies have reported the predictive value of impulsivity on substance use disorders like smoking or drinking (Granö, Virtanen, Vahtera, Elovainio, & Kivimäki, 2004; Stautz, Pechey, Couturier, Deary, & Marteau, 2016; Rømer Thomsen et al., 2018; de Wit, 2009; Bø, Billieux, & Landrø, 2016), on eating disorders and food addiction (Meule, de Zwaan, & Müller, 2017; Meule & Platte, 2015; Evans et al., 2019). Higher impulsivity also predicts the development of, as well as accounting for the severity of psychiatric symptoms. In the general population, higher impulsivity was found to predict a higher risk of depressive syndrome two years later (Granö et al., 2007) and of experiencing suicidal ideations (Sarkisian, Van Hulle, & Goldsmith, 2019). It was finally reported to account for borderline and antisocial personality disorders symptoms (Fossati et al., 2004). Therefore, impulsivity is an even more relevant research topic for clinical work as it increases the risk of developing psychiatric disorders. This final clinical relevance to conduct research on impulsivity was the main topic that motivated my desire to engage in a PhD program.

My interest in research is to gain a better understanding of the cognitive mechanisms that link impulsivity in the general population to a higher vulnerability for psychiatric disorders.

The PhD project

To understand how impulsivity is a vulnerability factor for psychiatric disorders, my PhD project focused on the investigation of the relationship between the cognitive control system and impulsivity, in the general population. More particularly, I investigated the implementation and the adaptation of reactive and proactive control mechanisms as a function of external and internal demands in individuals with high and low impulsivity traits.

The first part of the present manuscript is dedicated to precisely defining impulsivity and cognitive control, as well as describing the methodological tools and experimental indices used to assess and investigate them (see Part II). Impulsivity is a multifaceted construct that comprises (1) a personality component, referred to in this manuscript as impulsiveness, and (2) behavioral components, referred to in this manuscript as impulsive behaviors (see Chapter 1). Higher impulsiveness reflects a higher vulnerability for psychiatric disorders, whereas impulsive behaviors are used to identify and diagnose psychiatric disorders. Additionally, higher impulsiveness in pathological populations predicts the emergence of impulsive behaviors, behaviors that lead the diagnosis. Interestingly, in the general population, impulsiveness does not predict impulsive behaviors. Therefore, to understand how impulsivity may be a vulnerability factor for psychiatric disorders, one must investigate how impulsiveness predicts impulsive behaviors in the general population by uncovering the cognitive mechanisms that mediate this relationship. Some previous studies have shown that the efficiency in cognitive control moderated the link between impulsiveness and impulsive behaviors. Therefore, after arguing against a direct association between impulsivity and inhibition (see Chapter 2.1), I describe the cognitive control model in which I anchored my PhD project (see Chapter 2.2). In this framework, the cognitive control system is composed of three main components: conflict monitoring, reactive control and proactive control. The three components are simultaneously at play to adapt behaviors to a constantly changing and thus, unpredictable environment. Also, I argue that cognitive control can be investigated at two levels. Firstly, one can individually investigate the efficiency of the three components, as the efficiency of all the components is crucial for adaptive behaviors (see Chapter 3.1 for a review of the experimental indices). Secondly, one can investigate the flexible use of reactive and proactive control mechanisms as a function of external (i.e., contextual characteristics) and internal demands (i.e., inter-individual characteristics). Indeed, implementing and adapting the use of the optimal control mechanism is a key for adaptive behaviors (see Chapter 3.2 for the operationalisation of this capacity).

During my PhD project, I investigated mostly the relationship between impulsivity and cognitive control at the level of the flexible shift between reactive and proactive control mechanisms, to understand what could explain the vulnerability to psychiatric disorders in high impulsive individuals. Indeed, I hypothesized that the three components of cognitive control would be efficient in the general population. However, the implementation and the adaptation of the optimal control mechanism could be impacted by the degree of expression of the impulsivity traits. Following Dickman (1990)'s perspective, impulsivity in the general population could be a vulnerability factor for psychiatric disorders only when the control mechanisms at play are not adapted to external and internal constraints.

The second part of the present manuscript summarizes the experimental contributions of my PhD project on the above-mentioned research interest (see Part III). My experimental contributions are organized in five sections. The first three sections explore the capacity to adapt the use of proactive and reactive control mechanisms as a function of external and internal constraints, both in general and pathological populations. In these sections, findings revealed that higher impulsivity is associated with a slower (or an absence of) adaptation in control mechanisms both to external (see Studies I and II, Chapters 5.1 and 6.1, respectively) and to internal demands (see Study III, Chapter 7.1). The fourth experimental section investigates the efficiency of the monitoring system to have a complete overview of the functioning of the cognitive control system in the general population. An EEG study was conducted (Study IV, see Chapter 8.1) and revealed a reduction in the activity of the monitoring system in high aggressive individuals, but not in high impulsive individuals. Finally, a fifth experimental axis is dedicated to preliminary findings on the role of heart rate variability (HRV) in the capacity to adapt cognitive control mechanisms. Across studies, I observed that higher HRV improved the capacity to adapt control mechanisms to external demands in high impulsive individuals. It seems that HRV can normalize the activity of the monitoring system in high aggressive individuals. These findings suggest a potential interest in using HRV-targeted interventions to improve the capacity to adapt control mechanisms.

The third part of this manuscript provides a summary of the main findings of my PhD project and their integration into the existing literature (see Part IV). Overall, my PhD research work revealed that impulsive individuals show less adaptation toward the use of proactive control as a function of external and internal demands, potentially leading to impulsive behaviors in some situations. The capacity to adapt control mechanisms could identify at-risk individuals for psychiatric disorders. I will discuss several hypotheses to explain this main finding in the general population and in pathological populations, and propose different remediation interventions to improve the capacity to adapt control mechanisms.

Part II

Introduction

Chapter 1

Impulsivity, impulsiveness and impulsive behaviors: the factorial structure of a multifaceted construct

Impulsivity is globally defined as a "*predisposition towards rapid, unplanned reactions to internal or external stimuli with a lack of regard for the negative consequences of these reactions to the impulsive individual or to the others*" (Moeller, Barratt, Dougherty, Schmitz, & Swann, 2001). This definition reveals that impulsivity conveys distinct behavioral features under a single label (Enticott & Ogloff, 2006). Indeed, the term *impulsivity* is used to describe a variety of behavioral manifestations and each author emphasizes different aspects of impulsivity. For Metcalfe and Mischel (1999) and Loewenstein (1996), impulsivity is a primitive hedonic reaction to tempting stimuli. Ainslie (1975) and Rachlin and Green (1972) defined impulsivity as a tendency to act without forethought and without consideration for consequences. Hence across the literature, impulsivity can be defined as an inability to withhold a response, a lack of sensitivity to negative or delayed consequences, a tendency for sensation seeking and risk-taking or a higher distractibility (Berry, Sweeney, Morath, Odum, & Jordan, 2014). Moreover, in clinical settings, the DSM-IV and DSM-V describe impulsivity as a difficulty awaiting turn, a desire for immediate rewards or an inability to delay gratification, actions and decisions without forethought and without consideration of the long-term consequences (e.g., "blurting out responses before the completion of the question", "interruption or intrusion on others"). As a consequence of these numerous descriptions, there is a great variability in the methodological tools to assess impulsivity. The tools include self-reported measures of personality and behavioral tasks. The present manuscript does not intend to list all the tools used in the impulsivity literature. However, in front of the various methodological tools, one can ask if impulsivity is an unitary or a multifaceted construct. In the following sections, I will discuss several studies that investigated this question to better define the factorial structure of impulsivity. Then, I will define the main components of impulsivity and describe the experimental tools to assess them.

1.1 Defining impulsivity

In front of the variability of methodological tools, researchers have questionned the unity of impulsivity. In other words, researchers have asked if all of the methodological tools used to measure impulsivity assess the same construct or distinct impulsivity aspects. Numerous studies have therefore tried to uncover the factorial structure of impulsivity (e.g., Reynolds, Ortengren, Richards, & de Wit, 2006; Meda et al., 2009; Verdejo-García, Lawrence, & Clark, 2008). To do so, authors have simultaneously analyzed multiple experimental and psychometric tools used to assess impulsivity, to investigate equivalences and differences in these methodologies using principal component analyses (PCAs). PCAs measure correlations between all the impulsivity assessment tools to extract components (or factors) to which multiple impulsivity measures contribute. The PCAs studies differ in the nature and the number of the impulsivity measures used in the analysis and therefore, the number of extracted components is not consistent between authors (e.g., Meda et al., 2009; Reynolds et al., 2006; Fineberg et al., 2014; Verdejo-García et al., 2008). However, studies have identified at least two components in the factorial structure, already suggesting that impulsivity is a multifaceted construct.

One of the first studies that investigated the factorial structure of impulsivity distinguished two broad components: behavioral and cognitive impulsivity (White et al., 1994). More recently, Meda et al. (2009) extracted five factors from the tools they choose for their analysis (i.e., five self-reported and two behavioral measures). They reported three self-reported factors (i.e., behavioral activation, reward/punishment sensitivity and

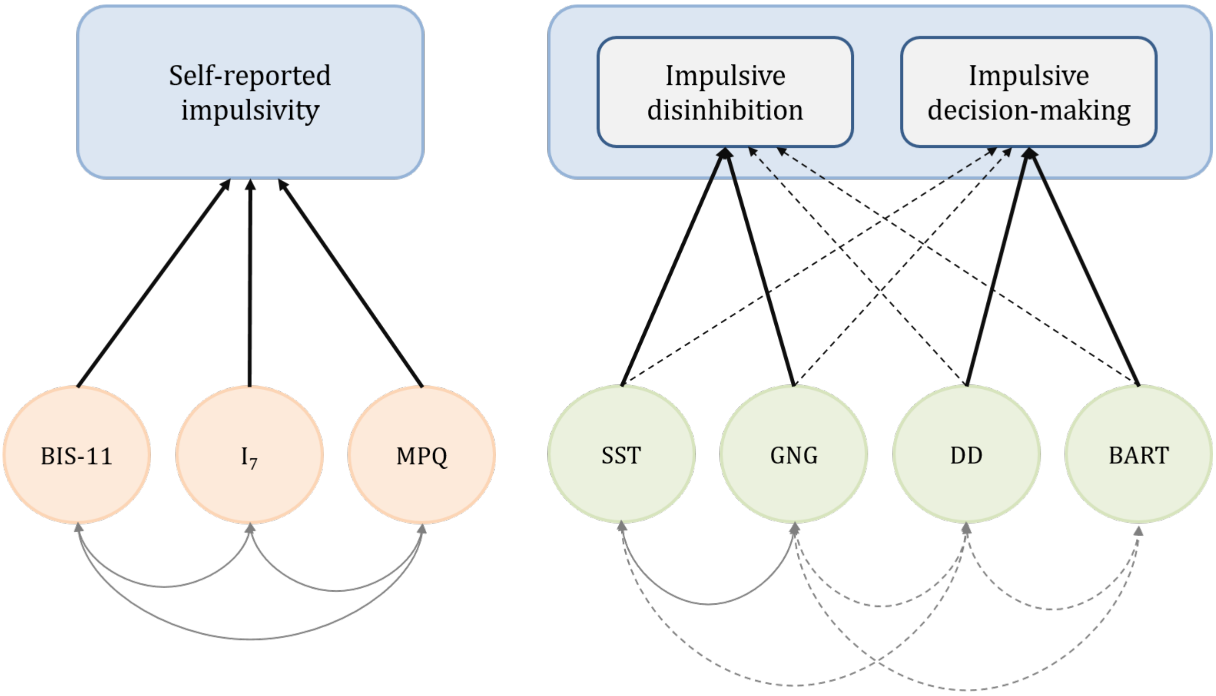

Figure 1.1 – **Factorial structure of the impulsivity construct** A total of three self-reported measures in orange (BIS-11, Patton et al., 1995; I7, Eysenck et al., 1985; MPQ, Patrick et al., 2002) and four behavioral measures in green were used (SST: Stop Signal Task, Logan et al. 1997, GNG: Go/No-Go, Newman et al., 1985, DD: delay discounting, Richards et al., 1999 and BART: Balloon Analog Risk Task, Lejuez et al., 2002). Bold and dashed arrows refer to significant and non-significant associations, respectively. Arrows in the bottom of the graph represent correlations between the measures. Correlations between self-reported and behavioral measures were not reported on the graph to facilitate reading. Arrows in the top of the graph represent contribution to the factor.

impulsivity) and two behavioral factors (i.e., temporal discounting and risk-taking). Importantly, in their study, self-reported measures mostly correlated with each other, and behavioral tasks revealed two distinct behavioral factors. These findings were consistent with previous studies (Lane, Cherek, Rhoades, Pietras, & Tcheremissine, 2003; Reynolds et al., 2006), but with a less parsimonious factorial structure. Using three self-reported measures of impulsivity and four behavioral tasks (assessing delay gratification, risk-taking and two forms of inhibition), Reynolds et al. (2006) indeed revealed a three-factor structure. All self-reported measures correlated with one another, whereas behavioral performances contributed to two distinct factors (cf. Figure 1.1). Additionally, no significant correlations were observed between self-reported and behavioral measures. One behavioral factor included both behavioral inhibition paradigms while the second was composed of the behavioral measures of delay gratification and risk-taking (cf. Figure

1.1). Reynolds et al. (2006) referred to these two components as reflecting “impulsive disinhibition” and “impulsive decision-making”, respectively (cf. Figure 1.1). This factorial structure was consistent with the one reported by Lane et al. (2003) and was replicated by MacKillop et al. (2016) using similar paradigms.

Beyond the discrepancy in the nature and the number of methodological tools used in the analysis and the difference in the nature and the number of components obtained, the different factorial analyses of impulsivity converged in certain ways (Meda et al., 2009). Firstly, all the analysis revealed at least two components, suggesting that impulsivity is not an unitary construct. Secondly, all factorial structures show a first level of distinction between behavioral and self-reported measures (e.g., Lane et al., 2003; Reynolds et al., 2006; Meda et al., 2009; Cyders & Coskunpinar, 2012). Impulsive-related personality traits consistently failed to correlate with behavioral measures. Finally, a second level of distinction is observed within the behavioral components mostly between "impulsive disinhibition" and "impulsive decision making" (Reynolds et al., 2006; Lane et al., 2003; MacKillop et al., 2016). Therefore, the convergent factorial structure reported in the literature reveals three components: a personality component, hereafter referred to as **impulsiveness**, and two behavioral components, hereafter referred to as **impulsive behaviors**. A detailed analysis of the factorial structure of impulsivity is discussed in the following sections.

1.2 Impulsivity: impulsiveness and impulsive behaviors

Although the studies diverged on the number and on the definitions of their components, a convergent factorial structure of impulsivity has emerged from experimental studies. Impulsivity comprises impulsiveness and impulsive behaviors. However, this categorization can be detailed even further. Indeed, impulsiveness encompasses various personality aspects whereas impulsive behaviors gather various behavioral manifestations both in decision-making and in motor actions. The following sections will be dedicated to the exploration of the complete structure of the impulsivity construct, and the corresponding methodological tools. A schematic overview is presented in the Figure 1.2.

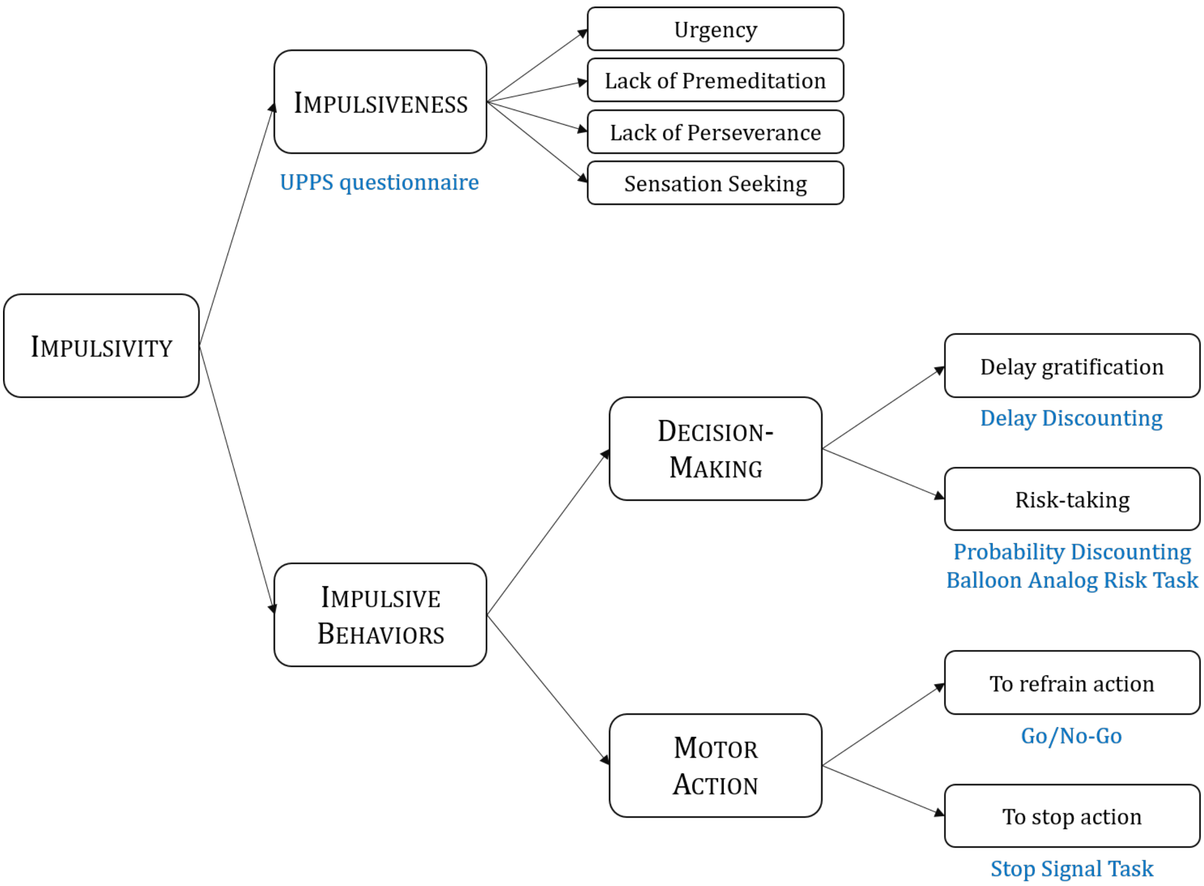

Figure 1.2 – **Schematic representation of the factorial structure of the impulsivity construct.** Impulsivity can be distinguished into personality traits (i.e., impulsiveness) and behavioral manifestations (i.e., impulsive behaviors). The latter distinguishes impulsive decision-making and motor action that can be both divided into two behavioral manifestations.

1.2.1 Assessing impulsiveness

Personality is defined as distinctive and recurrent patterns of thoughts, feelings and behaviors that occur in response to particular situational demands (Poletti & Bonuccelli, 2012). The personality component of impulsivity, hereafter referred to as **impulsiveness**, refers to the inter-individual differences in the predisposition to reveal impulsive behaviors under certain situations and contexts. Impulsiveness is therefore an individual characteristic that is stable over time. These predispositions are mostly assessed by self-reported measures. Self-reported impulsivity measures are abundant and try to cover the large range of impulsive aspects reported earlier (e.g., failure to wait, lack of regard for future consequences, disinhibition, novelty and sensation seeking). Some questionnaires assess impulsiveness as a facet of a more general personality profile (e.g., EASI-III, PRF), whereas others focused on one or multiple specific impulsive-related personality aspects (e.g., SSS, BIS-11). Hereafter, I will briefly present some of the questionnaires and then, I will describe how the UPPS questionnaire (Whiteside & Lynam, 2001), that I used to assess impulsiveness, came to be developed.

Subscales of personality questionnaires to assess impulsive-related aspects

As impulsiveness is considered as a large facet of the personality spectrum, some impulsive-related aspects (e.g., action on the spur of the moment, lack of deliberation) are often assessed with general personality questionnaires. Hence, impulsiveness is one of the four factors of the EASI-III (Buss & Plomin, 1975) and one of the 20 personality dimensions that should be assessed following the third edition of the Personality Research Form (PRF, Jackson, 1984). In the Five Factor Model (FFM, Costa & McCrae, 1992), the *Neuroticism, Extraversion* and *Conscientiousness* facets of personality are thought to capture some impulsive-related aspects. More specifically, the *Impulsiveness* and the *Self-Discipline* facets of both the *Neurotiscism* and the *Conscientiousness* factors assess impulsiveness as the inability to resist the temptation to act. Moreover, *Excitement Seeking* and *Deliberation* facets of the *Extraversion* and the *Conscientiousness* factors, respectively, evaluate impatience, the lack of forethought and the need for adventure. This need for adventure, and other associated personality aspects, were specifically assessed by the Sensation Seeking Scale (SSS, Zuckerman, 1994). Each of these personality questionnaires assesses specific impulsive-related aspects with a few number of items only (e.g., 5 to 16 for the EASI-III and the PRF, respectively). Therefore, these questionnaires are not specific to the assessment of impulsiveness as they do not cover the whole spectrum.

To increase the specificity of the psychometric tools for impulsiveness, authors have therefore constructed questionnaires to evaluate impulsiveness only. The Dickman Impulsivity Inventory (Dickman, 1990) was constructed to differentiate functional from dysfunctional impulsiveness. Integrating views from medical, psychological, behavioral and social approaches, Barratt and colleagues developed a questionnaire broadly used in research (Barratt, 1993; Gerbing, Ahadi, & Patton, 1987; Patton, Stanford, & Barratt, 1995). In the latest version of the Barratt Impulsiveness Scale (BIS-11 Patton et al., 1995), a total of three factors were identified: *Attentional*, *Motor* and *Non-planification* impulsiveness. *Attentional Impulsiveness* refers to the inability to focus on a task and the tendency to experience intrusive and racing thoughts (attention and cognitive instability subscales). This aspect of impulsiveness is related to boredom during complex tasks (e.g., I get easily bored when solving tough problems). *Motor Impulsiveness* is composed of the tendency to act on the spur of the moment and not to follow a consistent lifestyle (e.g., often changes of jobs or homes). Finally, the *Non-planification Impulsiveness* corresponds to the lack of planification and careful thoughts before acting. Notably, the assessment of impulsiveness in the BIS-11 appears to lack of an evaluation of sensation and novelty seeking.

The UPPS questionnaire

The UPPS questionnaire, a 45-item questionnaire, was created on the basis of all of the aforementioned cited specific and unspecific self-reported measures of impulsivity and includes affective aspects of emotion (Whiteside & Lynam, 2001). In order to do so, a factorial analysis was conducted using different personality scores collected through different impulse-related personality items taken from of total of nine questionnaires (Whiteside

& Lynam, 2001). The factorial analysis revealed four distinct aspects of impulsiveness (Table 1.1). The *Urgency* factor was constituted of the *EASI-III inhibitory control* and the *BIS-11 Attentional* subscales. It refers to the tendency to "commit rash and regrettable actions as a result of intense negative affect" (Whiteside & Lynam, 2001). *Sensation Seeking* characterizes the tendency to seek adventures and excitement, and the *Functional Impulsivity* subscale from the DII contributed to this factor. Among others, low deliberation (NEO-PI-R), decision time (EASI-III) and *BIS-11 Attentional* subscale were used to create *a posteriori* labelled *Premeditation* (the lack of) factor. Accordingly, this factor is defined as the tendency to carefully think and plan actions. Finally, *Perseverance* (the lack of) corresponds to the ability to remain on a task until completion and was composed, for example, of self-discipline items taken from the NEO-PI-R and persistence items from the EASI-III questionnaires. The *Urgency* and the *Sensation Seeking* subscores code for higher impulsivity with greater scores. However, the *Premeditation* and *Perseverance* subscores code for higher impulsivity with smaller scores. The global UPPS (i.e., the sum of the scores in the four subscales) is used as a global index of impulsiveness. In 2006, a revised version of the UPPS was published to take into account impulsive reaction following a positive emotion (Positive Urgency, UPPS-P, Lynam, Smith, Whiteside, & Cyders, 2006).

Table 1.1 – Description of the four UPPS questionnaire subscores items.

Factors	Example of items
Urgency	When I am upset I often act without thinking It is hard for me to resist acting on my feelings
Premeditation	I am a cautious person I am not one of those people who blurt out things without thinking
Perseverance	I generally like to see things through to the end I concentrate easily
Sensation Seeking	I quite enjoy taking risks I'll try anything once

Impulsiveness, the personality component of impulsivity, is therefore sub-divided into different personality traits, which can be specifically assessed through specific questionnaires or subscores. As the scope of this thesis is to gain a better understanding of the role of impulsivity as a whole in the vulnerability for psychiatric disorders, I assessed the global tendency to act impulsively using the global UPPS score in most of my studies.

1.2.2 Measuring impulsive behaviors

Impulsive behaviors refer to the temporary impulsive responses observed within a predefined window of time (i.e., what an impulsive individual produces in the current situation). In experimental settings, the set-up intends to capture the behavioral manifestations of the underlying personality traits (Sharma, Markon, & Clark, 2014). In cognitive research, most studies exploring the factorial structure of impulsivity revealed a distinction between behavioral activation and behavioral inhibition, commonly referred to as decision-making and action, respectively (e.g., Meda et al., 2009; Reynolds et al., 2006; Lane et al., 2003; MacKillop et al., 2016). Both behavioral components can be further divided as a function of the methodological tools used to conduct the assessment (see Figure 1.2). The two behavioral components of impulsivity, and their subdivisions, will be defined and described in the following sections.

Decision-making

The first behavioral component of the impulsivity spectrum is differently labelled across the literature: slow impulsivity (Bari & Robbins, 2013), hot impulsivity (Metcalfe & Mischel, 1999), choice impulsivity (Hamilton, Mitchell, et al., 2015). In this manuscript, I only refer to this component as “Impulsive Decision-Making”. Decision-making is here defined as a conscious and deliberate choice when consequences of all the alternatives are known (Bechara, 2005). Therefore, impulsive decision-making refers to the preference for the most disadvantageous alternative when presented with multiple choices. The unfavorable decision is made despite the knowledge of the outcomes and is thought to reflect the lack of consideration for the consequences (Arce & Santisteban, 2006). Within this definition, two impulsive decision-making components can be considered: the absence of delay gratification (i.e., choosing smaller-sooner over larger-later rewards) and risk-taking (i.e., voluntary endangerment of one-self, Lupton & Tulloch, 2002) (see Figure 1.2).

The inter-temporal choice tasks (ITCTs) and in particular the *Delay Discounting* task (Logue, 1988; Ainslie & Haslam, 1992), assess impulsive decision-making. In these paradigms, the participant is asked to choose between smaller-sooner rewards and larger-later rewards. In the original *Delay Discounting* task, the rewards were financial amounts but the rewards vary as a function of the population under investigation (e.g., number of cigarettes or drinks for patients with substance use disorder). The smallest reward is available immediately, whereas the largest is delayed in time with different time periods (e.g., two weeks, one month, six months, one year). For example, the participant has to choose between 10€ now or 100€ in a week, and between 10€ now or 100€ in a year. Generally, it is observed that the participant chooses the later-larger reward when the delay is short (one week), but the smaller-sooner reward when the delay is long (one year). Experimentally, it was reported that the subjective value (V) of a reward (A) decreases with the delay (D) to obtain it, following a hyperbolic function (Mazur, 1987), represented in the Figure 1.3:

$$V = \frac{A}{1 + kD}$$

In the above hyperbolic function, the k-value represents the steepness of the discounting function (i.e., the rate of delay discounting). The k-value is used as an index of impulsive decision-making: a higher k reveals higher impulsive decision-making, as observed in several pathological populations compared to controls (e.g., Bickel, Jarmolowicz, Mueller, Gatchalian, & McClure, 2012; Hamilton & Potenza, 2012; Albein-Urios, Martinez-González, Lozano, & Verdejo-Garcia, 2014; Leeman & Potenza, 2012; Kollins, 2003; Ahn et al.,

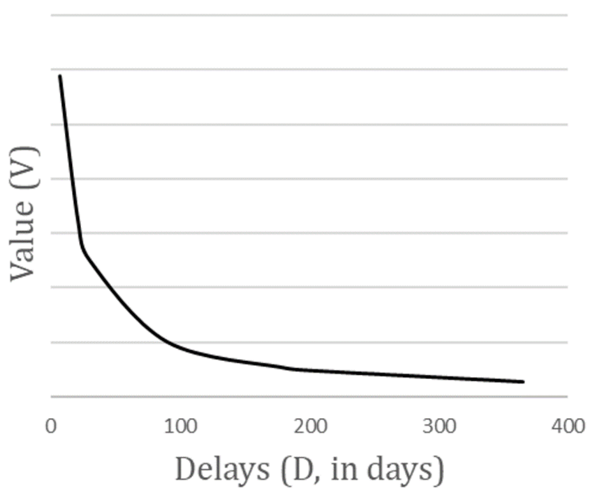

Figure 1.3 – Representation of the decrease in the value of a reward with delays. Fictive data.

2011; Lawrence, Allen, & Chanen, 2010). It is thought that a higher k reflects a higher tendency to choose smaller-sooner rewards (i.e., the delayed outcomes are more steeply discounted). An impulsive individual will choose the smaller-sooner option more often than a less impulsive individual, even when the larger reward can be obtained after a short delay.

The *Probability Discounting* is a variant of the *Delay Discounting* task, used to assess the risk-taking tendency by asking participants to choose between two financial amounts with differential probability of occurrence (e.g., 50€ with 100% of chances to obtain it vs. 100€ with 50% to obtain it). Generally, a potential reward is devalued compared to the same reward available for certain (e.g., the value of 50€ with 100% of chances to obtain it is higher than the value of 50€ with 50% to obtain it). In this paradigm, risk-taking is defined as a choice towards uncertainty (Shead & Hodgins, 2009). Other paradigms such as the Balloon Analog Risk Task (BART, Lejuez et al., 2002) or the Iowa Gambling Test (IGT, Bechara, Damasio, Damasio, & Anderson, 1994) are also thought to assess risk-taking. However, in the IGT, the consequences of the choice are not explicitly presented to the participant. The participant learns through experience which choices are advantageous and which ones are not. Impulsive behaviors in the IGT task may be more associated with perseveration on the disadvantageous choices. Hence, they do not fall into the impulsive decision-making category, as defined in this thesis.

Through the investigation of both *Delay Discounting* and *Probability Discounting* performances, Green and Myerson (2013) showed that delay gratification and risk-taking can be considered as two distinct behaviors. Smaller delay gratification (i.e., higher k-value) is not associated with higher risk-taking in the Probability Discounting task. Therefore, impulsive decision-making is subdivided into delay gratification and risk-taking (see Figure 1.2).

Motor action

The second aspect of impulsive behaviors is labelled differently across the literature: rapid-response impulsivity (Hamilton, Littlefield, et al., 2015; Bari & Robbins, 2013), motor impulsivity (Caswell, Morgan, & Duka, 2013). In this manuscript, I will refer to it as "Impulsive Motor Action". Impulsive motor actions are defined as involuntary risky and inappropriate executions of prematurely expressed motor actions (Herman & Duka, 2018). It is an immediate action that occurs with diminished forethought and which is out of context with the present demands of the environment (Hamilton, Mitchell, et al., 2015).

To assess the impulsive motor action component of the impulsivity spectrum, reaction times paradigms such as Go/NoGo (Donders, 1969) and Stop Signal tasks (Logan, Cowan, & Davis, 1984) have often been used. In these paradigms, the participant is invited to respond as fast and as accurately as possible to the stimulus. However, depending on the nature of the stimulus, the participant has to refrain from responding in some trials. In Go/NoGo-type tasks, the participant is required to respond as soon as a stimulus appears on the screen (i.e., Go trials). However, he/she is instructed to respond only to specific stimuli (e.g., letters) and to not respond if other stimuli appear (e.g., numbers). In Stop Signal tasks, the participant is instructed to respond as fast and as accurately as possible to a stimulus (e.g., an arrow pointing left or right - Go trials). In some trials, a Stop Signal occurs (e.g., visual or auditory signal - Stop trials) after the stimulus presentation at a variable delay. This delay is called the Stop Signal Delay (SSD). Errors in these tasks are therefore thought to reflect impulsive motor action, as they are inappropriate execution of prematurely expressed motor actions.

The nature of the errors in the Go/No-Go and in the Stop Signal tasks offers two forms of impulsive motor action (see Figure 1.2). According to Hamilton, Littlefield, et al. (2015), an impulsive action can be the result of the incapacity to refrain from acting (e.g., in the Go/NoGo task) or of the incapacity to stop an engaged action (e.g., in the Stop Signal task).

Synthesis

The analysis of the factorial structure of impulsivity, on the basis of methodological and statistical tools used to assess it, demonstrates the multidimensionality of the construct (Figure 1.2). Impulsivity encompasses personality traits, hereafter referred to as impulsiveness, and behavioral manifestations, hereafter referred to as impulsive behaviors. The number of dimensions that fall into these categories vary across studies. However, the precise structure of impulsivity is beyond the scope of the present research. Indeed, my PhD project aimed at providing empirical evidence to gain a better understanding of the relationship between impulsivity in the general population and psychiatric disorders. Sharma et al. (2014) showed that both impulsiveness and impulsive behaviors predict daily-life maladaptive behaviors, such as substance abuse, aggression and delinquency, suggesting a unique variance between both dimensions of impulsivity. Investigating the common feature between impulsiveness and impulsive behaviors could lead to understand why impulsivity, taken as a whole, may be a vulnerability factor for psychiatric health issues.

Several issues have been raised to explain the lack of correlation between impulsiveness and impulsive behaviors. Firstly, according to Odum (2011), the absence of correlation purely results from a methodological issue. Self-reported measures assess multiple facets of impulsivity whereas behavioral tasks tap into specific behavioral aspects of impulsivity, explaining the weak correlations between the two methodological tools. Secondly, impulsiveness refers to personality traits, a stable and consistent pattern over time, whereas impulsive behaviors are measures of state impulsivity in a short window of time. Therefore, the lack of correlation could be due to inherent limitations of the relationships between traits and states (Cyders & Coskunpinar, 2011, 2012). Thirdly, Sharma et al. (2014) postulated that a conceptualization issue could explain the lack of correlation between impulsiveness and impulsive behaviors. Indeed, impulsive behaviors should be viewed as manifestations of the "response style" which predisposes to act impulsively (i.e., impulsiveness). However, impulsive behaviors are measured as cognitive deficits (e.g., inability to delay gratification or to consider consequences, inability to inhibit a prepotent response). Finally, it is important to note that the factorial analyses reporting an absence of correlations between impulsiveness and impulsive behaviors were based on general population performances.

The absence of correlation in the general population might be due to efficient control

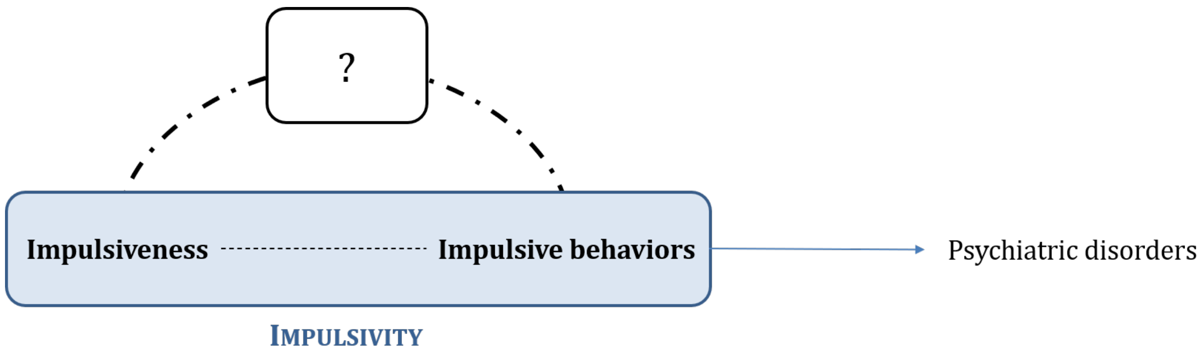

Figure 1.4 – **Relationships between impulsivity, impulsiveness, impulsive behaviors and psychiatric disorders.** Impulsivity, dissociated into two components: impulsiveness and impulsive behaviors, is strongly associated with psychiatric disorders. Self-reported and behavioral measures of impulsivity do not correlate in the general population, but are found to correlate in pathological populations. A component, related to the capacity to control impulses, moderates the link between impulsiveness and impulsive behaviors in the general population. In pathological populations, this component is impaired, resulting in the frequent emergence of impulsive behaviors, potentially leading to a psychiatric disorder.

capacities, that prevent the emergence of impulsive behaviors in experimental paradigms resulting from an impulsive response style (see Figure 1.4). Indeed, when impulse control capacities are impaired, the impulsive response style results in impulsive behaviors (correlations between impulsiveness and impulsive behaviors in pathological populations, e.g., Kirby, Petry, & Bickel, 1999; Swann, Bjork, Moeller, & Dougherty, 2002; Dougherty, Bjork, Marsh, & Moeller, 2000; Lawrence et al., 2010). Therefore, to identify the common feature between impulsiveness and impulsive behaviors, we must investigate impulse control capacities in the general population. For a long time, impulse control was thought to be strongly associated with inhibition capacities and therefore, studies investigated inhibition in relation to impulsivity. In the following chapter, I will claim that the association between inhibition and impulsivity is a shortcut, and that it is necessary to consider cognitive control for the study of impulsivity.

Chapter 2

From inhibition to cognitive control to investigate impulsivity

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"*The ability to suppress irrelevant or interfering stimuli or impulses is a fundamental executive function essential for normal thinking processes and, ultimately, for successful living*" (Garavan, Ross, & Stein, 1999, p. 8301)

To quote Diamond (2013), *"without inhibitory control, we could be at the mercy of impulses, old habits of thought and action and/or stimuli in the environment that pull us this way or that"*. In that statement, impulsive behaviors are directly linked to the lack of inhibition (i.e., disinhibition). Accordingly, for a long time, impulsivity was defined as the inability to inhibit prepotent and automatic responses (Barkley, 1997; Strack & Deutsch, 2003; Logan et al., 1984). Inhibition is a crucial feature in the limited-strength model to explain behaviors (Muraven & Baumeister, 2000). The association between inhibition and impulsivity was so strong that "impulsivity" and "disinhibition" were sometimes used as interchangeable terms (Nigg, 2017). Consequently, in the DSM-V (American Psychiatric Association, 2013), impulsivity has been defined as a facet of the broad domain "disinhibition". In the following sections, I will define the inhibition process through the description of its taxonomy. Then, I will review the link between inhibition and impulsivity to argue in disfavor of the use of "disinhibition" as another word for impulsivity. This conclusion will lead me to shift the investigation of impulsivity within the theoretical framework of cognitive control.

2.1 Impulsivity is not disinhibition

Inhibition is a cognitive process associated with the reduction or the suppression of activation. Tasks requiring the suppression of a prepotent response (i.e., the Go/NoGo task), stopping an ongoing response (i.e., the Stop Signal task) or the control of a variety of interferences (i.e., flanker tasks) are used to assess the efficiency in the inhibition process. However, performances in the different inhibition paradigms weakly correlate (e.g., Gärtner & Strobel, 2019), suggesting that inhibition is not an unitary construct. The inhibition process gathers a family of functions (for an extended review of the different taxonomies, see Rey-Mermet, Gade, & Oberauer, 2017) that will be defined and described in the following sections. Then, I will review the literature on impulsivity and inhibition that focused on one specific inhibition function. These points will lead to the conclusion that impulsivity can not be simply defined as disinhibition.

2.1.1 Taxonomy of the inhibition process

A convergent structure of the inhibition process emerges from the different taxonomies that have been theorized through the years (Rey-Mermet et al., 2017). A first distinction in the inhibitory construct is made between inhibition and interference control (Harnishfeger, 1995; Friedman & Miyake, 2004). Wilson and Kipp (1998) postulated that "*inhibition is an active suppression process that operates on the contents of working memory, whereas resistance to interference is a gating mechanism that prevents irrelevant information or distracting stimuli from entering working memory*". A second distinction made within the concept of inhibition is the differentiation between cognitive and behavioral inhibition (Harnishfeger, 1995; Nigg, 2000). According to Friedman and Miyake (2004), "*behavioral inhibition controls behavior and is reflected in such processes as inhibiting motor responses and controlling impulses, whereas cognitive inhibition controls mental processes such as attention and memory, and is reflected in suppressing unwanted of irrelevant thoughts*". In the following sections, I will define precisely each one of these complementary but yet distinct, inhibition functions (i.e., interference control, cognitive inhibition and behavioral inhibition, see Table 2.1 for the other terminologies used in the literature).

Table 2.1 – Taxonomies of the inhibition process, associations with the terms used in the present manuscript and the corresponding experimental paradigms. Adapted from Rey-Mermet et al. (2017).

References	**Interference control**	**Cognitive inhibition**	**Behavioral inhibition**
Harnishfeger (1995)	Resistance to interference	Cognitive inhibition	Behavioral inhibition
Nigg (2000)	Interference control	Cognitive inhibition	Behavioral inhibition
Friedman and Miyake (2004)	Distracter interference	Proactive interference	Prepotent response inhibition
Stahl et al. (2014)	Stimulus interference	Proactive interference	Response interference/ Behavioral inhibition
Experimental paradigms	Flanker, Word naming	Brown-Peterson, AB-AC-AD	Stop Signal task, Stroop task

Interference control

Interference control (also called distractor and stimulus interferences, Cragg, 2016; Friedman & Miyake, 2004) operates at an early stage of information processing, when relevant information has to be selected whereas the irrelevant information must be ignored (Friedman & Miyake, 2004) to help us guide our thoughts and our actions (Cragg, 2016). "Interference" refers to all external irrelevant information that interferes with information processing and task execution. A notification alert for a new mail (e.g. as a visual or an auditory pop-up) while working is an interference. At a perceptual level, the mail notification interferes with the goal-directed action and task execution. Thus, interference control refers to "the ability to resist or resolve interference from information in the external environment that is irrelevant to the task at hand" (Friedman & Miyake, 2004). Paradigms such as the flanker task (Eriksen & Eriksen, 1974), word naming (Kanes, Hasher, Stoltzfus, Zacks, & Connelly, 1994) and shape matching (Treisman & Schepper, 1996) are thought to assess interference control capacities. In these paradigms, participants are asked to respond to a target stimulus (e.g., a letter, a word or a shape) while ignoring distractors (e.g., other letters, words or shapes). The main consequence of these distractors is to slow down the processing of the target stimuli. Interference control is thus assessed as the difference in reaction times between conditions with and without distractors.

Cognitive inhibition

Cognitive inhibition (also called resistance to proactive interference) refers to the suppression of an irrelevant information present in working memory (Nigg, 2000; Friedman & Miyake, 2004) and operates at an intermediate stage of information processing. In daily situations, cognitive inhibition would be involved in suppressing an old memorized grocery list when doing groceries with a new list of items in memory. This inhibitory function is less studied. However, paradigms such as the AB-AC-AD (Rosen & Engle, 1998) and the Brown-Peterson type tasks (Brown, 1958; Peterson & Peterson, 1959) are thought to assess cognitive inhibition. In both of these paradigms, there is a learning phase and a recall phase. First, the participant is instructed to learn two lists of words (or pairs of words). In the Brown-Peterson paradigm, the two lists are composed of words from the same categories. In the AB-AC-AD paradigm, multiple pairs of words are composed with an identical word (e.g., dog/cat, dog/kennel). The participant is asked to recall one list of words (or paired-words) while resisting the memory intrusions from the other set of items.

Behavioral inhibition

Behavioral inhibition, also called response interference (Stahl et al., 2014; Cragg, 2016) refers to the suppression of dominant, automatic or prepotent responses (Nigg, 2000; Friedman & Miyake, 2004). It operates at a later stage, during the execution of a motor response in which relevant responses must be selected and incorrect ones resisted (Friedman & Miyake, 2004). A slight difference can be observed between response interference and behavioral inhibition. Cragg (2016) defined the response interference as the capacity to refrain from acting whereas behavioral inhibition is the capacity to stop an engaged action (Nigg, 2000; Friedman & Miyake, 2004). Continuing with the notification alert example, response interference would refrain a person from moving towards the notification whereas behavioral inhibition would correspond to the action being stopped whereas the movement had already been set in motion. To simplify, throughout the manuscript, behavioral inhibition will refer to both response interference and behavioral inhibition functions. Behavioral inhibition is the most largely studied inhibition functions through paradigms such as the Stop Signal task (Logan et al., 1984), the Stroop task (Stroop, 1935), the Go/No-Go (Donders, 1969) and the antisaccade task (Hallett, 1978). In these paradigms, the participant is asked to inhibit an engaged motor response if a stop signal appears, to name the color of a word without reading the word, to refrain from acting upon a specific stimulus and to make a saccade in the opposite direction of a cue, respectively.

Inhibition is a cognitive process that encompasses several functions, assessed by various tasks requiring the suppression of a prepotent response, stopping an ongoing response or the control of a variety of interferences (cf. Table 2.1). It is interesting to note that, in the study of impulsivity, it is behavioral inhibition that has mainly been targeted. Indeed, the capacity to inhibit prepotent and automatic responses is central in several definitions of impulsivity (Barkley, 1997; Strack & Deutsch, 2003; Logan et al., 1984). Moreover, Friedman and Miyake (2004) directly linked behavioral inhibition capacities with impulse control[1]. Accordingly, behavioral inhibition impairments, as revealed by errors in Go/No-Go-type task or the Stop Signal task, are thought to reflect impulsive motor action, a behavioral component of the impulsivity construct defined in Chapter 1.

2.1.2 Inhibition in impulsive individuals

Some studies reported behavioral inhibition deficits in eating disorder patients (Rosval et al., 2006), alcohol-dependent patients (Lawrence, Luty, Bogdan, Sahakian, & Clark, 2009), cocaino-dependent patients (Li, Milivojevic, Kemp, Hong, & Sinha, 2006) and problematics gamblers (Kertzman, Vainder, Aizer, Kotler, & Dannon, 2017; Billieux et al., 2012). However, all studies did not report deficits in behavioral inhibition in the same impulsive-related pathological populations, such as eating disorders (Claes, Nederkoorn, Vandereycken, Guerrieri, & Vertommen, 2006) and problematic gamblers (Lawrence et al., 2009). Moreover, behavioral inhibition impairments were not reported in other impulse-

1. Friedman and Miyake (2004) postulated that behavioral inhibition was reflected in processes such as inhibiting motor responses and *controlling impulses*.

related pathological populations such as skin picking patients (i.e., a form of impulse-control disorder, Snorrason, Smári, & Ólafsson, 2011), borderline personality disorder patients (Jacob et al., 2010) or in cannabis users (Dafters, 2006). Hence, behavioral inhibition capacities deficits are not consistently observed in these pathological populations. Although impulsivity is a key characteristic of the aforementioned disorders, it does not always involve behavioral inhibition impairments. Moreover, inhibition failed to predict a broad array of impulsive-related behaviors such as compulsive spending, risky-sexual behaviors and aggression in a large sample of healthy individuals (Von Gunten, Bartholow, & Martins, 2019).

Behavioral disinhibition seems to be associated with specific sub-types of impulsiveness and impulsive behaviors, but fails to explain the variability in impulsivity as a whole (Caswell et al., 2013; Enticott, Ogloff, & Bradshaw, 2006; Wilbertz et al., 2014). Indeed, Enticott et al. (2006) investigated the relationship between inhibition and impulsiveness in normal adults. Impulsiveness, assessed with the BIS-11 questionnaire (Patton et al., 1995), was associated with a larger Stroop conflict, revealing decreased behavioral inhibition capacities in high impulsive individuals. However, no significant correlations were found between impulsiveness and other indices of behavioral inhibition capacities. According to the findings reported by Wilbertz et al. (2014), the SSRT was only predicted by the *Urgency* subscale of the UPPS questionnaire. Finally, efficient inhibitory control capacities did not prevent from impulsive decision-making (Caswell et al., 2013) and therefore, does not contribute to other behavioral components excepted impulsive motor action.

The review of the literature on the link between inhibition and impulsivity was dominated by results in behavioral inhibition capacities and therefore, little is known about the relationship between impulsivity, interference control and cognitive inhibition. Moreover, the above results are heterogeneous. Indeed, behavioral inhibition deficits are not always reported in impulse-related pathological and in the general population.

Synthesis

In the above sections, I reported two main aspects that suggest that disinhibition should not be used as an interchangeable term for impulsivity (Nigg, 2017). Firstly, inhibition is a cognitive process that encompasses several functions (i.e., interference control, cognitive inhibition and behavioral inhibition). Studies investigating impulsivity and inhibition mostly focused on behavioral inhibition capacities, as it was associated to impulse control (Friedman & Miyake, 2004). According to Rey-Mermet et al. (2017), results from studies that investigate inhibition through one paradigm can not be generalized to inhibition process as a whole. Secondly, beyond the generalization issue, results from these studies are mixed. Behavioral disinhibition explains specific impulsive behaviors and impulsiveness aspects (Caswell et al., 2013; Enticott et al., 2006), but not the entire impulsivity spectrum.

2.2 Investigating the cognitive control system

"*Thus, only with the concerted action of attention, inhibition and cognitive flexibility we can successfully monitor our performance in relation to external or internal feedback and update our plans/goals to better cope with an ever-changing environment.*" (Bari & Robbins, 2013)

Associating disinhibition and impulsivity is a shortcut as it blurs the multidimensionality of both constructs. Additionally, one can argue that the control of impulses does not require behavioral inhibition mechanisms only. Indeed, we do not act on every information our brain processes and therefore, we do not have to constantly inhibit impulses. Though behavioral inhibition is a crucial component of control capacities, other functions are indeed required to control impulses (Bari & Robbins, 2013). Therefore, to investigate how impulsiveness may predict impulsive behaviors and thus, be a vulnerability factor for psychiatric disorders, one must explore other cognitive functions that are involved in impulse control. Interestingly, previous studies have reported that the relationship between impulsiveness and impulsive behaviors was moderated by the efficiency of cognitive control. Bulimic symptoms and risk-taking behaviors were reduced in high impulsive individuals with an efficient cognitive control system (Robinson, Pearce, Engel, & Wonderlich, 2009; Youssef et al., 2016). The cognitive control system is therefore a promising target in the understanding of the relationship between impulsiveness and impulsive behaviors. The following sections will define the cognitive control system through the description of two theoretical models.

2.2.1 Definition and paradigms

Humans live in a complex and ever-changing environment as several sources of stimulation are always overflowing our cognitive system. When driving, we have to monitor the road and our own behaviors in order to stay adapted to external demands (e.g., speed limits, the other drivers' behaviors) and to internal goals (e.g., not contributing to a traffic accident). The ability of oneself to appropriately behave in such a complex and unpredictable situation is therefore crucial and relies on cognitive control. As the environment is always changing, the cognitive control is constantly involved to adapt behaviors to the new context.

Defining cognitive control

Cognitive control refers to a set of basic executive functions that allow us to pursue goal-directed behaviors and to vary them appropriately depending on our current goals, in the face of otherwise more habitual or immediately compelling behaviors (Cohen, 2017; Inzlicht, Bartholow, & Hirsh, 2015; Nigg, 2017). Executive functions (i.e., inhibition, working memory and shifting, Miyake et al., 2000) are partially independent cognitive functions involved in top-down control of emotion and cognition, supporting goal-directed behaviors (Nigg, 2017). Executive functions are orchestrated, coordinated and directed in their temporal structure in accordance with internal and external demands (Ridderinkhof, Forstmann, Wylie, Burle, & van den Wildenberg, 2011). The cognitive control allows us to resist the temptation to act upon every stimulation our system is processing by constantly reconfiguring the cognitive system, through perceptual selection of goal-relevant information, response biasing and online maintenance of contextual information (Botvinick, Braver, Barch, Carter, & Cohen, 2001). Various theoretical models have been proposed to explain cognitive control through the investigation of executive functions (e.g., Cohen, Dunbar, & McClelland, 1990; Norman & Shallice, 1986; Baddeley et al., 1996). However, these models account for the control capacities as the executive level, but not for how the system determines when control is required (Botvinick et al., 2001).

According to Botvinick et al. (2001)'s model, the cognitive control system must measure the competition between several response alternatives at the current trial (i.e., called a conflict) to evaluate the need for control in subsequent trials. However, according to the dual mechanisms of control (DMC) postulated by Braver (2012), these behavioral adjustments are not only set for subsequent trials (i.e., proactive control), but can also can be involved online (i.e., reactive control). In the next sections, both Botvinick et al. (2001)'s and Braver (2012)'s cognitive control models will be presented. However, prior to the models, I will expose how conflicts are created in laboratory settings to investigate cognitive control.

Stimulus-response manipulation paradigms

To investigate cognitive control (i.e., the capacity to adjust behaviors to external and internal demands), experimenters need to create a complex environment to promote the emergence of inappropriate behaviors (i.e., errors). In order to do so, the stimulus-response congruency is manipulated in paradigms such as the Stroop task (Stroop, 1935) or the Simon task (Simon, 1990). In these experimental paradigms, the stimulus bears relevant and irrelevant attributes. The relevant attribute is the information associated with the expected response, whereas the irrelevant attribute interferes with the response execution. In the Stroop task, the participant is instructed to name the color of the ink (i.e., the relevant attribute) without reading the word (i.e., the irrelevant attribute). In the Simon task, the participant has to press a right or a left button as a function of the stimulus color (i.e., the relevant attribute) without taking into account the localization of the stimulus on the screen (i.e., the irrelevant attribute). When the irrelevant attribute does not interfere

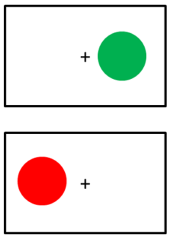
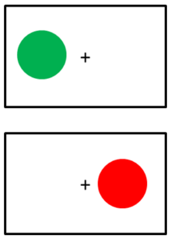
Paradigms	**Instructions**	**Congruent trials**	**Incongruent trials**
Stroop (1935)	Name the color of the ink as fast and as accurate as possible.	RED BLUE GREEN	RED BLUE GREEN
Simon (1990)	Press right if the circle is green and left if the cercle is red as fast and as accurate as possible.		

Figure 2.1 – **Experimental paradigms using the stimulus-response congruency manipulation to create conflictual situations (i.e., incongruent trials).**

with the response (the word "Red" written in red, or the stimulus appearing on the same side as the response to be given), the trial is defined as **congruent** (cf. Figure 2.1). On the contrary, when the irrelevant attribute does interfere with the response (the word "Red" written in blue, or the stimulus appearing on the opposite side of the response), the trial is defined as **incongruent** (cf. Figure 2.1).

According to Kornblum, Hasbroucq, and Osman (1990)'s dual-route hypothesis, the relevant and irrelevant attributes activate two distinct roads of information processing in the cognitive system. One, fast and automatic, processes the irrelevant attributes (see Figure 2.2). The other road, slow and controlled, processes the relevant attribute. When both roads trigger the same response output (congruent trials), there is no interference. However, when both roads trigger different responses (incongruent trials), two responses are simultaneously activated and compete for execution: this co-activation is called **conflict**. Moreover, when the processing of the irrelevant attribute is faster than the processing of the relevant attribute (e.g., reading is an automatic process and the localization of an object is more rapidly processed than its visual features), inhibition of the automatic response is required to produce the correct response in an incongruent trial. Reaction times (RTs) are thus longer in incongruent trials than in congruent trials: this effect is called the **congruency effect** and reveals the presence of control processes to inhibit the prepotent response driven by the irrelevant attribute of the stimulus. A smaller congruency effect reflects a more efficient cognitive control system. Moreover, the congruency effect varies as a

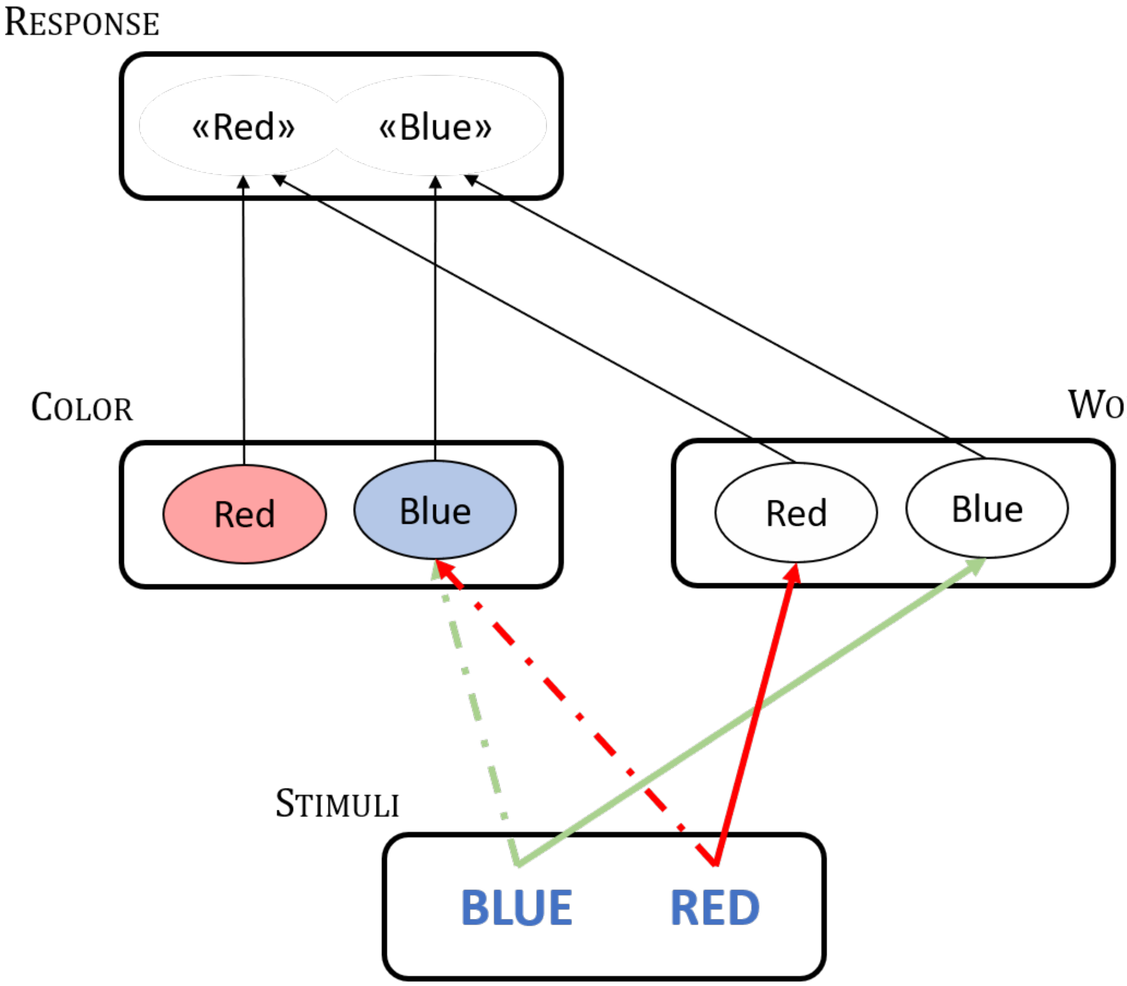


Figure 2.2 – **Graphical representation of the dual route hypothesis model in a Stroop task.** Bold arrows represent the fast and automatic processing of the irrelevant attribute (i.e., reading of the word). Dotted arrows represent the slow and controlled processing of the relevant attribute (i.e., the color of the ink). In congruent trials ("Blue" written in blue), both the processing of the relevant and the irrelevant attribute (i.e., green arrows) activate the same response: there is no conflict between the responses. In incongruent trials ("Red" written in blue), the two roads (i.e., red arrows) activate two different responses, creating a conflict. Adapted from Kornblum et al. (1990).

function of the reaction times. The longer the RT is (i.e., slow response), the less the irrelevant attribute disturbs the response execution and thus, smaller is the congruency effect (Burle, Possamaï, Vidal, Bonnet, & Hasbroucq, 2002). The suppression of the irrelevant attribute takes time (Ridderinkhof, 2002). Therefore, one strategy to better perform the task is to slow down the response, to have more time to suppress the irrelevant attribute. To prevent this strategical slowing of reaction times in the stimulus-response congruency paradigm, the instructions emphasize both speed and accuracy (i.e., to respond as fast and as accurately as possible). The stimulus-response congruency manipulation under time pressure promotes cognitive control by creating conflictual situations that need to be controlled and resolved in order to execute the appropriate behavior.

The co-activation of multiple responses creates conflicts and thus, increases the need of control as the correct response must be selected and the incorrect responses must be inhibited. Therefore, conflicts are considered to trigger behavioral adjustments (Botvinick et al., 2001; De Pisapia & Braver, 2006).

2.2.2 What controls control: The conflict-monitoring loop theory

Early in the 1960's, the occurrence of a conflict (i.e., the co-activation of competitive responses) was suggested to lead to behavioral adjustments for conflict resolution (Berlyne, 1960). In their model, Botvinick et al. (2001) therefore placed the conflict at the center of the cognitive control processes by considering the conflict as the information that modulates the need of behavioral adjustments. On the basis of this postulate, a system must exist in the brain that is sensitive to conflict. A (or multiple) brain region(s) should be differently activated in congruent trials (i.e., low conflict trials) compared to incongruent trials (i.e., high conflict trials).

Functional magnetic resonance imaging (*f*MRI) measures and localizes the brain activity during the completion of a task, by detecting changes in the blood oxygenation. Using this technique, MacDonald, Cohen, Stenger, and Carter (2000) observed a greater activation in the anterior cingulate cortex (ACC) in incongruent trials compared to congruent trials during a Stroop task. This observation was consistent with previous findings (e.g., Pardo, Pardo, Janer, & Raichle, 1990; Carter, Mintun, & Cohen, 1995) and suggested that the ACC is sensitive to the presence of a conflict. Interestingly, the ACC is strongly connected to prefrontal regions (PFC). Several studies have reported that ACC and PFC activations often co-occur (e.g., Carter et al., 1995; Posner, Petersen, Fox, & Raichle, 1988). Consistently, in MacDonald et al. (2000)'s study, the activity of the dorsolateral PFC (DLPFC) was stronger when the task was to name the color of the ink (i.e. task that requires cognitive control) compared to the activity observed when the task was to read the word. The study by MacDonald et al. (2000) suggests that two brain regions are involved during the execution of a cognitive control paradigm. The DLPFC is activated when the task requires control whereas the ACC is sensitive to the level of conflict.

Both the ACC and the DLPFC are represented in the conflict-monitoring loop theory of Botvinick et al. (2001). Layers and pathways are integrated to account for the modulation of control by the conflict. The **conflict layer**, supported by the ACC, strongly activates when competitive responses are activated in the response layer (e.g., RED written in blue activates both the response "red" and the response "blue", see Figure 2.3). The activity of the conflict layer reflects the level of conflict in the current trial. The detection of a conflict thus activates the conflict layer, which then triggers behavioral adjustments in the **task layer**, supported by the PFC brain regions, including the DLPFC (MacDonald et al., 2000). The PFC regions bias information processing by strengthening the processing of relevant information and weakening the processing of irrelevant information for the subsequent trial. It is thought that the detection of a high degree of conflict in the conflict layer increases the activation of the relevant task layer to bias processing in favor of the relevant information for the subsequent trial. In the model by Botvinick et al. (2001), the behavioral adjustments are triggered as a function of conflict level, computed in the ACC. The conflict leads control for subsequent trials only. No mechanism is presented to explain how the online resolution of a conflict may be achieved.

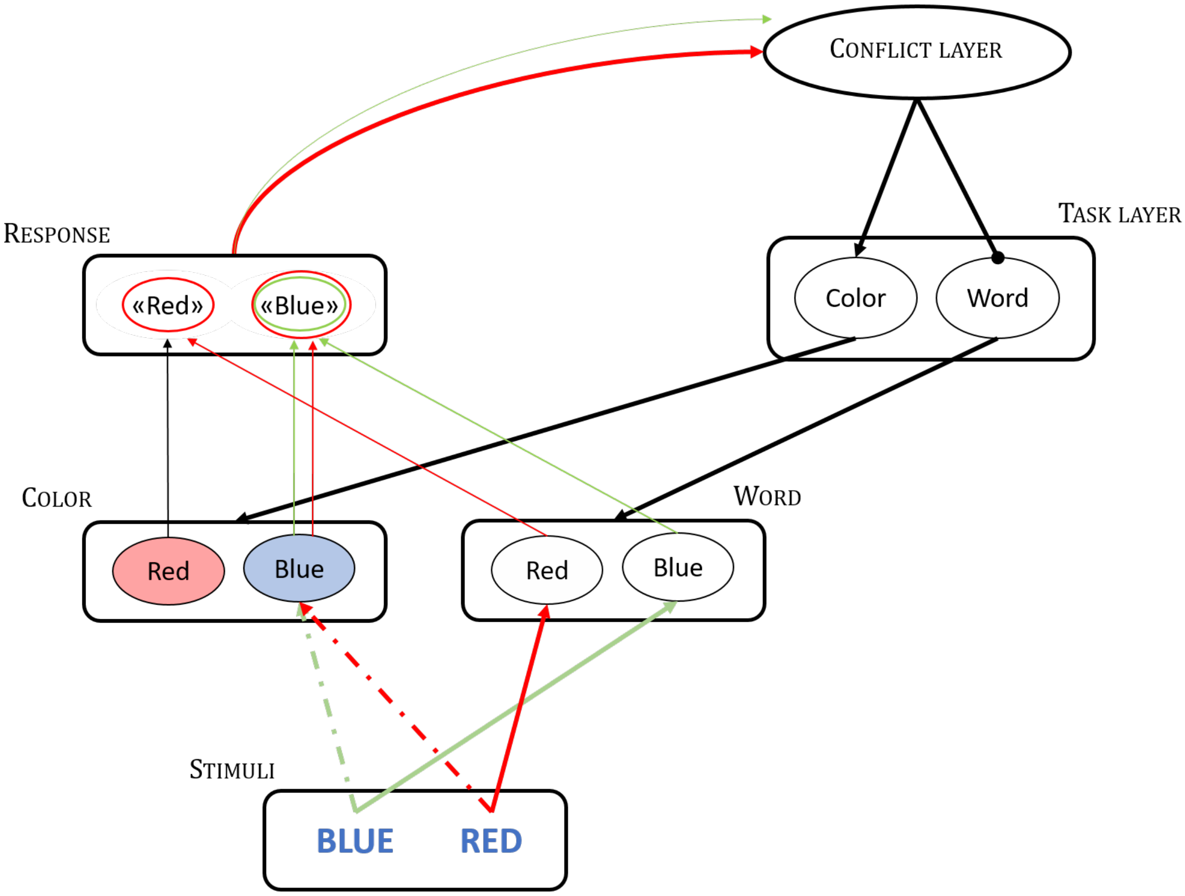


Figure 2.3 – **Graphical representation of the original conflict monitoring theory of cognitive control.** The processing of a congruent stimulus (i.e., low conflict situation) is represented in green. The processing of an incongruent stimulus (i.e., high conflict situation) is represented in red. The level of conflict (i.e., co-activation of competitive responses) in the response layer activates the conflict layer. This activation biases the processing of the stimulus in the subsequent trial, by inhibiting the processing of the irrelevant task (circle-head connection) and favoring the processing of the relevant attribute (arrow-head connection). Adapted from Botvinick et al. (2001).

2.2.3 How do we control: The dual mechanisms of control (DMC)

As mentioned earlier, cognitive control processes are crucial to adjust constantly behaviors according to external constraints and to internal goals, and especially in complex situations such as driving. Botvinick et al. (2001)'s model provides elements to describe how behavioral adjustments are triggered as a function of the situation. In the same theoretical line of research, Braver (2012) postulated the existence of two distinct control mechanisms, involved in behavioral adjustments: the proactive and the reactive control mechanisms. In the following sections, I will define the two components of the dual mechanisms of control (DMC) and then, describe how the Botvinick et al. (2001)'s model may be adapted to account for the two control mechanisms.

Proactive and reactive control mechanisms

Proactive control refers to a early goal-driven selection and active maintenance of goal-relevant information, in order to optimally bias attention, perception and the action system to facilitate the resolution of future conflicts (Braver, 2012). On the contrary, reactive control is a stimulus-driven late correction mechanism, mobilized when needed, after the detection of a conflict (Braver, 2012). Both control mechanisms aimed at adjusting behaviors to external and internal demands, but they differ in their temporal dynamics. The proactive control mechanism relies on the prevention of interference, prior to its occurrence, whereas the reactive control mechanism relies on the resolution of the interference, after its occurrence.

Let's head back to the driving example to illustrate these control mechanisms. When arriving in a crowded area, one can slow down the car to anticipate the sudden crossing of a pedestrian. In this case, proactive control mechanisms are involved. The behavior is changed before an interference occurs, to facilitate its resolution if it does occur. However, if one does not change his/her behavior, but rather waits and brakes when the pedestrian is crossing, reactive control is involved. Proactive and reactive control are complementary and independent mechanisms that can be simultaneously engaged (Braver, 2012; Mäki-Marttunen, Hagen, & Espeseth, 2019a). Indeed, slowing down the car does not prevent from braking the car if necessary. However, one control mechanism may dominate over the other as a function of the situations.

Each control mechanisms have different costs and benefits, making them more or less optimal depending on the context or on inter-individual differences (Braver, 2012; Chiew & Braver, 2017). Proactive control mechanisms rely on sustained attention on goal-relevant information to anticipate interferences and are therefore robust against distractors (Del Giudice & Crespi, 2018). However, this robustness is at the expense of flexibility (Hefer & Dreisbach, 2016) and is resource-consuming compared to reactive control mechanisms. Reactive control is indeed more flexible, as it is transiently involved when an interference is detected. However, it is more vulnerable to distractors. Overall, reactive control is flexible but fragile whereas proactive control is robust but costly (Del Giudice & Crespi, 2018). In unpredictable environments, such as the crowded area of our example where pedestrian can randomly cross the road, proactive control mechanisms are favored to reduce the risk of inappropriate behaviors. However, in predictable environments (e.g., the usual route between home and work), reactive control mechanisms will be favored by the system to limit the cognitive costs. The flexible shift between these two control mechanisms, as a function of the cost/benefit ratio of the cognitive control system, is the key to adaptive behaviors (Braver, 2012; Braver, Gray, & Burgess, 2007).

The conflict-monitoring model in the DMC

Modifying the original cognitive control model proposed by Botvinick et al. (2001) to support the DMC, De Pisapia and Braver (2006) postulated that the ACC-PFC interactions are divided into two conflict-control loops (cf. Figure 2.4). In their model, there are two task layers, a reactive one and a proactive one, supported by two distinct PFC units, and two conflict layers supported by two distinct ACC units. Similarly as Botvinick et al. (2001)'s model, the conflict layers compute the level of conflict in the response layer (i.e., the co-activation of competitive responses). However, one conflict unit measures conflict in a short time-scale window and modulates the activity of the reactive-task unit. The second conflict unit measures conflict in a long time-scale window, as an average of

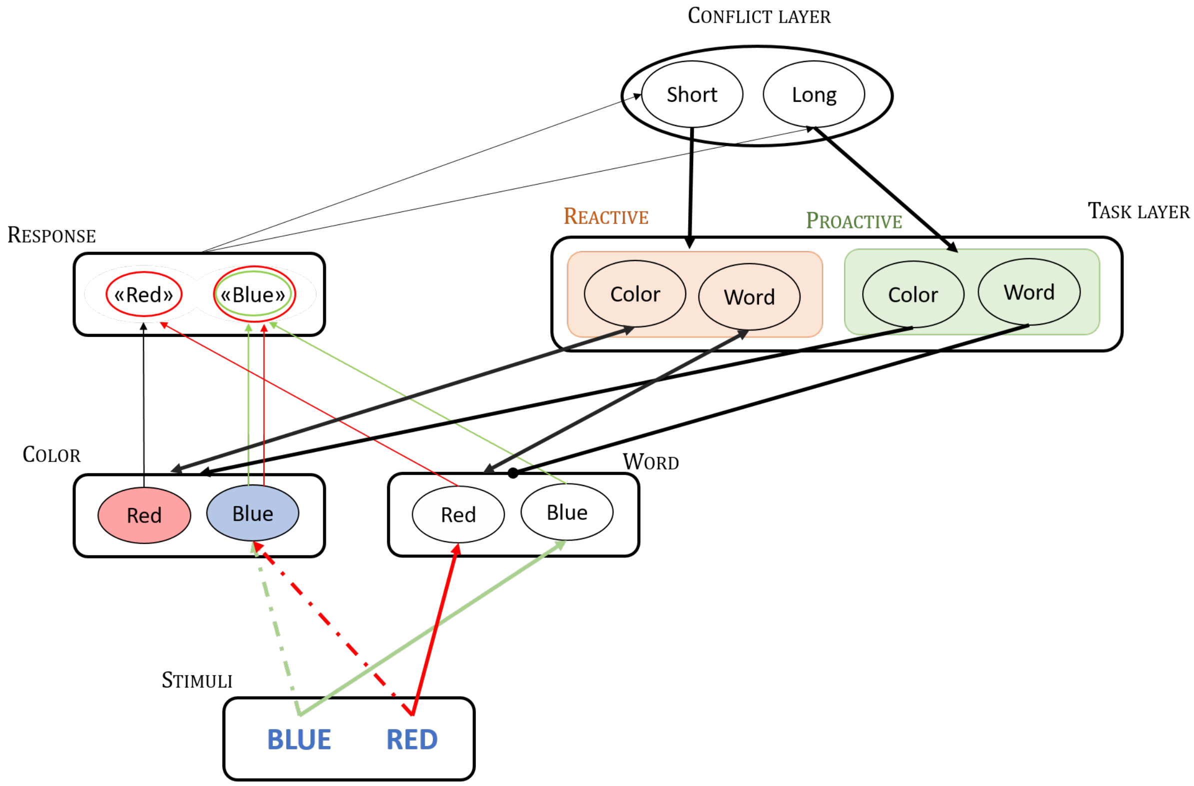


Figure 2.4 – **Graphical representation of the De Pisapia & Braver (2006)'s cognitive control model.** Arrows and circle-heads connections refer to excitatory and inhibitory connections, respectively. The orange area refers to the reactive task unit, activated by the short time-scale conflict unit. The green area refers to the proactive task unit, activated by the long time-scale conflict unit. Adapted from De Pisapia & Braver (2006).

previous short time-scale conflicts, and modulates the activity of the proactive-task unit. The proactive-task unit has self-recurrent weights that are selectively increased or decreased following each trial as a function of long time-scale conflict input. These weights reflect the active maintenance of task information during the task. The loop between the long time-scale conflict and the proactive-task units is similar to the model exposed by Botvinick et al. (2001), but De Pisapia and Braver (2006)'s model included the online behavioral adjustments, which correspond to the loop between the short time-scale conflict and reactive-task unit.

When the congruent trials are more frequent than the incongruent trials, the conflicts are rare. This situation is called MC (i.e., most congruent) and promotes reactive control. In such case, the activation in the long time-scale conflict unit is small and the self-recurrent weights in the proactive-task unit decay. On the contrary, when the incongruent trials are more frequent than the congruent trials, the conflicts are frequent. This condition is called MI (i.e., most incongruent) and promotes proactive control. In such case, the activation in the long time-scale conflict unit is greater and the proactive-task unit is activated to maintain task information. Both in the MC and in the MI conditions, the short time-scale conflict unit reacts to conflict and triggers reactive behavioral adjustments, but the activation of the long time-scale conflict increases throughout the task in the MI condition only, to engage proactive control resources. Proactive and reactive control mechanisms are therefore distinguishable by the temporal dynamics of the lateral PFC activity (Braver, 2012). The anterior lateral PFC activation is sustained in the proactive MI condition in order to actively maintain goal-relevant information (De Pisapia & Braver, 2006). On the contrary, the lateral PFC activity is transient in the reactive MC condition, revealing punctual bottom-up reactivation of task goals (De Pisapia & Braver, 2006). The model also accounts for different patterns of transient ACC activations between reactive and proactive conditions (see Figure 2.5). It has been reported experimentally that the percentage of signal change in BOLD signals in the ACC was greater in incongruent trials compared to congruent trials in the reactive MC condition only (De Pisapia & Braver, 2006). When proactive control is required, in the MI condition, the change in the ACC activation did not differ as a function of the congruency nature of the trials.

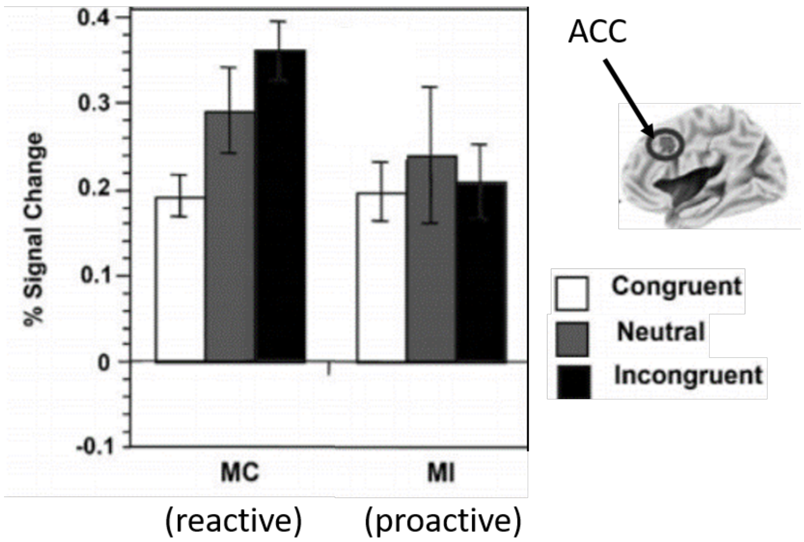


Figure 2.5 – **Transient percentage change in BOLD signals in the ACC as a function of congruency and conditions.** *MC*: most congruent condition (70% congruent, 15% neutral, 15% incongruent). *MI*: most incongruent condition (15% congruent, 15% neutral, 70% incongruent). Adapted from De Pisapia & Braver (2006).

Conclusion

Inhibition capacities are largely targeted in the investigation of impulsivity. Among the cognitive functions gathered under the umbrella term "inhibition", behavioral inhibition capacities have been the most studied. However, a brief review of the literature has revealed mixed results. Therefore, the shortcut that we made by saying that being impulsive is being disinhibited is false (Nigg, 2017). Impulsivity and inhibition are multidimensional constructs and the relationship between disinhibition and impulsivity is only true for some specific aspects of the two constructs.

Even if crucial for impulse control, inhibition is not sufficient to explain the lack of control over impulses. Previous studies have shown that efficient cognitive control can play the role of moderator between impulsiveness and impulsive behaviors (e.g., Robinson et al., 2009; Youssef et al., 2016). These findings suggest that cognitive control can be thought as the moderator between impulsiveness and impulsive behaviors as seen in Chapter 1. According to the models by Botvinick et al. (2001)'s and Braver (2012)'s models, the cognitive control system can be decomposed into three main components: conflict monitoring, reactive control and proactive control and their interplay that all

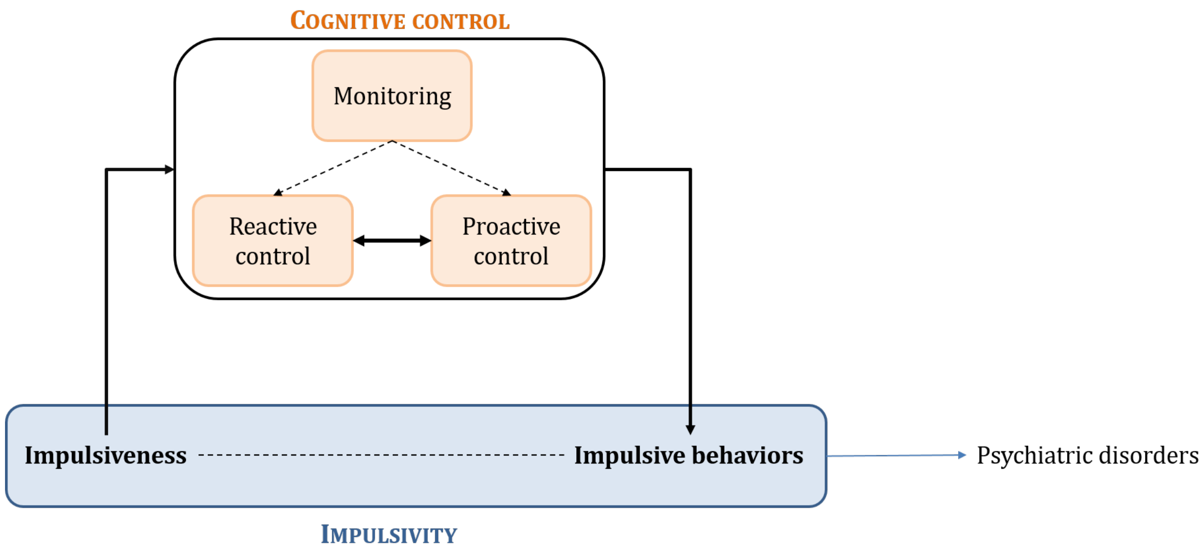


Figure 2.6 – **Moderation of the relationship between impulsiveness and impulsive behaviors through the efficiency of the cognitive control system.** Cognitive control is composed of three components that are orchestrated in order to adjust behaviors to external and internal demands. Efficiency in each components, and the flexible shift between reactive control and proactive control mechanisms (represented by the double-head arrow), are crucial for adaptive behaviors.

ensure adaptive behaviors (see Figure 2.6).

To investigate the relationship between impulsiveness, impulsive behaviors and cognitive control, one can therefore study the individual efficiency of each cognitive control components, but also exploring the implementation and the adaptation of the dual mechanisms of control. The following chapter will be dedicated to the investigation of cognitive control through the behavioral and electrophysiological indices of the efficiency of conflict monitoring, reactive control and proactive control. It will also aim at reporting results offering the possibility to operationalize the dual mechanisms of control (Braver, 2012).

Chapter 3

The two-level investigation of the cognitive control system

Impulsiveness is considered as a vulnerability factor for the emergence of psychiatric disorders diagnosed through the observation of impulsive behaviors. Efficient cognitive control, assessed with behavioral performances, ensures adaptive behaviors through the reduction in impulsive behaviors in high impulsive individuals (Youssef et al., 2016; Robinson et al., 2009; McKewen et al., 2019). However, what makes the cognitive control system efficient? On the one hand, adaptive behaviors rely on the efficiency of the three cognitive control components described in Chapter 2.2: conflict monitoring, proactive and reactive control. On the other hand, according to the dual mechanisms of control (Braver, 2012; Braver et al., 2007), the flexible shift between reactive and proactive control is key to adaptive behaviors. Therefore, impulsive behaviors may result from impairments in cognitive control at two levels. The first section of this chapter is dedicated to the indices used to explore the efficiency in the cognitive control components, and their relationships with impulsivity. The second section of this chapter aims at defining the experimental paradigm used to explore the implementation and adaptation of proactive and reactive mechanisms. It will also review the contextual and inter-individual factors that impact the use of proactive and reactive mechanisms.

3.1 Efficiency in the cognitive control components

To ensure adaptive behaviors, the cognitive control system requires the efficiency in its three components defined in Chapter 2.2. The error(-related) negativity (ERN/Ne), the

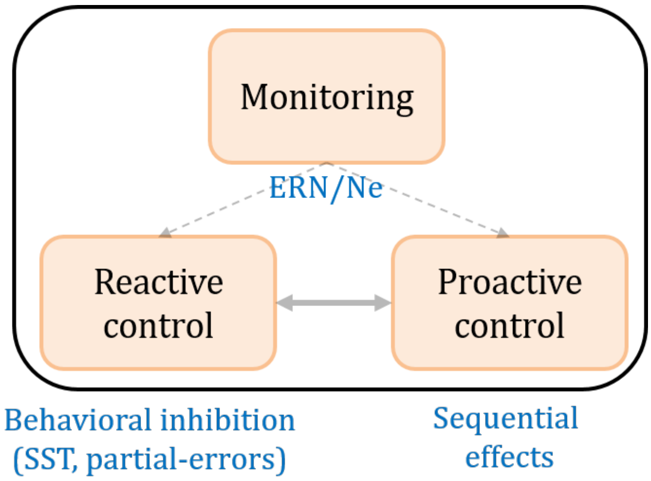


Figure 3.1 – **Indices used to investigate the efficiency in the three cognitive control components.**

sequential effects and the behavioral inhibition indices are thought to reflect the efficiency in conflict monitoring, proactive control and reactive control, respectively (see Figure 3.1). These indices will be described and discussed in the following sections.

3.1.1 Monitoring conflicts in the environment

According to the models by Botvinick et al. (2001) and De Pisapia and Braver (2006), the detection of a conflict triggers behavioral adjustments, which can be proactive or reactive as a function of the situational demands. In both models, conflict monitoring is thought to be supported by the anterior cingulate cortex (ACC), as this brain region is sensitive to the presence of conflicts. Therefore, the activity of the ACC should be analyzed to investigate the efficiency in conflict monitoring.

The ERN/Ne component: from error to conflict monitoring index

In 1991 and 1993, two research teams discovered a negative fronto-central activity that peaked around 50-100 ms after an error (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991; Gehring, Goss, Coles, Meyer, & Donchin, 1993) later localized in the ACC (Veen & Carter, 2002). This error(-related) negativity (ERN/Ne) was originally interpreted as a marker of the error detection mechanism. Indeed, the ERN/Ne was reported to be larger when the manipulation of the experimental context increased the error significance (e.g., by financial sanctioning) than in neutral situations. In a task where the accuracy was more important than the speed, Gehring et al. (1993) observed a larger ERN/Ne amplitude than when the speed was emphasized compared to the accuracy. Overall, the ERN/Ne was considered as an index of the efficiency of an error-monitoring system, which is impacted by the importance we give to errors. Following the ERN/Ne, Falkenstein et al. (1991) and Falkenstein, Hohnsbein, and Hoormann (1995) observed a positive wave in incorrect trials only. This error positivity (Pe) peaks between 150 and 400 ms (Overbeek, Nieuwenhuis, & Ridderinkhof, 2005; van Veen & Carter, 2006) in centro-parietal sites. Nieuwenhuis, Ridderinkhof, Blom, Band, and Kok (2001) found that the Pe was only observable in trials for which participants consciously detected their error and its amplitude varies with the degree of consciousness of the error (Leuthold & Sommer, 1999). The Pe is therefore thought to reflect conscious evaluation of errors (Falkenstein, Hoormann, Christ, & Hohnsbein, 2000) whereas earlier ERN/Ne indicates automatic internal performance feedback (cf. Figure 3.2).

The interpretation of the ERN/Ne as an error detection mechanism was however challenged in results reported by Vidal, Hasbroucq, Grapperon, and Bonnet (2000). Using the Laplacian transform to improve the spatial resolution of the EEG technique (Babiloni, Cincotti, Carducci, Rossini, & Babiloni, 2001; Burle et al., 2015), Vidal et al. (2000) uncovered an ERN/Ne-like activity after correct responses, which was usually masked by a large parietal positivity in reason of its small amplitude (Roger, Bénar, Vidal, Hasbroucq, & Burle, 2010; Vidal, Burle, Bonnet, Grapperon, & Hasbroucq, 2003). This correct-related negativity (CRN/Nc) peaks at 50-100 ms after a correct response onset. Interestingly, the ERN/Ne and the CRN/Nc are thought to be generated by the same cerebral region, and only differ by their magnitudes (i.e., the ERN/Ne is larger in error than in correct trials, Roger et al., 2010). These findings led to the shift of theoretical interpretation of the ERN/Ne from an error-monitoring system to a conflict-monitoring system (Yeung, Botvinick, & Cohen, 2004). The ERN/Ne component may not only reflect that the brain is able to detect when an error has been made, but that the brain is sensitive to the levels of conflict, to potentially trigger behavioral adjustments (Botvinick

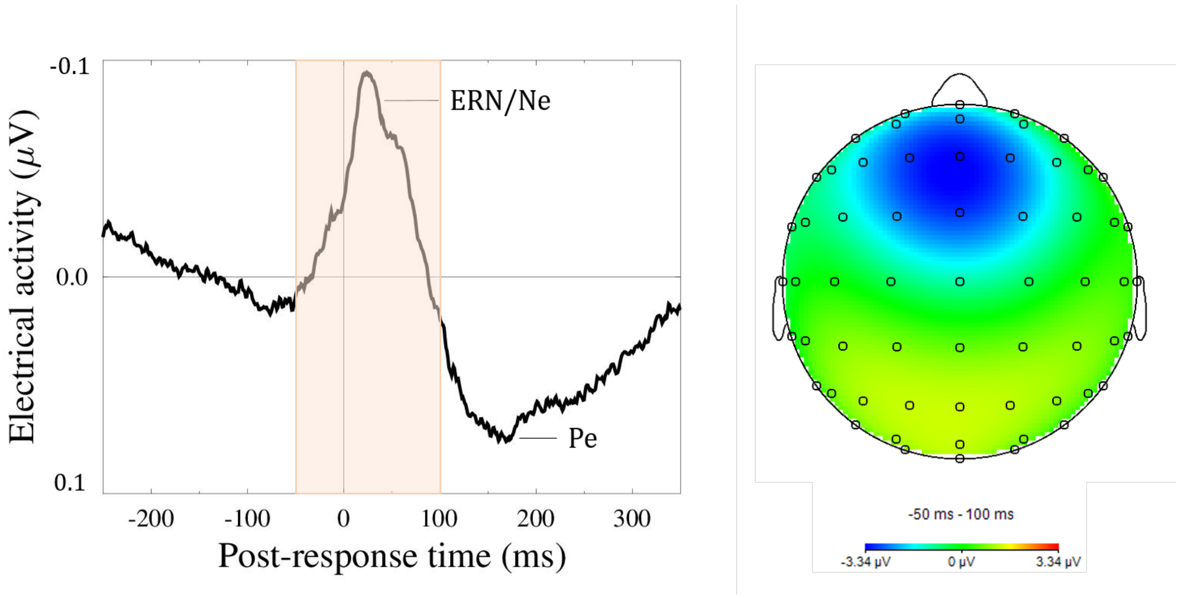


Figure 3.2 – **Electrical activity (μV) and the corresponding topography observed after an error in fronto-central sites (FCz electrode).** Time 0 refers to the occurrence of errors. The ERN/Ne peaks around 50-100 ms after the error at fronto-central sites, whereas the Pe peaks later around 150-400 ms after the error. The topography localizes the electrical activity from the highlighted section of the graph. Data collected in the Study IV.

et al., 2001; De Pisapia & Braver, 2006). Thus, the ERN/Ne amplitudes is now widely used as an index of the efficiency in conflict monitoring.

The precise significance of the ERN/Ne component as an index of conflict monitoring is still widely debated. First, the supplementary motor area (SMA) was also found to be activated during errors (e.g., Bonini et al., 2014; Dehaene, Posner, & Tucker, 1994). The ACC, thought to support the conflict layer (Botvinick et al., 2001), would thus not be the only brain region to monitor performances in order to adjust behaviors. Indeed, action monitoring and error processing may be hierarchically organized within frontal regions (Bonini et al., 2014). Second, and similarly, some results showed that the amplitudes of the ERN/Ne were unrelated or not sufficient to account for behavioral adjustments, as I will discuss in the following sections. Finally, Burle, Roger, Allain, Vidal, and Hasbroucq (2008) revealed that the amplitude of the ERN/Ne did not correlate with the levels of conflict, and suggested that the ERN/Ne could be a global *alarm signal*, which lasts until remediation processes take place.

Overall, despite the debates on its precise significance, the ERN/Ne component is thought to be an index of monitoring to signal the need for control processes to take place. Therefore, in this thesis, the ERN/Ne component will be used as an index of the efficiency in the monitoring system.

Unravelling the relationship between the ERN/Ne component and impulsivity

Numerous factors differentially modulate the magnitudes of the ERN/Ne (for a review, see Overbeek et al., 2005). In this section, findings on the ERN/Ne will be reported for both pathological and general populations. In pathological populations, several studies reported increased ERN/Ne amplitudes in anxiety-related populations (Moser, Moran, Schroder, Donnellan, & Yeung, 2013; Weinberg, Olvet, & Hajcak, 2010), in OCD patients (Endrass, Klawohn, Schuster, & Kathmann, 2008; Gehring, Himle, & Nisenson, 2000; Ruchsow, Spitzer, Grön, Grothe, & Kiefer, 2005) and in depression (Aarts, Vanderhasselt, Otte, Baeken, & Pourtois, 2013). On the contrary, smaller ERN/Ne amplitudes are often reported in impulsive-related psychiatric disorders such as schizophrenia (Mathalon et al., 2002), borderline disorder (cf. Figure 3.3, de Bruijn et al. (2006)) and ADHD (Liotti, Pliszka, Perez, Kothmann, & Woldorff, 2005). Similar patterns are often reported in addictive populations, also characterized by high impulsivity. Smaller ERN/Ne amplitudes were observed in participants with Internet addiction (Zhou, Li, & Zhu, 2013) and in excessive online gamers (Littel et al., 2012). Also, Franken, Nijs, Toes, and van der Veen (2018) revealed reduced ERN/Ne and Pe amplitudes in participants with high scores of food addiction, suggesting both diminished monitoring activity and less error consciousness in this population. Interestingly, Gorka et al. (2019) observed that the ERN/Ne amplitudes were reduced in individuals with current alcohol use disorder (AUD), but not in individuals in remission. The authors suggested that the ERN/Ne may be a marker of the status of the alcohol use disorder (AUD). Conversely, an inverse pattern (i.e., a larger ERN/Ne amplitude) was observed in binge drinkers compared to control participants (Lannoy, D'Hondt, Dormal, Billieux, & Maurage, 2017). However, the Pe component was impacted and delayed in binge-drinkers, suggesting a higher latency in error awareness in these impulsive individuals.

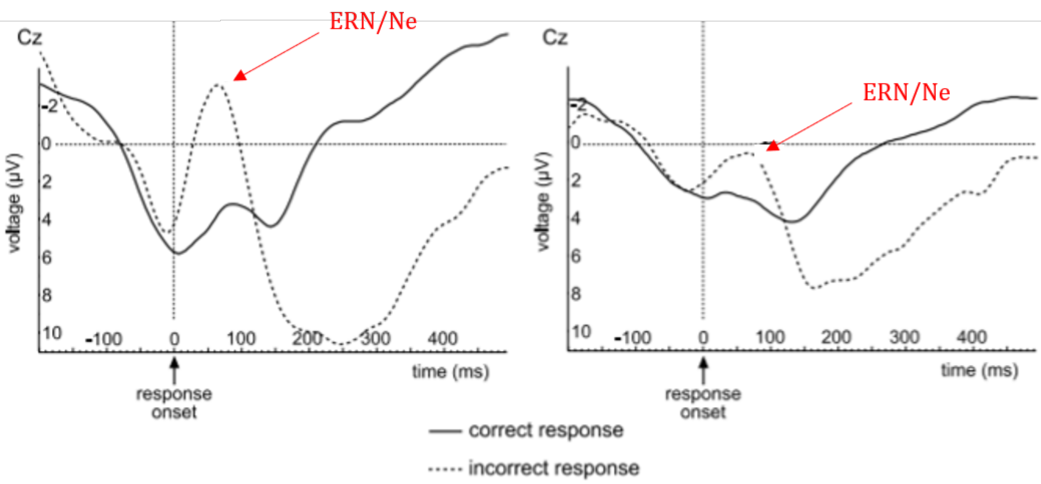


Figure 3.3 – Comparison of the ERN/Ne component in incorrect and in correct trials at the Cz electrode between control (left panel) and borderline personality disorder (right panel) groups. Adapted from De Bruijn et al. (2006).

Overall, a reduction in the ERN/Ne amplitudes is often reported in impulsive-related psychiatric populations. These findings led to postulate that a reduced ERN/Ne may be a diagnostic marker of psychiatric disorders in the externalizing spectrum (Olvet & Hajcak, 2008; Pasion & Barbosa, 2019; Weinberg, Dieterich, & Riesel, 2015). Moreover, the reduction in the ERN/Ne amplitudes could be a marker for the emergence of psychiatric disorders.

Seow et al. (2019) thus investigated the relationship between ERN/Ne amplitudes and several psychiatric symptoms in the general population (i.e., OCD, anxiety, depression, social anxiety, impulsivity, eating disorders, alcohol addiction, schizotypy and apathy). Indeed, one could expect that the reduction in ERN/Ne amplitudes could be a vulnerability marker for psychiatric disorders. However, Seow et al. (2019) reported an absence of association between the psychiatric scores and the ERN/Ne amplitudes. Similarly, Gorka et al. (2019) revealed that the vulnerability for alcohol use disorder in the at-risk group was not observed in the ERN/Ne component. Seow et al. (2019) suggested that the ERN/Ne marker may be "more sensitive to the categorical comparison of patients versus controls than dimensional variation in the general population". Moreover, the reduction in the ERN/Ne amplitudes is not only observed in psychiatric populations. Indeed, Vilà-Balló, Hdez-Lafuente, Rostan, Cunillera, and Rodriguez-Fornells (2014) also showed reduced ERN/Ne amplitudes in a non-clinical juvenile offender population. Both psychiatric and offender populations are characterized by high levels of impulsivity (Archer & Webb, 2006; Moeller et al., 2001). Therefore, the reduced ERN/Ne could simply be a marker of high impulsive tendencies. Studies have thus tried to replicate the reduction in the ERN/Ne amplitude in the general population, characterized by their degrees in impulsivity. To assess impulsivity in the general population, Ruchsow et al. (2005) used a behavioral index derived from RTs in correct and error trials. Short RTs in errors trials compared to the RTs in correct trials was used to characterize an individual as high impulsive. With this index, Ruchsow et al. (2005) succeeded to confirm the hypothesis of reduced ERN/Ne amplitudes with impulsive behaviors. However, other studies investigating the monitoring system in impulsive general populations, using self-reported questionnaires to assess impulsiveness, failed to observed the same pattern (Luu, Collins, & Tucker, 2000; Potts, George, Martin, & Barratt, 2006; Hill, Samuel, & Foti, 2016). Using the Multidimensional Personality Questionnaire (MPQ - Tellegen & Waller, 2008) or a more specific questionnaire (the Barratt Impulsivity Scale, BIS-11 - Patton et al., 1995), neither Luu et al. (2000) nor Potts et al. (2006) observed an effect of impulsiveness on the amplitudes in the ERN/Ne component. However, Taylor, Visser, Fueggle, Bellgrove, and Fox (2018) reported that the ERN/Ne amplitudes predicted motor impulsiveness scores in adolescents, when using a specific subscale of the BIS-11 questionnaire. Using the UPPS-P questionnaire (Lynam et al., 2006), Hill et al. (2016) observed a reduction in the ERN/Ne amplitude with negative urgency (i.e., impulsive reactions to negative emotions). High scores in negative urgency were associated with reduced ERN/Ne amplitudes. However, smaller ERN/Ne amplitude were not consistently associated with higher degrees in impulsivity in the general population. More particularly, the reduction in the ERN/Ne amplitudes were reported only when the methodological tools used to assess impulsivity took into account behavioral components, such as error speed (Ruchsow et al., 2005), motor impulsiveness (Taylor et al., 2018) and impulsive reactions to emotions (Hill et al., 2016).

Synthesis

Reduction in the ERN/Ne amplitudes is often reported in impulse-related pathological populations. However, reduced ERN/Ne amplitudes do not predict psychiatric symptoms and do not reflect a vulnerability for psychiatric status. Moreover, smaller ERN/Ne amplitudes are not consistently associated with high levels of impulsivity in the general population. Interestingly, only specific impulsive-related behavioral components (e.g., error speed) and specific impulsiveness traits (e.g., motor impulsiveness and urgency) are associated with a reduction in the ERN/Ne amplitudes in the general population. The reduction in ERN/Ne amplitudes, thought to reflect a reduced activity of the monitoring system, may only be observed when high impulsiveness is associated with impulsive behaviors.

3.1.2 Preparing and reacting to conflicts in the environment

According to the dual mechanisms of control (Braver et al., 2007; Braver, 2012), behavioral adjustments triggered by the detection of a conflict can be proactive and reactive, as a function of the timing in which the control processes take place. Proactive control anticipates the occurrence of a conflict, to facilitate its resolution, whereas reactive control is involved if and only if, a conflict is detected. The efficient involvement of proactive and reactive control is thought to be reflected in the sequential effects and in the partial-errors, respectively. The following sections are dedicated to the descriptions of these indices.

Proactive control and sequential effects

Beyond the analysis of the congruency effect (i.e., the RT difference between congruent and incongruent trials, see Chapter 2.2) that reveals the presence of global control processes, the analysis of reaction times (RTs) also brings evidence of the presence of proactive control. As a reminder, the DMC defines proactive control as a goal-driven preparatory attentional bias towards goal-relevant information prior to the imperative stimuli, to facilitate the conflict resolution when it occurs (Braver, 2012). Sequential effects are behavioral changes that occur as a function of the previous event (i.e., an error or a conflict, Wiemers & Redick, 2018). They are thought to reflect proactive behavioral adjustments. Error and conflict trigger proactive behavioral adjustments to avoid the occurrence of another error and/or to facilitate conflict resolution in subsequent trials. These sequential effects, namely the post-error slowing (PES, Rabbitt, 1966) and the Gratton effect (Gratton, Coles, & Donchin, 1992) are defined in the following subsections.

On the one hand, the post-error slowing (PES), originally observed by Rabbitt (1966), refers to the lengthening of RTs in correct trials after an error compared to RTs in correct trials after a correct trial (cf. Figure 3.4A). The slowing of the response times can persist two trials after the error and even beyond (Forster & Cho, 2014). The PES is interpreted as the reallocation of attention and an increase in control processes upon the goal-relevant information to avoid the commission of another error in subsequent trials. Indeed, according to the postulate of the selective suppression of goal-irrelevant information (Ridderinkhof, 2002), the resolution of the conflict is facilitated by an increase in RT (see Chapter 2.2). On the other hand, Gratton et al. (1992) observed that the congruency effect was smaller after incongruent trials compared to that observed after congruent trials (cf. Figure 3.4B). After a congruent trial, it is easy to answer to another congruent trial whereas it is costly to respond to an incongruent trial. However, this effect is substantially reduced after an incongruent trial. Indeed, an incongruent trial, which triggers a conflict, biases attention and control processes upon the goal-relevant information in order to facilitate the resolution of a future incongruent situation. Naturally, this reallocation of executive attention also slows down RTs in a congruent trial. Overall, the PES refers to the increase in RTs after an error and the Gratton effect refers to the decrease in the congruency effect after an incongruent trial (see Figure 3.4). Both sequential effects reveal that errors and conflicts elicit an anticipatory attention bias and selection of the goal-relevant information to better perform in the subsequent trials. They are thus considered as indices of proactive control.

According to the model by Botvinick et al. (2001), sequential effects (i.e., proactive behavioral adjustments) should be predicted by the activity of the conflit monitoring layer, thought to be reflected in the ERN/Ne amplitudes. Consistently, Debener (2005)

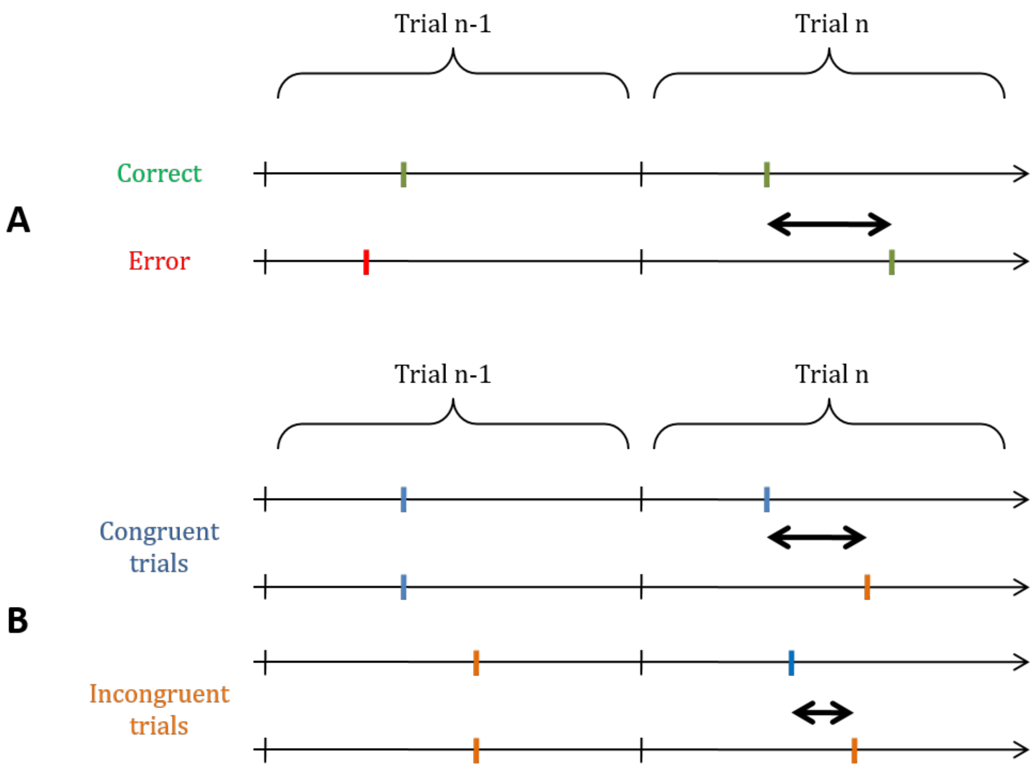


Figure 3.4 – **Graphical representation of the post-error slowing (A) and the Gratton effect (B).** Sequential effects refer to the effect of an event at trial *n-1* (left column) on the correct response RTs at trial *n* (right column). The post-error slowing (A) refers to the lengthening of RTs after an error (red bars) compared to that observed after a correct response (green bars). The Gratton effect (B) refers to the reduction in the difference between RTs in congruent (blue bars) and incongruent (orange bars) trials (i.e., the congruency effect) after incongruent trials. Both of these sequential effects are used as indices of proactive control.

and Maier, Yeung, and Steinhauser (2011) reported positive associations between the ERN/Ne amplitudes and the proactive behavioral adjustments. The larger the ERN/Ne amplitudes, the stronger the proactive behavioral adjustments in the subsequent trials. These findings are in favor of the interpretation of the sequential effects as proactive control indices and of the ERN/Ne component as an index of conflict monitoring. However, in the results reported by Maier et al. (2011), the relationship between the ERN/Ne amplitudes and the proactive behavioral adjustments was only observed for the errors caused by speed pressure, and not after errors caused by the failure of conflict resolution. Other studies also failed to observe an effect of ERN/Ne amplitudes on sequential effects (e.g., Gehring & Fencsik, 2001; Hajcak, McDonald, & Simons, 2003; Burle, Allain, Vidal, & Hasbroucq, 2005). The ERN/Ne amplitudes are therefore not always associated with proactive behavioral adjustments.

The interpretation of the ERN/Ne component as an index of conflict detection within the conflict-monitoring loop model is thus challenged by these inconsistent results. Moreover, some authors suggested that the post-error slowing might not reflect control processes, but an orienting response towards an infrequent event (e.g. Notebaert et al., 2009; Steinborn, Flehmig, Bratzke, & Schröter, 2012). However, across the different theories to explain the PES, Dutilh et al. (2012) showed that the effect is due to an increase in response cautious, confirming that it can be used as an index of control processes.

Reactive control and partial-errors

The DMC defines the reactive control as a stimulus-driven late correction mechanism that relies on the detection and the online resolution of an interference (Braver, 2012). Reacting to the current conflict requires to control the interference but also to correct an inappropriate engaged response, if needed. Therefore, reactive control relies mostly on inhibition capacities and in particular, interference control and behavioral inhibition capacities (see Chapter 2.1). Classical experimental paradigms such as the Stroop task, the Go/No-Go, the antisaccade and the Stop Signal tasks offer indices to describe behavioral inhibition capacities (see Chapter 2.1). In these paradigms, behavioral inhibition capacities are mostly evaluated through error rates, that means how many times inhibition failed. Electromyographic (EMG) recordings are used to measure behavior and provides the means to uncover specific trials in which inhibition did not fail. In the following sections, I will discuss the contribution of the EMG technique in the investigation of behavioral inhibition capacities.

Early in 1978, Rabbitt (1978) observed that in typists, the ink print was less marked for a typing error than for a correct letter. This observation indicated that, when making a typing error, the typists pressed less the key letter in comparison to what is observed in correct letters, suggesting the presence of an online inhibition mechanism. In a more experimental setting and using EMG, Allain, Carbonnell, Burle, Hasbroucq, and Vidal (2004) replicated this finding. By placing electrodes above the muscle involved in the response, the EMG signal offers the means to quantify muscular contractions variations that are invisible to the eye.

Using this technique, Allain et al. (2004) observed a reduced EMG activity during errors compared to the one observed during a correct response (Figure 3.5). This finding evidenced a failed attempt to catch up the engaged error and therefore, demonstrates the presence of online (reactive) inhibition mechanisms. Interestingly, the EMG technique also allowed to uncover trials for which the engaged error was successfully inhibited. Indeed, Eriksen, Coles, Morris, and O'hara (1985) observed that some trials contained a double muscular activation. In these trials, a small incorrect muscular activity precedes the correct response. An error engaged at the muscular level was detected and inhibited in time to give the correct response: these muscular patterns are called **partial-error** trials. Most of the partial-errors are observed in incongruent trials (Hasbroucq, Possamaï, Bonnet, & Vidal, 1999) and are unconscious to the participant (Rochet, Spieser, Casini, Hasbroucq, & Burle, 2014), suggesting that the correction of engaged errors is automatic. Interestingly, partial-errors elicit an ERN/Ne-like component (Vidal et al., 2000; Roger, Castellar, Pourtois, & Fias, 2014). Its amplitude is smaller than the ERN/Ne in errors and greater than the CRN/Nc observed in correct responses. The ERN/Ne in partial-error peaks when the engaged error is inhibited (Bonini et al., 2014), confirming that the ERN/Ne is an alarm signal that extinguishes when control processes are at play. Moreover, partial-errors elicit sequential adjustments, similar to those observed after overt errors (or full-errors - Burle et al., 2002; Allain, Burle, Hasbroucq, & Vidal, 2009).

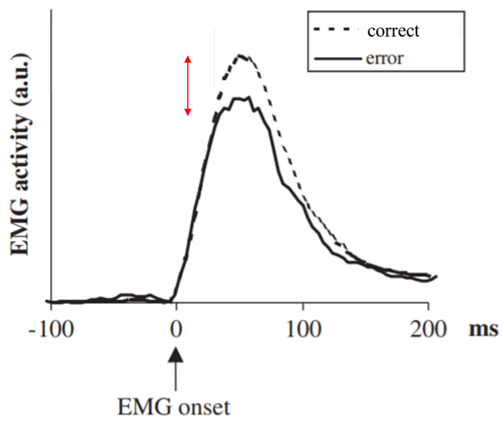


Figure 3.5 – Electromyographic activities locked to the onset of an error (continuous line) and of a correct response (dashed line). Adapted from Allain et al. (2004).

Partial-errors are used in a similar way as errors by the cognitive control system.

Moreover, the presence of partial-errors uncover the presence of reactive control processes through two indices. First, the investigation of the EMG bursts chronometry has revealed different temporal components during response execution. The duration between the onset of the partial-error and the onset of the corrective EMG burst, represented by the dashed arrow in Figure 3.6A, indexes the time necessary to correct the engaged error (Rochet et al., 2014). Second, the proportion of partial-errors among all the engaged errors, i.e., the correction ratio (Burle et al., 2002), reflects the capacity to inhibit an engaged error. The correction ratio takes into account the variability in the number of engaged errors and thus, allows to distinguish individuals on the basis of their behavioral inhibition capacities only. An elevated correction ratio is an indicator of a greater capacity to detect and correct an engaged error. These indices of online inhibition mechanisms are similar to those collected in a Stop Signal task (i.e., the Stop Signal reaction, SSRT, and the number of successful stop). However, first, the correction of a partial-error does not require an external signal to trigger the inhibition process. Second, without taking into account the EMG data, two individuals (X and Y) with the same error rates would be considered as having similar behavioral inhibition capacities. However, when considering the partial-errors uncovered by the EMG data, this conclusion could be wrong. Indeed, if individual Y makes more partial-errors than individual X for the same amount of overt errors, then individual Y can be considered as having better correction capacities than individual X (see Figure 3.6B).

Overall, the analysis of partial-errors through the recordings of EMG signal allows to measure fine-grained indices of behavioral inhibition capacities, for the study of reactive online control of actions. Moreover, as partial-errors are more frequently observed in incongruent trials, this EMG index also reveals the capacity to resist acting upon interferences. Thus, partial-errors are an interesting index for the study of impulsivity.

Proactive and reactive control in light of impulsivity

The PES was reported to be smaller in various pathological populations than in control participants, such as impulsive violent offenders (Chen, Muggleton, & Chang, 2014),

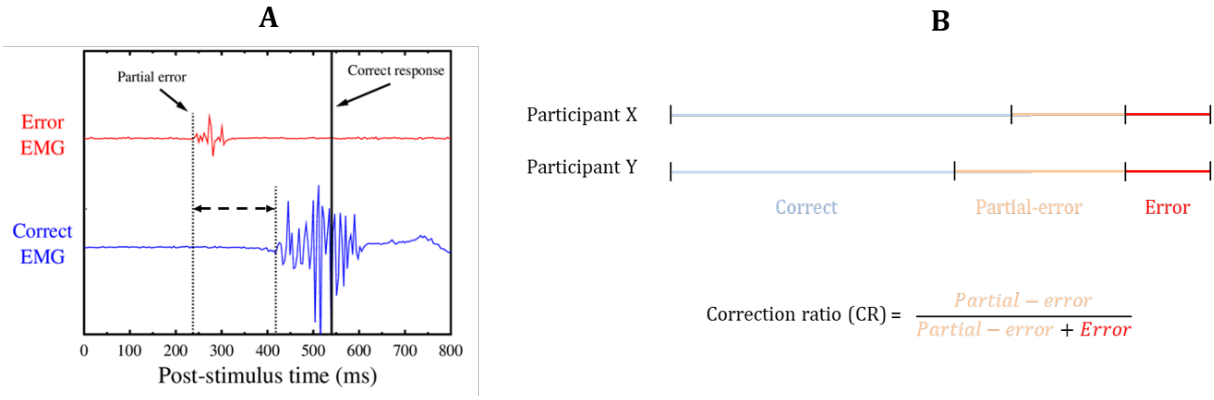


Figure 3.6 – **Graphical representation of a partial-error (A) and calculation of the correction ratio (B).** (A) In this hypothetical trial, the participant gives the correct response (blue line). However, the recording of muscular activities reveal an incorrect activation in the opposite hand (red line): the partial-error. The correction time (dashed arrow) refers to the time difference between the onset of the partial-error and the onset of the corrective response. (B) The correction ratio is calculated as the proportion of partial-errors among all the engaged errors (i.e., partial-errors and errors) and can outline differences in behavioral inhibition capacities between two participants with the same error rates.

in smokers (Luijten, van Meel, & Franken, 2011) and in ADHD-inattentive subtype patients (Shiels, Tamm, & Epstein, 2012) . However, results in ADHD populations are non conclusive. Indeed, Ehlis, Deppermann, and Fallgatter (2018) did not observe PES differences between ADHD and controls. Interestingly, Schiffer et al. (2014) and Michałowski, Droździel, and Harciarek (2015) also did not observe PES differences between antisocial personality disorder patients and controls. Finally, considering the Gratton effect, Sellaro and Colzato (2017) showed that the congruency effect after an incongruent trial was less reduced in overweight students than in normal-weight students, suggesting less involvement of proactive control. Numerous studies have reported smaller proactive behavioral adjustments in impulse-related individuals when compared to control subjects. In these populations, after a conflict or an error, the cognitive control system seems to trigger smaller proactive behavioral adjustments, but the results are mixed.

To the best of my knowledge, few studies have investigated partial-errors in relation to impulsivity. Therefore, little is known about the link between impulsivity and the reactive online control of errors without external feedback. Suarez et al. (2015) compared EMG data between ADHD and control subjects performing a Simon task. In their sample, ADHD patients and control participants did not differ on the number of engaged errors (i.e., partial-errors and full-errors) nor on the correction ratio (i.e., the proportion of engaged errors successfully corrected). This finding suggests an absence of differences in the efficiency of reactive control mechanism between ADHD patients and control subjects.

Synthesis

The efficiency of proactive and reactive control mechanisms can be revealed through the observation of the behavioral adjustments that are implemented after an error and/or a conflict (i.e., sequential effects) and during an error commission (i.e., partial-errors), respectively. There are few results on the relationship between partial-errors and impulsivity, but the investigation of the sequential effects suggests that impulsivity, in at least some pathological populations, is associated with weaker proactive behavioral adjustments.

Debates on the cognitive control indices

In the previous paragraphs, I have exposed several indices that can be used in the investigation of the efficiency of the monitoring system, proactive and reactive control. However, some critics may be made toward the use of these indices.

Empirical evidence have challenged the interpretation of the ERN/Ne as an index of conflict monitoring (Burle et al., 2005; Gehring & Fencsik, 2001; Hajcak et al., 2003; Maier et al., 2011). Results from Burle et al. (2008) and Bonini et al. (2014) suggested that the ERN/Ne is a broad alarm signal, that reflects the need for control, and extinguishes when control processes are in place. Moreover, proactive and reactive control are mechanisms that are supported by a set of several, but not clearly defined, capacities. The sequential effects reflect only the presence of the proactive control mechanism, but not its supporting capacities. Partial-errors allow the evaluation of behavioral inhibition capacities but the reactive control mechanism is not supported by behavioral inhibition capacities only. Finally, as mentioned in the Chapter 2.2, proactive and reactive mechanisms are engaged simultaneously to resolve interferences and to adapt behaviors. It can thus be challenging to dissociate the influence of one mechanism from the other in a unique measure. It would be interesting to rather question the dominance of one mechanism over the other. This is the objective of the following section.

3.2 Flexible shift between the proactive and reactive mechanisms

The flexible shift between reactive and proactive control mechanisms as a function of external and internal demands is the key for adaptive behaviors. In the following sections, I will describe the AX-CPT that can be used to investigate this aspect of the cognitive control system, and review several factors that can impact the control mechanisms (Figure 3.7).

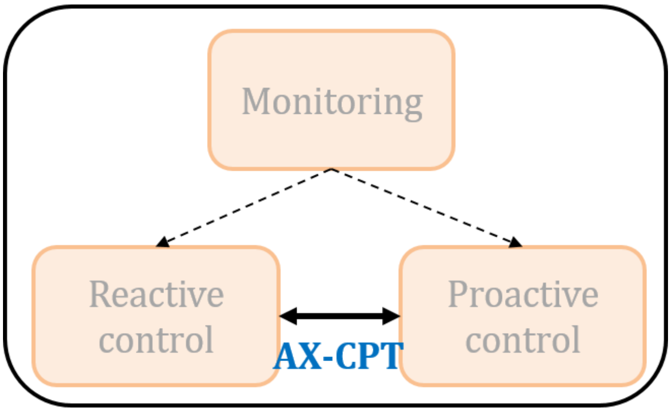


Figure 3.7 – **Investigation of the flexible shift between reactive and proactive control mechanisms.**

3.2.1 The AX-CPT paradigm

The Continuous Performance Task (CPT, Rosvold, Mirsky, Sarason, Bransome, & Beck, 1956) was originally developed as a measure of attention. In this Go/No-Go-type task, a series of stimuli are sequentially presented on a screen. The participant is required to respond to a rare target stimulus (e.g., the letter "X") and to refrain from responding when presented with the non-target stimuli (e.g., all other letters). An omission (i.e., not responding to the target stimulus) is used as an index of inattention and a commission error (i.e., responding to a non-target stimuli) is used as an index of impulsivity.

The CPT task was modified by the integration of a cue stimuli that needs to be processed to optimize performance. The AX variant of the CPT (AX-CPT, Braver, Paxton, Locke, & Barch, 2009; Servan-Schreiber, Cohen, & Steingard, 1996; Cohen & Servan-Schreiber, 1992) is thus used to assess the strength of proactive control relative to reactive control. In the AX-CPT task, a cue-letter precedes a probe-letter with a delay that can vary across studies (Figure 3.8). The participant is required to press a right button if the probe-letter "X" was preceded by the cue-letter "A" (i.e., AX trials). For the other pairs of letters (i.e., AY, BX and BY trials), he/she is instructed to press the left button. The AX trials are more frequent (i.e., generally 70% of trials) than the AY, BX and BY trials (i.e., 10% each). The frequency of the AX trials sets a strong association between both the cue-letter A and the probe-letter X and the target response. Therefore, the AY and BX trials are conflictual situations that need to be resolved. Longer RTs on correct trials (and greater error rates) in these trials reveal the cost of the conflict resolution.

In both AY and BX trials, conflicts occur at the presentation of the probe-letter, but the AY and BX conflicts are not generated by the same information (Figure 3.8). In AY trials, the cue-letter A automatically triggers the prepotent response toward the right button. However, this prepotent response must be inhibited when the probe-letter Y appears on the screen. Therefore, longer RTs (or greater error rates) in AY trials reflect the use of the goal-relevant information provided by the cue-letter and its active maintenance during the cue-probe delay. Thus, performances in AY trials reveal the involvement of proactive control processes. In BX trials, the probe-letter X activates the prepotent response toward the right button. However, this prepotent response must be inhibited as the cue-letter was not an A. Therefore, longer RTs (or greater error rates) in BX trials reflect the non-use of the goal-relevant information and its retrieval when the probe-letter appears to resolve the interference. Hence, performances in BX trials reveal the involvement of reactive control processes.

The investigation of the performances (i.e., reaction times and error rates) in AY

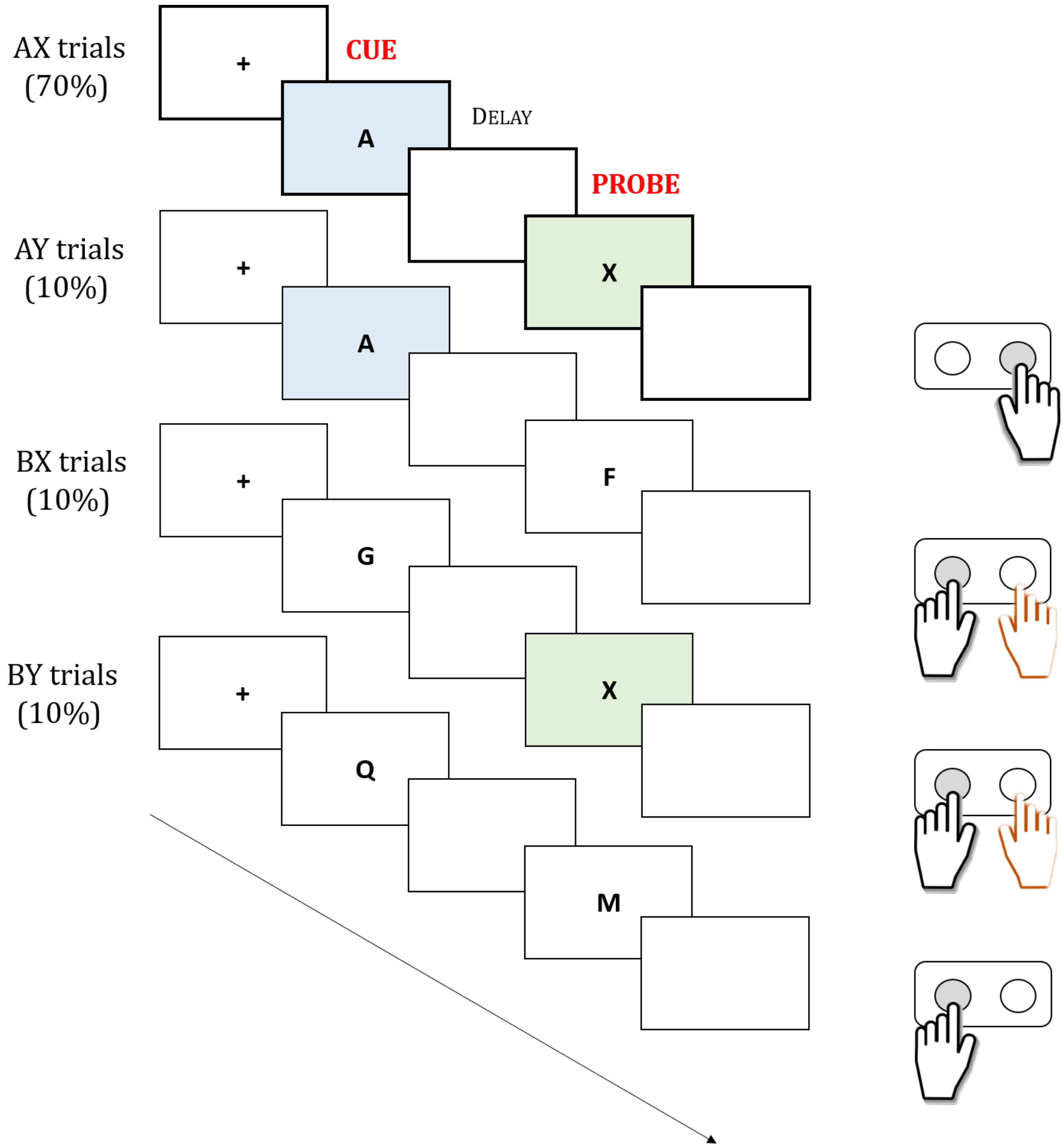


Figure 3.8 – **Graphical representation of the four types of trials in an AX-CPT paradigm**. In this hypothetical task, the participant had to press the right button if the probe-letter "X" (in green) was preceded by the cue-letter "A" (in blue) and the left button for another letter combination. These AX trials are the most frequent trials (bold line) and, therefore, the response associated with the "A" and the "X" is prepotent. In AY and BX trials, the cue-letter "A" and the probe-letter "X" activate the prepotent response (represented here by the red hands) that needs to be inhibited to give the correct response (represented by the black hands). The AY and BX trials are thus conflictual trials that require cognitive control. The difference of both conflicts calculated in the PBI reflects the predominant use of proactive control (AY trials) over reactive control (BX trials).

and BX trials informs on the involvement of both control mechanisms and allows the comparison of the conflict costs across populations. However, another information on control mechanisms can be derived from RTs (or error rates) in AY and BX trials through the calculation of the proactive behavioral index (PBI) as follows:

$$PBI = \frac{AY - BX}{AY + BX}$$

This index uses the difference between the two conflict costs to measure the relative weight of one control mechanism over the other: it indicates the dominant control mechanism. Calculated with the correct RTs in AY and BX trials, a positive PBI reflects the predominant use of proactive control mechanism as the RTs in the AY trials are longer than the RTs in the BX trials. Inversely, a negative PBI reflects the predominant use of reactive control mechanism.

3.2.2 Implementation of the optimal control mechanism

The implementation of proactive and reactive control mechanisms is driven by the costs and benefits of such mechanisms as a function of external and internal demands (see Chapter 2.2). To resolve conflictual situations, it is not one mechanism or the other, but one mechanism favored and dominating over the other to reduce the cognitive cost and to optimize the efficiency of the control. Notably, proactive control is thought to be the "default state" of the cognitive control system that dominates over reactive control (Criaud, Wardak, Ben Hamed, Ballanger, & Boulinguez, 2012). However, some contextual and inter-individual characteristics increase or decrease the dominance of proactive control. The following sections discuss these aspects.

Proactive control as the "default state"

Proactive control is the most robust control mechanism, and is favored in unpredictable environment. Criaud et al. (2012) tried to identify how it is implemented. In their study, participants from a general young population (i.e., age ranged from 21 to 28) performed a cued-Go/No-Go task. Some trials, cued by a red cross, were classical Go/No-Go trials. In other trials, a white cross cued that the subsequent trial was a Go trial. Therefore, the white cross cued a predictable situation whereas the red cross cued an unpredictable situation. Proactive control would be therefore more involved in the red-cross cued trials compared to the white-cross cued trials, to prepare the system to refrain from acting if case of a NoGo trial. The delay between the cue and the Go/No-Go stimulus was also manipulated to test two hypothesis to explain the implementation of proactive control.

First, proactive control may be implemented when an unpredictable context is detected (i.e., when the red cross appears). In this hypothesis, the performance in red-cross cued trials should increase with the delay between the cue and the Go/No-Go stimulus, giving time for proactive control to take place. Secondly, proactive control may be the "default state" of the cognitive control system and thus, would always be involved. In such case, the performance in white-cross cued trials should increase with delay, but there would be no differences in performance in red-cross cued trials with delay. Results confirmed the second hypothesis, thus revealing that proactive control is the default state of control, which is actively released when the situation becomes predictable (Criaud et al., 2012).

Proactive control is thought to be the preferential control mechanism to resolve conflict and adapt behaviors. However, this control mechanism is flexible. As mentioned earlier, when the environment becomes predictable, proactive control is too costly and reactive control can take over without decreasing performance level. Several contextual and inter-individual characteristics indirectly increase or decrease the dominance of proactive control (Braver, 2012; Chiew & Braver, 2017) by increasing or decreasing the costs and the benefits of this control mechanism.

Adapting to external and internal demands

Contextual and inter-individual characteristics impact differently the dual mechanisms of control and influence the implementation of reactive and proactive mechanisms. According to Wardak, Ramanoël, Guipponi, Boulinguez, and Hamed (2012), the level of proactive control is adjusted to the context and the structure of the task. For example, motivational contexts (e.g., expecting a reward for correct responses) drive proactive control (Hefer & Dreisbach, 2016; Langford, Schevernels, & Boehler, 2016; Fröber & Dreisbach, 2016). Interestingly, when the reward is randomly attributed, proactive control is less involved during task performance (Hefer & Dreisbach, 2016). Similarly, provinding feedback on the performance in the Stroop task promotes proactive control (Bejjani, Tan, & Egner, 2020). Conversely, Mäki-Marttunen, Hagen, and Espeseth (2019b) showed that the increase in task load during the AX-CPT task drives reactive control. Indeed, in high cognitive-load situations, the accuracy in BX trials was decreased compared to the one observed in low cognitive-load situations. Error rates on BX and BY trials in the AX-CPT increased when participants could randomly receive electric shocks compared to neutral situations, revealing a higher reliance on reactive control in stressful situations. Hence, inducing an anxious state also favors reactive control (Yang, Miskovich, & Larson, 2018). Interestingly, the dominance of proactive control over reactive control can also vary as a function of individual characteristics. Individuals with high working memory capacities favored proactive control mechanisms (Redick, 2014; Richmond, Redick, & Braver, 2015; Wiemers & Redick, 2018). It is possible that high working memory capacities reduce the cost of proactive processes (by facilitating the active maintenance of goal-relevant information). Similarly, age favors the use of reactive control (Paxton, Barch, Racine, & Braver, 2008). The cognitive decline with age seems to promote the use of the less costly reactive control.

Many studies have investigated AX-CPT performances in pathological populations to analyze the difference in the use of control mechanisms. Similarly to what is found in the general population, reaction times in AY trials are generally longer than the ones in BX trials in a large number of pathological populations (van Dijk et al., 2014; Lorsbach & Reimer, 2008; Iselin & DeCoster, 2009; Kam, Dominelli, & Carlson, 2012). In borderline personality disorders (BPD) patients, van Dijk et al. (2014) observed an inverse pattern with longer reaction times in BX trials compared to that observed in AY trials. However, RTs both in AY and BX trials are longer in pathological populations than in healthy controls (see Table 3.1) suggesting that proactive and reactive control costs are larger in pathological populations than in the general population. However, it could also reflect a general slowing of the reaction times. The proactive behavioral index (PBI) overlooks the global difference in RTs, to measure the dominance of proactive control. Unfortunately, the PBI was not reported in these studies. When calculating the PBI in different pathological populations based on the AY and BX RTs reported in the papers (see the last column of the Table 3.1), I was able to get an insight in a common pattern of findings. Although the significance of such conclusion remains to be statistically established, it is possible to suggest that in these populations, the proactive control is less dominant than in control subjects. At the descriptive level, the PBI is smaller in ADHD patients (van Dijk et al., 2014), in bipolar disorder patients (Smucny et al., 2019; Brambilla et al., 2007), in schizophrenic patients (Lesh et al., 2013; Smucny et al., 2019) and in addictive populations (Kräplin, Scherbaum, Bühringer, & Goschke, 2016) compared to that observed in the control data. For the BPD population, a negative PBI is observed: reactive control is dominant.

Synthesis

The AX-CPT paradigm is used to assess the dominance of proactive control over reactive control, through the calculation of the proactive behavioral index (PBI). This index is associated with several impulsive-related populations in a consistent pattern: the PBI is smaller in patients than in control subjects. These findings suggest that the proactive control mechanism is less dominant with impulsivity, potentially causing a higher sensitivity to distractors in impulsive individuals and leading them to act on impulses more often than less impulsive individuals. More than the investigation of the capacity to reactively or proactively adjust behaviors or to monitor for the need of control, the shift in the dominance of the proactive control mechanism (i.e., the default state of the cognitive control system) could explain impulsive behaviors. However, to the best of my knowledge, the capacity to flexibly adapt control mechanisms to external and internal demands has not yet been investigated in normal and pathological impulsive individuals.

Table 3.1 – Reaction times (RTs, ms) in AY and BX trials, and associated proactive behavioral index (PBI) across several pathological and general populations.

References	Population	AY RTs (ms)	BX RTs (ms)	PBI
Brambilla et al. (2007)	BP	584	401	0.19
Brambilla et al. (2007)	HC	580	378	0.21
Brambilla et al. (2007)	SZ	668	664	0.00
Kam et al. (2012)	HC	604.1	438.34	0.16
Kam et al. (2012)	HC (Males)	600.93	431.97	0.16
Kam et al. (2012)	HC (Females)	605.66	441.47	0.16
Kräplin et al. (2016)	D - Gambling	554.71	550.58	0.00
Kräplin et al. (2016)	D - Nicotine	563.94	548.50	0.01
Kräplin et al. (2016)	HC	547.06	522.65	0.02
Lesh et al. (2013)	HC	711	625	0.06
Lesh et al. (2013)	SZ	774	761	0.01
Lorsbach and Reimer (2008)	HC (Children)	625	550	0.06
Lorsbach and Reimer (2008)	HC (Young adults)	550	410	0.15
Minzenberg et al. (2015)	SI-	822	766	0.04
Minzenberg et al. (2015)	SI+	821	766	0.03
Minzenberg et al. (2015)	SI+/SB-	820	765	0.03
Minzenberg et al. (2015)	SI+/SB+	823	767	0.04
Smucny et al. (2019)*	BP	631.49	501.16	0.12
Smucny et al. (2019)*	HC	569.26	413.08	0.16
Smucny et al. (2019)*	SZ	645.85	522.76	0.11
Smucny et al. (2019)*	SZ-A	643.57	535.68	0.09
van Dijk et al. (2014)	ADHD	549.91	390.01	0.17
van Dijk et al. (2014)	ADHD+BPD	509.32	396.95	0.12
van Dijk et al. (2014)	BPD	447.74	521.58	-0.08
van Dijk et al. (2014)	HC	455.75	302.63	0.20

Note. *: the study used a variant of the AX-CPT task using dots instead of letter (DPX task). **ADHD**: attention-hyperactivity disorder; **BP**: bipolar disorder; **BPD**: borderline personality disorder; **D**: dependence disorder; **HC**: healthy controls; **SI**: suicidal ideation; **SB**: suicidal behavior; **SZ**: schizophrenia; **SZ-A**: schizo-affective disorder.

Conclusion

As mentioned in the Chapter 2.2, cognitive control can be investigated at two levels. Firstly, we can investigate the individual efficiency of the three components of the cognitive control system. Despite the evoked criticisms, the ERN/Ne amplitudes, the sequential effects and the partial-errors can be used as indices of monitoring, proactive control and reactive control, respectively. Secondly, we can investigate the implementation and the adaptation of the use of proactive and reactive control as a function of external and internal demands, through the performances in the AX-CPT task. Indeed, adaptive behaviors do not only rely on the efficiency of the cognitive control components, but also on the flexible shift between proactive and reactive control.

Impulsive pathological populations seem to be characterized by a less dominant proactive control compared to the general population. According to the dual mechanisms of control (Braver, 2012), a weaker proactive control would lead the cognitive control system to be more sensitive to distractors and may explain the actions and decisions on impulses observed in impulsive individuals. However, the capacity to flexibly adapt control mechanisms to external and internal demands, crucial for adaptive behaviors, has not been yet investigated in normal and pathological impulsive individuals. My PhD project thus aimed at investigating the effects of impulsivity in the general population on the dominance of proactive control over reactive control and the adaptation of control mechanisms to external and internal demands.

Chapter 4

The aim of my thesis: the study of impulsivity and cognitive control in the general population

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Impulsivity is a key component of several psychiatric disorders both as a diagnostic feature and as a vulnerability factor, making impulsivity a relevant research topic for clinical work. As defined in Chapter 1, impulsivity refers to both personality traits (i.e., impulsiveness) assessed through self-reported questionnaires and behavioral manifestations (i.e., impulsive behaviors) measured with various laboratory tasks. Both impulsiveness and impulsive behaviors predict daily-life impulsive behaviors (Sharma et al., 2014), suggesting shared features between the two constructs. However, impulsiveness often failed to predict impulsive behaviors in the general population. One hypothesis to explain this lack of correlation is that, in the general population, efficient impulse control capacities reduce the impact of impulsiveness on behaviors. Therefore, to understand whether impulsivity is a vulnerability factor for psychiatric disorders, we must investigate the relationship between impulsivity and impulse control capacities in the general population.

The cognitive control system seems to support impulse control capacities. Indeed, cognitive control, a set of cognitive functions that are orchestrated to adjust behaviors to external and internal demands (see Chapter 2.2), moderates the relationship between impulsiveness and impulsive behaviors (Robinson et al., 2009; Youssef et al., 2016; McKewen et al., 2019). Impulsive behaviors are less frequently observed in high impulsive individuals with efficient cognitive control capacities compared to high impulsive individuals with poorer cognitive control capacities. However, it is still unclear which component of the cognitive control system mediates the link between impulsiveness and impulsive behaviors. Botvinick et al. (2001) and De Pisapia and Braver (2006) cognitive control's models postulate the presence of three components of cognitive control: (1) conflict monitoring, (2) reactive control to resolve a current interference and (3) proactive control to prevent and facilitate the resolution of future interference. To ensure appropriate behaviors, the cognitive control system requires the efficiency in all its components, and the capacity to flexibly adapt the use of reactive and proactive control mechanisms as a function of external and internal demands (see Chapter 2.2).

Impulsivity was largely studied through the angle of the analysis of the efficiency of each of the three components of cognitive control. Studies strongly considered the capacity to inhibit prepotent and automatic responses (see Chapters 2.1 and 3.1). However, the literature reports mixed results across populations and methodologies, and discussions on the validity of the indices used to investigate the cognitive control components are still ongoing. Moreover, it seems that researches on impulsivity have confounded the outcomes with the processes and thus, the processes have been viewed as dysfunctional (Kopetz, Woerner, & Briskin, 2018). To quote Kopetz et al. (2018), "*the literature is still dominated by the notion that impulsive behavior is the reflection of a maladaptive tendency, that researchers and practitioners should aim to "fix" to afford better behavioral outcomes*". However, with an evolutionary perspective, some authors postulate in favor of an adaptive side of impulsivity.

Impulsivity is an adaptive response style in some situations (e.g., to seize opportunities - Winstanley, 2011), but becomes dysfunctional in others (Kopetz et al., 2018; Dickman, 1990; Stevens & Stephens, 2010). Indeed, if impulsive behaviors persisted across evolution, impulsivity may have an unknown or neglected adapted value. Choosing a smaller-sooner reward instead of a larger-later reward, as it is observed in the *Delay Discounting* task, might indeed be a strategical choice to survive in an unpredictable environment (Stevens & Stephens, 2010). Hunter-gatherers favored small amounts of food available now and for certain, rather than hypothetical and delayed larger amounts of food needed to survive.

The natural selection has favored the “short-sighted rules of choice” to improve the long-term intakes, and therefore survival. However, situations where choices are simultaneously presented (i.e., in more predictable environment), the “short-sighted rules of choice” would be no longer adapted. Within this perspective, the researches on impulsivity should not try to answer the question "What is impaired in impulsive individuals?", but instead "What process is maladapted in impulsive individuals?".

The notion of adaptation in the impulsive response style, rather the notion of cognitive dysfunction, is crucial to investigate impulsivity. Earlier suggested by Dickman (1990), impulsivity is a behavioral strategy that can be optimal in some situations, but also error-prone in others. Thus, dysfunctional impulsivity would be the manifestation of the inability to shift from this behavioral strategy in situations where it will be maladaptive. Interestingly, in the dual mechanisms of control (DMC, Braver, 2012), adaptive behaviors not only rely on efficient cognitive control components, but also on the flexible adaptation between reactive and proactive mechanisms, as a function of external and internal demands. Also, studies using the AX-CPT task to reveal the strength of the dominance of proactive control reported interesting results, suggesting that impulsivity in pathological populations could be characterized by a less dominant proactive control (see Chapter 3.2.1). The weaker dominance of proactive control might explain the emergence of impulsive behaviors as it lets the cognitive system to be more sensitive to impulses. However, these studies did not investigate the capacity to adapt the use of control mechanisms to external or internal demands. Therefore, my PhD project aimed at investigating the dominance of proactive control in the general population characterized by high or low impulsiveness, but also at exploring the capacity to flexibly adapt the use of the two control mechanisms as a function of external and internal demands.

Following the results previously obtained in pathological populations, I postulated that high impulsiveness would be characterized by a less dominant proactive control. Also, following Dickman (1990)’s and Kopetz et al. (2018)’s visions of impulsivity, I hypothesized that high degrees of impulsiveness in the general population could be associated with impairments in the adaptation of cognitive control mechanisms. The lack of adaptation of control mechanisms could explain the increased risk of psychiatric disorders in high impulsive individuals, through the emergence of impulsive behaviors when the control mechanism at play is not adapted to the external or internal demands.

Overall, my PhD project aimed at investigating the effects of impulsivity in a general population through the angle of cognitive control mechanisms, to gain a better understanding of the cognitive process that could explain the vulnerability for psychiatric disorders in impulsive individuals. The Part III of the present manuscript presents the original experimental contributions to this research question. During my PhD, I conducted four studies that are organized in five experimental sections. The first two studies were dedicated to the investigation of the capacity to adapt control mechanisms to external demands. To do so, I compared the proactive behavioral index (PBI) and its adaptation over time between high and low impulsive individuals both in the general population (Chapter 5) and in an alcohol-dependent population (Chapter 6). A third study, conducted in collaboration with the ECCA-Conduite company, allowed me to investigate the capacity of healthy adults to adapt control mechanisms to internal demands in a large sample (Chapter 7). To do so, I compared the strength of proactive behavioral adjustments as a function of reactive inhibition capacities and risk-taking propensity. To complete the overview of the functioning of the cognitive control system in impulsivity in the general population, I conducted a fourth study using EEG to investigate the activity of the monitoring system (Chapter 8). Finally, the fifth experimental section is dedicated to preliminary results obtained on the role of heart rate variability (HRV) in the capacity to adapt control mechanisms (Chapter 9).

Part III

Experimental contribution

Chapter 5

Adaptation of cognitive control mechanisms to external demands in the general population

Foreword

Cognitive control is a set of cognitive processes (i.e., monitoring, proactive and reactive mechanisms) required to adjust behaviors to a constantly changing environment (see Chapter 2.2). Previous studies have shown that an efficient cognitive control system moderated the relationship between impulsiveness and impulsive manifestations, such as bulimic symptoms (Robinson et al., 2009) or risk-taking behaviors (Youssef et al., 2016; McKewen et al., 2019). In these studies, cognitive control was investigated at the performance level (e.g., congruency effect, error rates). Therefore, little is known about the specific cognitive control process that drives the moderation effect. Which cognitive control process makes the impulsive individual vulnerable to impulsive behaviors?

The investigation of the dual mechanisms of control in impulsive populations has revealed promising results. Indeed, though proactive control was still the dominant control mechanism in impulse pathological populations, its dominance seems to be reduced in patients compared to control subjects (see Table 3.1). According to the dual mechanisms of control (Braver, 2012), this may lead to a less robust control system over impulses.

The aim of the first experimental axis of the thesis was to investigate the dominance of the proactive control mechanism in impulsivity in the general population. In two studies, the participants performed an AX-CPT task to calculate the proactive behavioral index (PBI). Impulsivity was assessed using the UPPS questionnaire (see Chapter 5.1) and three behavioral indices (i.e., the k-value for impulsive decision-making, the rates of engaged errors and the correction ratio for impulsive motor action, see Chapter 5.2). Moreover, as adaptive behaviors rely on the flexible shift between reactive and proactive control mechanisms, I investigated the adaptation of control mechanisms to external demands. In the AX-CPT task in neutral situations, proactive control is favored to perform the task. Indeed in this task, the use of the cue information prepares for the correct response in 90% of the trials (i.e., AX, BX and BY trials). Therefore in the Study I, the PBI was calculated in each AX-CPT blocks to explore its evolution over time (see Chapter 5.1).

5.1 Study I: Slower adaptation of control strategies in individuals with high impulsive tendencies

Grisetto, F., Delevoye-Turrell, Y. N., & Roger, C. (submitted). Slower adaptation of control strategies in individuals with high impulsive tendencies.

Abstract

Flexible use of reactive and proactive control mechanisms according to environmental demands is the key to adaptive behavior. In this study, forty-eight adults performed ten blocks of an AX-CPT task to reveal the strength of proactive control mechanisms by the calculation of the proactive behavioral index (PBI). They also fulfilled the UPPS questionnaire to assess their impulsiveness. The median-split method based upon the UPPS score distribution was used to categorize participants as having high (HI) or low (LI) impulsiveness traits. The analyses revealed that the PBI was negatively correlated with the UPPS scores: higher the impulsiveness, the weaker the dominance of proactive control processes. Moreover, we showed, at an individual level, that the PBI increased across blocks and revealed that this effect was due to the weakening of reactive control processes. Notably, the PBI increase was slower in the HI group than in the LI group. Moreover, participants who did not adapt to task demands were all characterized as high impulsive. Overall, the current study demonstrates that (1) impulsiveness is associated with less dominant proactive control due to (2) slower adaptation to task demands (3) driven by a stronger reliance on reactive processes. These findings are discussed in regards to pathological populations.

Keywords: impulsiveness, cognitive control, AX-CPT, adaptation, proactive behavioral index

Introduction

Driving is a complex behavior that requires efficient attentional and executive functions (e.g. inhibition, updating, working memory) to execute the appropriate action to stay adapted in a constantly changing and unpredictable environment. Imagine arriving in a crowded area where the visibility is low. As a driver, to avoid an accident, you face two choices. You can either wait and react with an emergency braking if something unexpected happens (e.g. a pedestrian crosses) or you can anticipate an event by slowing down the speed of the car. This choice is made as a function of the context (i.e. other cars in the street or not) and of inter-individual differences. These daily situations require cognitive control processes to resolve the conflict (i.e. co-activation of responses). The current study aimed at uncovering inter-individual differences in the implementation of cognitive control strategies.

Cognitive control is the ability to adjust goal-directed behaviors according to internal goals and external demands, supported by basic executive functions (Ridderinkhof et al., 2011; Nigg, 2017). Two distinct control strategies are involved in conflict resolution (Braver, 2012; Braver et al., 2007). On the one hand, reactive control corresponds to a late correction of the action when the conflict occurs (e.g. emergency brake). On the other hand, proactive control reflects an early attentional bias towards goal-relevant information to prepare the system to resolve future conflict (e.g. slowing down). In Braver (2012)'s dual mechanisms of control (DMC) framework, proactive and reactive mechanisms co-exist in the cognitive control system as two opposite poles of a continuum. Their involvement in conflict resolution relies on a tradeoff between the benefits and the costs of proactive and reactive strategies according to the current situation (Braver, 2012). However, it is also crucial to investigate which and how inter-individual differences affect control strategies to understand behavioral tendency differences.

In line with the DMC framework, the AX-variant of the Continuous Performance Task paradigm (i.e. AX-CPT) was developed to measure goal representation, maintenance and updating (Braver et al., 2009; Cohen & Servan-Schreiber, 1992; Servan-Schreiber et al., 1996). In this paradigm, the participant is required to respond "yes" when he/she sees an “X” following an “A”, and to respond “no” whenever another letter combination is presented. The manipulation of the expectancy of the cue letter “A” and the probe letter “X” (i.e. “AX” in 70% of the trials) creates two distinct conflictual situations. In “AY” trials, the participant expects to see an “X” after the “A” and must inhibit the prepotent response when facing a non-X letter, represented by a “Y". In “BX” trials, the “X” probe triggers an automatic response that must be inhibited since the cue was a non-A letter, represented by a “B”. The difference between mean reaction times (RTs) in “AX” trials and in “AY” trials on the one hand, and between RTs in “AX” and in “BX” trials on the other hand reveal two different conflict costs. The difference between these two types of conflict (i.e. mean RTs in AY trials and in BX trials) reflects the dominancy in the DMC. When proactive control mechanisms are dominant, RTs are longer in AY trials than in BX trials, indicating that the participant uses the cue letter to prepare for action. On the contrary, when reactive control mechanisms are dominant, RTs are longer in BX trials than in AY trials, revealing that the participant does not correctly process the cue and waits for the probe before retrieving the goal representation on which to base his/her answer. The proactive behavioral index (PBI) computes this difference to measure the relative strength of the engagement of proactive control mechanisms over reactive ones (Braver et al., 2009).

In young healthy adults, RTs in AY trials are often reported to be longer than those in BX trials, suggesting the predominant use of proactive control processes (van Dijk et al., 2014; Lorsbach & Reimer, 2008; Iselin & DeCoster, 2009; Kam et al., 2012). Using predictable and unpredictable environments to reveal the dynamics of proactive control, (Criaud et al., 2012) showed that proactive control processes are already set at trial start suggesting that this mechanism is the default state of cognitive control. Nevertheless, this default state varies as a function of inter-individual differences (Braver et al., 2009; Chiew & Braver, 2017) such as age (Paxton et al., 2008) and working memory capacity (Redick, 2014; Richmond et al., 2015). However, to our knowledge, little is known about the effect of personality traits on the default state of cognitive control. In pathological populations, van Dijk et al. (2014) compared AX-CPT performances between attention deficit hyperactivity disorder (ADHD), borderline personality disorder (BPD) patients and healthy controls (HC). In ADHD patients, although the pattern of results was similar to that observed in HC (i.e., longer RTs in AY trials than in BX trials), the AY - BX difference was smaller in these patients compared to HC. Moreover, in BPD patients, the RTs were longer in the BX than in the AY trials, resulting in a negative difference arguing in favor of a dominance of reactive control processes. Overall, these findings indicated that the dominance of proactive strategies, as the default state observed in HC, was less pronounced in ADHD and could even be shifted towards reactive control in BPD. Interestingly, both of these pathologies have been largely characterized by impulsive behaviors (e.g. Ende et al., 2016; Linhartová et al., 2019). Accordingly, we hypothesized that in the general population, individuals with high impulsive traits would adopt lower proactive control strategies compared to individuals with low impulsive traits (H1).

In addition, the default state may change as the environmental demands change. Indeed, Janowich and Cavanagh (2018) showed in a recent meta-analysis that the AY - BX difference in RTs increased in studies with a large number of trials, suggesting the possibility of a gradual adaptation of proactive processes over time in the AX-CPT task. To our knowledge, this hypothesis has not been investigated at the individual level so far (nor its potential modulation by inter-individual differences). If the adaptation over time is confirmed, then three possibilities can be considered to challenge the increase in the AY - BX difference: (1) an increase in AY trials RTs, reflecting a growing involvement of proactive processes over time (Figure 5.1A), (2) a decrease in BX trials RTs, reflecting a weakening of reactive processes over time (Figure 5.1B) or (3) the combination of the two possibilities (Figure 5.1C). Thus, dissecting the increase in proactive control over time offers a deeper understanding of the adaptation of cognitive strategies over time. The current study aimed at identifying which one of the three patterns could explain the shift towards a greater proactive control dominance observed in the normal adult population, while investigating the influence of impulsive personality traits on the adaptation ability of control strategies (H2).

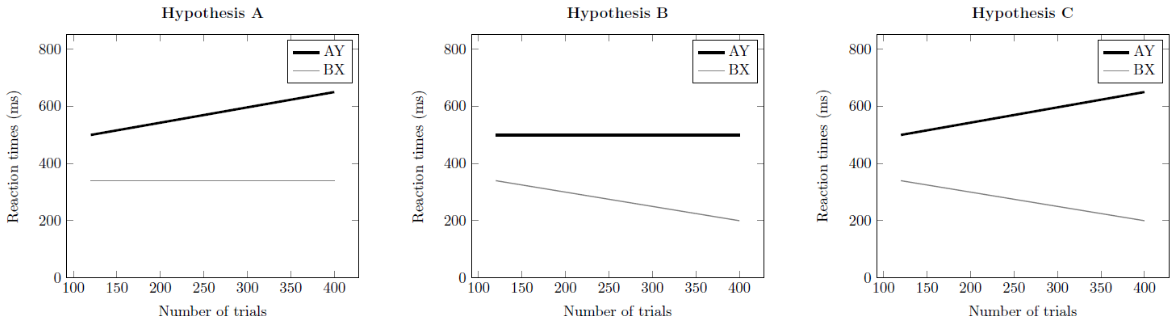

Figure 5.1 – **Graphical representations of the three alternatives to explain the increase in AY - BX difference with the increase in the number of trials.** Greater proactive behavioral index in studies with larger number of trials could be guided by three alternatives: the increase in proactive control reflected in the progressive increase of AY trials RTs **(A)**, the decrease in reactive control reflected in the progressive decrease in BX trials RTs **(B)**, or the combination of both **(C)**.

Method

Participants

A total of 48 volunteers recruited in the University of Lille participated in the study (31 women, mean age = 22 years, range from 18 to 39). Exclusion criteria included motor and/or sensory disorders and a current medical treatment that could affect task performance. They all gave written informed consent for taking part in this study that obtained ethics approval from the institutional board of ethics of the University of Lille (2019-341-S70, see Appendix VI).

Procedure and task

Task and stimuli. The participant performed the AX-continuous performance task (AX-CPT, Braver et al., 2009; Cohen & Servan-Schreiber, 1992; Servan-Schreiber et al., 1996) implemented using E-Prime experimental software (Psychology Software Tools, Inc.). He/she was invited to respond as quickly and accurately as possible as a function of pairs of letters composed with a cue-letter (i.e. the first letter) and a probe-letter (i.e. the second letter). He/she had to press a response button with the right hand if he/she saw a probe-X only if it was preceded by a cue-A. When the cue-letter was not an A (i.e. generic name "B") or when the probe-letter was not an X (i.e., generic name "Y"), he/she

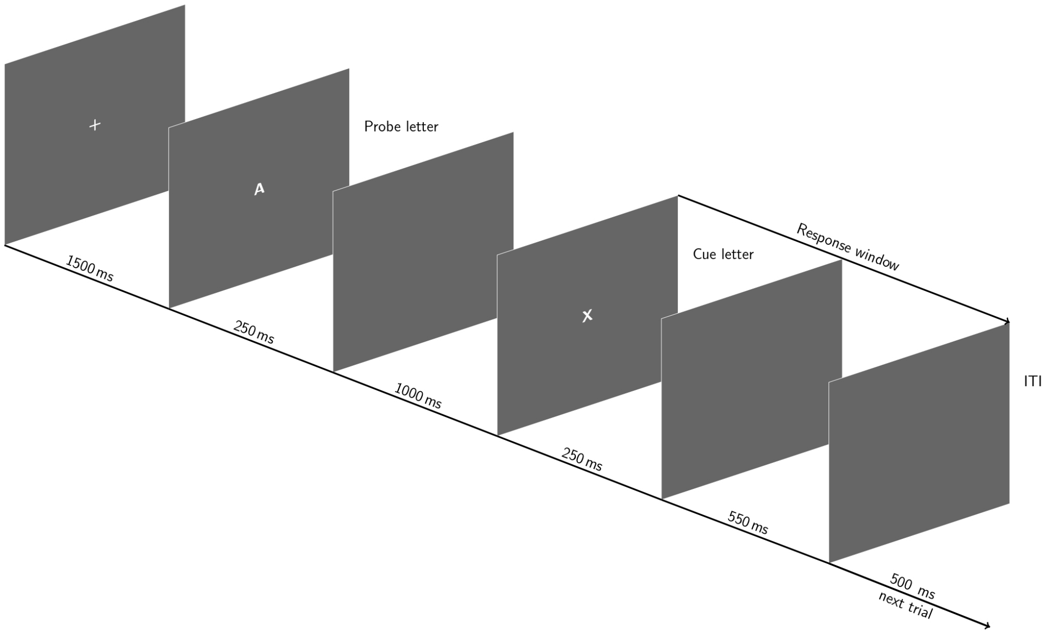

Figure 5.2 – **Procedure of the AX-CPT paradigm used in the current study.** The figure represents an "AX" trial, which appears in 70% of the trials, and that requires a right response for half the sample. The participant had 800 ms after the presentation of the probe to respond.

had to press with the left hand (cf. Figure 5.2). All letters were used for the cue-B and the probe-Y letters, excepted the K and the Y because of their visual similarity with the X. To ensure the predominance of the response to the cue-A and the probe-X, 70% of the trials were “AX” trials. The other three types of trial (i.e., AY, BX and BY) were each presented in 10% of the trials.

Personality questionnaires. The UPPS (Van der Linden et al., 2006; Whiteside & Lynam, 2001) is a 45-item questionnaire that assesses predispositions for impulsive actions. This questionnaire measures impulsiveness with four subscores: Urgency, Premeditation (the lack of), Perseverance (the lack of) and Sensation Seeking. In our sample, the internal consistency of the UPPS total score was adequate, α = .90, 95% CI [.85 - .94]. The median-split method was used to create high and low impulsiveness groups. Participants with an UPPS score below 99 were considered as low impulsive (LI), whereas participants with an UPPS score above 99 were considered as high impulsive (HI). Two participants with UPPS scores equal to 99 were not used in the statistical analysis (N = 46).

Experimental procedure. The participant sat in a closed room facing a computer screen. Each trial began with the presentation of a fixation cross at the center of the screen during 1500 ms. The letters were displayed on the center of the screen during 250 ms and were separated by an empty screen for 1000 ms. The participant had 800 ms to respond after the onset of the probe-letter. Then, an empty screen was presented during 500 ms before the start of the next trial. Figure 5.2 represents the implementation of the task. The experiment began with a training block of 20 trials. During this training, visual feedback appeared for 500 ms after each response providing information about the accuracy of the current trial ("*Bonne réponse*" for a correct response, "*Mauvaise réponse*" for an error, "*Aucune réponse enregistrée*" for anticipated responses or responses slower than 800 ms). If at least 90% of the training trials were correct, then the experimental part began. The participant performed 10 blocks of 70 trials. A pause was implemented between each block. The experiment lasted about 50 min. Both EEG and EMG data were recorded during the experimental part using the BioSemi©system (BioSemi ActiveTwo electrodes, Amsterdam), but will not be used for the current analysis (see Chapter 8.3 for their analysis).

Experimental groups and statistical analyses

Reaction times shorter than 50 ms or outside the 2*SD interval were removed to eliminate potential performance outliers. One participant was excluded from statistical analysis because of more than 30% of omissions in at least one of the four trial types (N = 45). Accuracy rates and mean RTs in correct trials were calculated for each of the four trial types (i.e., AX, AY, BX and BY) and for each participant. Following Braver et al. (2009) methodology, the proactive behavioral index (PBI) was calculated for correct RTs as follows:

$$PBI = \frac{AY - BX}{AY + BX}$$

The classical effects of an AX-CPT task were investigated with a one-factor ANOVA with Trial Type (4) as within-subject factor on accuracy rates and RTs in correct trials. The ability to adapt behaviors to task demands was investigated by applying a one-factor

ANOVA with Blocks (10) as within-subject factor on the PBIs. For this analysis only, one participant had to be removed for the mixed-ANOVA analysis because of less than 6 exploitable PBI (N = 44). Moreover, to investigate the three hypothetical patterns of results presented in Figure 5.1, a two-factor ANOVA with Blocks (10) and Trials (2) as within-subjects factors was performed on mean RTs in correct AY and BX trials. Finally, the effect of impulsiveness on the control strategy used was investigated using Pearson's correlation, Student t-test and two-factor mixed-ANOVA with Blocks (10) as within-subject factor and Impulsiveness (2) as between-subject factor. The individual estimates of the regression model explaining the PBI as a function of Blocks were used as index of the adaptation ability (see Appendix .1 for the detailed methodology to extract this index). This index was analyzed according to the UPPS scores using a Pearson's correlation and an independence $\chi 2$ test.

Results

Global analyses

Table 5.1 – Means and 95% Confidence Intervals of Global and By-Trials Accuracy (%) and Global Correct Trials Reaction Times (RT, ms), and the Proactive Behavioral Index (PBI) in Low (LI) and High (HI) Impulsiveness Groups.

	Total (n = 47)		LI (n = 22)		HI (n = 23)	
	M	95% CI	*M*	95% CI	*M*	95% CI
Total accuracy (%)	90.39	[88.89, 91.90]	90.59	[88.57, 92.61]	89.70	[87.31, 92.10]
Accuracy AX (%)	96.98	[96.30, 97.66]	97.17	[96.25, 98.09]	96.64	[95.53, 97.74]
Accuracy AY (%)	81.06	[76.82, 85.30]	80.71	[75.63, 85.80]	80.37	[72.91, 87.83]
Accuracy BX (%)	91.12	[89.05, 93.20]	91.23	[88.22, 94.24]	90.62	[87.31, 93.93]
Accuracy BY (%)	92.40	[90.49, 94.32]	93.25	[90.45, 96.05]	91.18	[88.24, 94.12]
Global RT (ms)	347.61	[333.48, 361.73]	335.99	[314.50, 357.48]	358.50	[338.58, 378.41]
RT AX (ms)	344.86	[331.16, 358.57]	338.46	[320.04, 356.87]	350.27	[327.64, 372.89]
RT AY (ms)	477.82	[466.82, 488.82]	479.23	[464.63, 493.84]	477.67	[458.95, 496.39]
RT BX (ms)	281.68	[260.70, 302.66]	261.45	[235.15, 287.75]	300.78	[265.86, 335.71]
RT BY (ms)	286.07	[365.65, 306.48]	264.84	[238.01, 291.67]	305.27	[272.45, 338.09]
PBI	0.27	[0.24, 0.30]	0.30	[0.27, 0.34]	0.24	[0.20, 0.28]

The ANOVA results revealed a main effect of Trial Type on RTs in correct trials and on accuracy, $F(3,184) = 503.1$, $p < .001$, $\eta^2 = 0.92$ and $F(3,184) = 43.91$, $p < .001$, $\eta^2 = 0.49$, respectively (cf. Table 5.1). In AY trials, participants were slower and less accurate than in other trial types revealing the dominant use of proactive strategy during the task. Accordingly, the mean proactive behavioral index (PBI) calculated with the RTs in AY and BX correct trials in all blocks was 0.27 (95% CI [0.24, 0.30]).

Effect of impulsiveness on the PBI

Accuracy rates and reaction times in the LI and the HI groups are presented in Table 5.1. The HI and LI groups did not differ on global accuracy rates, $t(174.28) = 0.56$, $p = .574$, Cohen's $d = 0.08$, neither on global RTs, $t(176.32) = 1.53$, $p = .129$, Cohen's $d = 0.23$. There was a main effect of Impulsiveness on the global PBI, $t(42.09) = 2.42$, $p = .020$, Cohen's $d = 0.72$ (medium effect), with smaller PBI in the HI group ($M = 0.24$, 95% CI [0.20, 0.28]) than in the LI group ($M = 0.30$, 95% CI [0.27, 0.34]). More specifically, the current study revealed a negative correlation between impulsiveness scores and the PBI, $r = -.33$, $p = .026$: higher the impulsiveness, poorer the dominance of proactive control.

Adaptation of the proactive control strategy across blocks

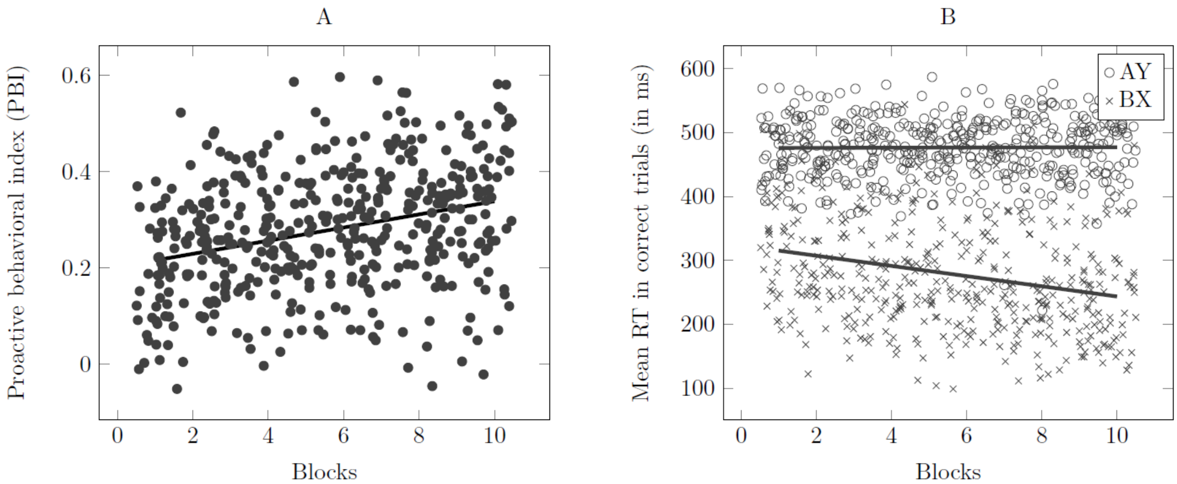

Figure 5.3 – **Evolution of the proactive behavioral index (A) and the RTs in correct AY and BX trials (B) across blocks. (A)** The proactive behavioral index (PBI), calculated as (AY - BX)/(AY + BX), increased across blocks. **(B)** The BX trials RTs progressively decreased whereas the AY trials RTs remained stable across blocks. The increase in the PBI is therefore due to a decrease in the involvement of reactive control processes.

The one-factor ANOVA revealed a main effect of Blocks on the PBI, $F\ (1{,}45) = 81.17$, $p < .001$, $\eta^2 = 0.64$. In all our sample, the PBI increased over time from 0.18 to 0.33

(cf. Figure 5.3A). To understand this increase, we investigated the changes in the RTs in AY and BX trials throughout the task. The mixed-ANOVA revealed an interaction effect between Trials and Blocks on the mean RTs in correct AY and BX trials, F (1, 812) = 52.11, $p < .001$, $\eta^2 = 0.08$ (cf. Figure 5.3B). The RTs in the BX trials decreased progressively across blocks whereas the RTs in AY trials remained stable, thus explaining the increase in the AY - BX difference used in the calculation of the PBI.

Concerning the impulsiveness effect, the ANOVA revealed an interaction effect between Impulsiveness and Blocks on the PBI, F (1,42) = 5.73, $p = .021$, $\eta^2 = 0.12$ (cf. Figure 5.4A). The PBI increased in both impulsiveness groups, but this increase was slower in the HI group. In the LI group, the PBI increased from 0.22 (95% CI [0.18, 0.27]) in the first block to 0.40 (95% CI [0.35, 0.46], $\delta = 0.18$) in the last block whereas, in the HI group, the PBI increased from 0.16 (95% CI [0.11, 0.21]) to 0.28 (95% CI [0.21, 0.24]), $\delta = 0.12$). In the first block, there was a close-to-significance difference between the HI and LI groups, $t(41) = 1.91$, $p = .063$, Cohen's $d = 0.57$ (medium effect), with smaller PBI in the HI group ($M = 0.16$, 95% CI [0.11, 0.21]) than in the LI group ($M = 0.22$, 95% CI [0.18, 0.27]). In the last block, this statistical tendency was confirmed, $t(40.60) = -2.99$, $p = .005$, Cohen's $d = 0.60$ (medium effect): the HI group had a smaller PBI ($M = 0.28$, 95% CI [0.21, 0.34]) than the LI group ($M = 0.40$, 95% CI [0.35, 0.46]). This difference in the PBI increase was due to the interaction effect between Trial Type (AY and BX) and Impulsiveness, $F(1,774) = 51.20$, $p < .001$, $\eta^2 = 0.06$: the HI group had longer RTs in the BX trials compared to that observed in the LI group, but there was no group differences in RTs in the AY trials (cf. Table 5.1 and Figure 5.4B). Moreover, the interaction of this effect with Blocks was close-to-significance, $F(1,774) = 3.77$, $p = .053$, $\eta^2 = 0.005$, indicating that the HI group slowly decreased the RTs in the BX trials throughout the course of the blocks compared to the LI group (cf. Figure 5.4C).

Estimation of individual adaptation capacities

The individual estimates of the model were used to investigate possible inter-individual differences in the capacity to adapt to task demands. The estimates did not correlate with

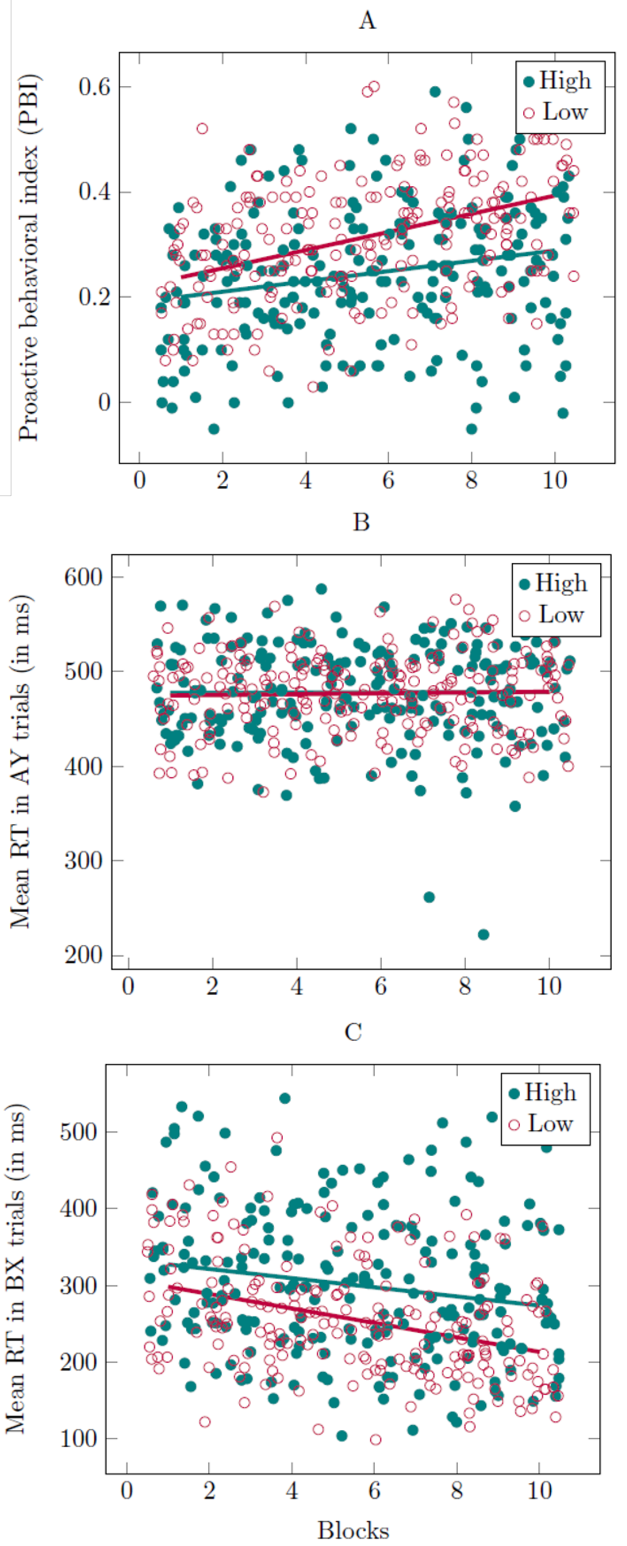

Figure 5.4 – **Effects of the impulsiveness groups on the PBI (A) and on the RTs in AY and BX trials (B and C) as a function of blocks.** The high and the low impulsiveness groups (green and red dots, respectively) were created using the median of the UPPS score distribution. The proactive behavioral index (PBI) in the high impulsiveness group increased slower than the PBI of the low impulsiveness group **(A)**. The difference in the PBI adaptation was due to a slower decrease in RTs in the BX trials in the HI group compared to the LI group **(C)** whereas RTs in the AY trials **(B)** remained stable for both groups.

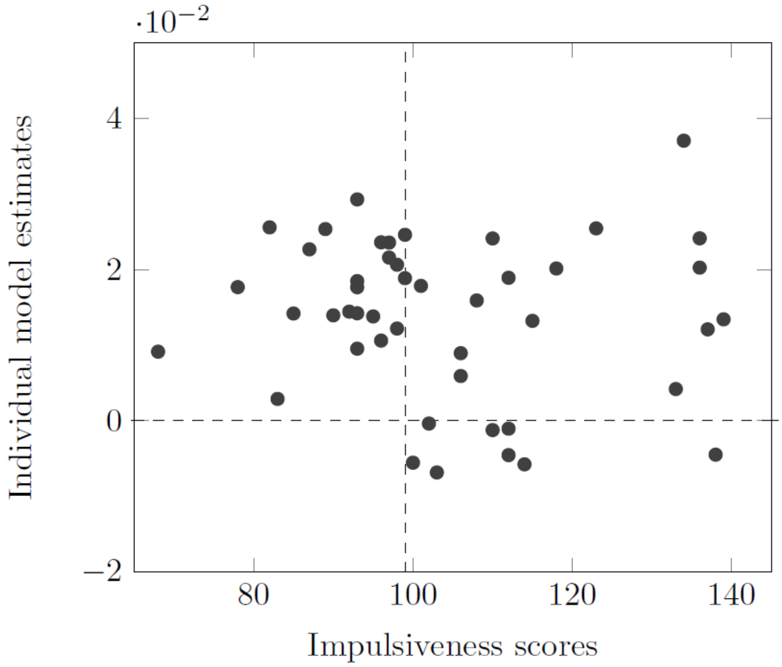

Figure 5.5 – **Individual estimates of the model according to the impulsiveness scores.** The estimates of the model were used as an index of the adaptation to task demands. The vertical dotted line represents the median of the UPPS score distribution that was used to create the low and the high impulsiveness groups. The horizontal dotted line represents the separation between negative slope (estimate < 0, no adaptation to task demands) and positive slope (estimate > 0, adaptation to task demands)..

UPPS scores, r = -.07, p = .630. However, the $\chi 2$ test revealed a significant association between Impulsiveness groups and the adaptation rate, $\chi 2$ (2, N = 44) = 6.74, p = .009 (cf. Figure 5.5). The frequency of observation of a negative estimate was null in the LI group, indicating that LI individuals always adapted their control strategies to the task. However, eight out of 23 individuals in the HI group were characterized by a negative regression model estimate, indicating an absence of adaptation to task demands in 35% of the HI group (cf. Table 5.2).

Table 5.2 – Contingency Table Between Impulsiveness Groups and the Adaptation of the PBI Across Blocks as Indexed by the Model Coefficients.

	LI	HI	Total
Positive estimate	21 (100%)	15 (65%)	36 (82%)
Negative estimate	0 (0%)	8 (35%)	8 (18%)
Total	21	23	44

Discussion

This study aimed at exploring the implementation of cognitive control strategies in healthy impulsive individuals. The AX-CPT paradigm (Braver et al., 2009) and the UPPS questionnaire (Whiteside & Lynam, 2001) were used to calculate the proactive behavioral index (PBI) and to assess impulsiveness, respectively. Results showed that the high impulsiveness group had a smaller PBI than the low impulsiveness group, suggesting that impulsive individuals relied less on proactive control mechanisms than less impulsive individuals to perform the task. Furthermore, the analysis of the PBI across blocks revealed that participants adapted their control strategy to task demands by reducing the involvement of reactive control. The PBI increased over time, but more slowly in the high impulsiveness group compared to that observed in the low impulsiveness group. Overall, the current study demonstrated that impulsiveness is associated with a poorer adaptation to a proactive task demands, due to a longer lasting reliance on reactive control mechanisms.

The proactive behavioral index (PBI) is an indicator of relative tendencies towards proactive versus reactive control strategies (Braver et al., 2009; Chiew & Braver, 2017). In the current sample, we found a global positive PBI, consistent with the results reported in Criaud et al. (2012) suggesting that proactive control is the default state of cognitive control. However, in the present study, the high impulsiveness group had a smaller PBI than the low impulsiveness group, revealing a less dominant proactive control mode in impulsive individuals. The PBI even correlated with the impulsiveness score, suggesting that less dominant the proactive control, the higher the impulsive tendencies. These findings are consistent with results from pathological studies: the proactive mode is less dominant in schizophrenic and bipolar patients (PBI = .10, Smucny et al., 2019). In some specific disorders, as borderline personality disorder, the default state even shifts to reactive control, revealed by a negative PBI (PBI = -.07, van Dijk et al., 2014). The current study suggests that the PBI may be an objective index of impulsiveness in both normal and pathological populations.

The default state of cognitive control (Criaud et al., 2012) is not the only parameter of cognitive control that can explain maladaptive behaviors. Indeed, a change in the default state is not dysfunctional if one can efficiently adapt control strategies according to task demands. In the current study, the AX-CPT task was constructed to encourage proactive control processes (Janowich & Cavanagh, 2018). Consequently, individuals adapted their control strategies to rely more and more on proactive processes throughout the task, as revealed by the increase in the PBI across blocks. This result was consistent with the findings of Janowich and Cavanagh (2018), but at the individual level. Moreover, the current results revealed an inter-individual variability in this adaptation capacity. The increase in the PBI was slower in the high impulsiveness group than in the low impulsiveness group. Therefore, high impulsive individuals were not less proactive *per se*, but had more difficulty to adapt their control strategy to task demands. Furthermore, no adaptation was observed in high impulsive individuals only. This finding suggests that the absence of adaptation in control strategies may be a vulnerability factor to the development of an impulsive-related psychiatric disorder. Future studies are needed to generalize the current findings to impulsive pathological populations.

The data presented here, along with those reported by Janowich and Cavanagh (2018), demonstrate that healthy individuals are able to adapt control strategies during the AX-CPT task to lean more on proactive processes. One aim of this study was to identify which pattern presented in Figure 5.1 explained this adaptation effect by analyzing the RT changes in AY and BX trials across blocks. Results revealed that the increase in the PBI was due to the weakening of reactive control processes, as observed in the decrease in BX trials RTs (Figures 5.1B and 5.3B). Therefore, the increase of proactive processes is not due to the increased automaticity of proactive control as suggested by Janowich and Cavanagh (2018), but to the decline of reactive control processes. Interestingly, this finding specified the difficulty in control strategy adaptation observed in the high impulsiveness group. The slow adaptation of control processes in the high impulsiveness group was due to a stronger reliance on reactive processes across blocks compared to that observed in the low impulsiveness group (cf. Figure 5.4C). Impulsive personality traits in a healthy population are associated with a more reactive control system, and not a less proactive one.

Conclusion

The current results showed that high impulsive individuals in a general population slowly adapt cognitive control strategies to task demands compared to low impulsive individuals. This slower adaptation was explained by a poorer weakening of reactive control processes. Both the default state and the adaptation of cognitive control strategies should be concurrently investigated to potentially differentiate profiles of pathological populations characterized by high impulsiveness.

5.2 Preliminary results with impulsive behaviors

The first study revealed that high impulsiveness, assessed with the UPPS questionnaire (Whiteside & Lynam, 2001; Van der Linden et al., 2006), was associated with a less dominant proactive control, as revealed by a smaller proactive behavioral index (PBI). As impulsivity comprises both impulsiveness and impulsive behaviors (see Chapter 1), we aimed at investigating if the smaller dominance of proactive control was also associated with impulsive behaviors.

In the current study, we therefore used the AX-CPT task to assess the dominance of the proactive control over the reactive one, through the calculation of the proactive behavioral index (PBI). To investigate the relationship between the PBI and impulsive decision-making, the *Delay Discounting* task was used to calculate the k-value (i.e., index of the rate of discounting, see Chapter 1.2.2). A higher k-value reveals a larger and steeper discounting of the value of a reward with delays (i.e., a tendency to choose smaller-sooner rewards instead of larger-later ones). Higher k-values were reported in several impulsive-related pathological populations, such as addictive disorders (e.g., Bickel et al., 2012; Hamilton & Potenza, 2012; Albein-Urios et al., 2014), bipolar disorder and schizophrenia (e.g., Ahn et al., 2011), borderline personality disorder (e.g., Lawrence et al., 2010) and eating disorders (e.g., Price, Lee, & Higgs, 2013; Steward et al., 2017).

Therefore, we expected that a higher k-value, revealing higher impulsive decision-making, would negatively be correlated with the PBI. In addition, to investigate the relationship between the PBI and impulsive motor action, we recorded electromyographic activities during a Simon task to uncover partial-errors (see Chapter 3.1.2) and to calculate the correction ratio (i.e., CR, the proportion of successfully corrected engaged errors). For the same amount of engaged errors, a participant with a high CR was more successful at inhibiting the erroneous action to give the correct answer than a participant with a lower CR (see Figure 3.6B). Therefore, a higher CR reveals better behavioral inhibition capacities, and therefore less impulsive motor action as defined in the factorial structure of impulsivity (see Chapter 1). However, the partial-errors could be a more precise index of impulsive motor action. Indeed, they reflect an impulsive response style (and not a deficit, Sharma et al., 2014) upon a stimulation. We thus expected that the rate of engaged errors (i.e., partial-errors and full-errors) would correlated with impulsiveness, and therefore could be an index of impulsive motor action.

The first study showed that higher impulsiveness was associated with a smaller dominance of proactive control (see Chapter 5.1). The current study aimed at replicating this effect with behavioral measures of impulsivity, using the k-value in the Delay Discounting task (i.e., impulsive decision-making), the rates of engaged errors and the correction ratio in a Simon task (i.e., impulsive motor action).

Method

Participants

The recruitment of participants was stopped due to the 2020 health crisis. The results presented hereafter are therefore preliminary. Twenty-five healthy volunteers (18 women, age ranged from 18 to 25 years) were recruited at the University of Lille. Exclusion criteria included motor, sensory, neurological and/or psychiatric disorders and a current medical treatment that could affect tasks performance. They all gave written informed consent for taking part in this study.

Experimental paradigms

The participant was invited to perform a Simon task (Simon, 1990), an AX-CPT task (Braver et al., 2009; Cohen & Servan-Schreiber, 1992; Servan-Schreiber et al., 1996) and finally, a Delay Discounting task (Logue, 1988; Ainslie & Haslam, 1992) in that order. Muscular activities were recorded using EMG during the Simon task only. At the end of the experimental session, participants fulfilled the UPPS questionnaire (Whiteside & Lynam, 2001; Van der Linden et al., 2006).

Simon task. In this task, the participant was invited to respond as fast and as accurate as possible to a stimulus as a function of its shape (i.e., a circle or a square). For 13 participants, the circle required a right button press and the square a left button press (this mapping rule was inverted for the other participants). The stimuli could appeared on the right or the left side of the fixation cross. Therefore, in 50% of trials, the stimulus appeared on the same side as the expected response (i.e., congruent trials). In the other 50% of the trials, the stimulus appeared on the opposite side of the expected response (i.e., incongruent trials). A trial was defined as follows. The fixation cross appeared on the center of the screen for 300 ms. Then, the stimulus was presented on the right or the left side of the fixation cross. When a response was given, or after a 1000 ms time lapse, a empty screen appeared for 1000 ms before the next trial.

The Simon task was modified by the implementation of an algorithm, adapted from Rinkenauer, Osman, Ulrich, Müller-Gethmann, and Mattes (2004)'s study. This algorithm was used to decrease or increase the maximum response time, hereafter referred to as *deadline*, according to both error and omission rates in the previous block. The main purpose of this adaptive algorithm was to set error rates around 8% (+/- 2%) using the 84th percentile of the reaction times distribution of the previous block as an estimation of the required deadline for the subsequent block. The algorithm allowed to adjust task difficulty at an individual level and to reduce the variability in error rates across the sample. For an extended description of the algorithm, see Appendix .3.

After three blocks to adjust the deadline, the participant performed five experimental blocks of 129 trials (i.e., a total of 645 trials). Muscular activities were recorded during the experimental blocks only, using two electrodes Ag/AgCl electrodes with the BioSemi© system (BioSemi ActiveTwo electrodes, Amsterdam) placed on each hand above the *flexor pollicis brevis* to uncover partial-errors. The sampling rate was set to 1024 Hz (filters: DC to 208Hz, 3dB per octave). The raw electromyographical (EMG) data were processed with the BrainVision Analyzer 2.1© software (Brain Products, Munich, Germany). The EMG data were filtered with a 10 Hz high-pass filter. Onsets of EMG activities were manually marked after visual inspection as it remained more precise than automatic algorithms (Staude, Flachenecker, Daumer, & Wolf, 2001). Based on the markers, the trials were classified as (1) pure-correct trials (i.e., trials with only one muscular burst on the correct side), (2) full-error trials (i.e., trials with only one muscular burst on the incorrect side), and (3) partial-error trials (i.e., trials containing two EMG activations, one on the incorrect side preceding the correct response). The precise classification of the nature of the performance allowed the calculation of the correction ratio (CR) as follows:

$$CR = \frac{Partial - errors}{Engaged\ errors}$$

with engaged errors referring to the number of trials that contain an incorrect EMG activity (i.e., partial-error and full-error trials). As failures of behavioral inhibition are thought to reflect impulsive motor action (see Chapter 1), we used the CR to index impulsive motor action in the current study. Higher the CR, the weaker the impulsive motor action. However, the rates of engaged errors (i.e., partial-errors and full-errors) could also be considered as an index of impulsive motor action, as it reflects an impulsive response style. Both the CR and the number of engaged errors were used as index of impulsive motor action.

Delay Discounting task. The stimuli were pairs of virtual monetary rewards available now or after a delay (i.e., one week, two weeks, one month, three months, six months and one year). The participant was required to choose between a smaller reward, available now, and a larger, but delayed, reward. The smaller reward was fixed (10€) and the larger but delayed reward varied across trials as a function of the previous choice. For example, for the "one week" delay, the participant has to first choose between 10€ now or 100€ in a week. Choosing the delayed alternative, the second choice was between 10€ now or 50€ in a week. The indifference point (i.e., the mean of the two last delayed rewards) was calculated for each of the six delays. The indifference points as a function of the delays follow an hyperbolic function:

$$V = \frac{A}{k + 1D}$$

where A refers to the reward amount, D to the delay to obtain the reward and k to the slope of the curve. The k value is the parameter used as an index of impulsive decision-making. A higher k (i.e., a steeper curve) reveals that the participant strongly discounts the value of the reward with delays, and therefore is more impulsive.

AX-CPT task. The AX-CPT task performed by the participant in this study was the same as the protocol presented in the Study I (see Chapter 5.1). However, as the present study comprised two other tasks, the participant performed four blocks of 70 trials only. The AX-CPT task was used to calculate the proactive behavioral index (PBI) as:

$$PBI = \frac{AY - BX}{AY + BX}$$

with AY and BX referring to the mean reaction time (RT) in correct AY and BX trials, respectively.

Statistical analysis

Correlation analyses were performed to investigate the relationship between PBI and each impulsive behaviors indices. Spearman's method was used with the k-value and Pearson's method was used for the correction ratio and the rates of engaged errors indices. Moreover, to investigate the predictive values of the different impulsivity indices on the PBI (i.e., k-value, CR and UPPS scores), a multiple regression analysis was performed using the *lm* function of the *stats* package on R.

Results

Global analysis

The classical effects of the AX-CPT task were observed in our sample. ANOVA analysis revealed a main effect of Trial Type (i.e., AX, AY, BX and BY) on both the mean correct RTs and on accuracy, $F(3, 128) = 38$, $p < .001$, $\eta^2 = 0.47$ and $F(3, 128) = 18.98$, $p < .001$, $\eta^2 = 0.31$. The average PBI was 0.23 (*SD* = 0.14, ranged from -0.06 to 0.49).In the Simon task, among exploitable trials, 68% were categorized as pure-correct trials (*SD* = 8%, ranged from 56% to 84%), 24% as partial-errors (*SD* = 7%, ranged from 11% to 36%) and 8% as full-errors (*SD* = 3%, ranged from 1% to 14%). On average, 74% of engaged errors were successfully corrected (*SD* = 10%, ranged from 64% to 92%). Finally, in the Delay Discounting task, the average *k*-value was 0.01 (*SD* = 0.01, ranged from 0.00 to 0.05).

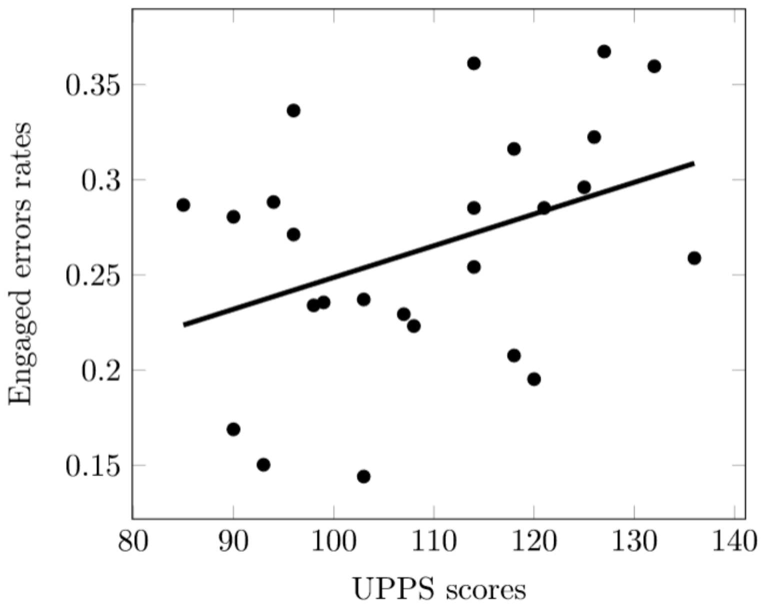

Figure 5.6 – **Correlation between the UPPS scores and the engaged errors rates.** Engaged errors refer to the sum of partial-errors and full-errors. Higher impulsiveness was significantly correlated with higher rates of engaged errors.

Impulsiveness and partial-error rates analysis

The UPPS scores significantly correlated with the rate of engaged errors, r = 0.39, p = .056 (see Figure 5.6). Decomposing the number of engaged errors, results showed that the UPPS scores tended to correlate with partial-error rates, r = 0.38, p = .060, but not with error rates, r = 0.18, p = .39. High impulsive individuals significantly produced more partial-errors (M = 27%) than low impulsive individuals (M = 21%), t(21.49) = 2.39, p = .026, Cohen's d = 0.98 (large). There was no effect of UPPS scores on the correction ratio, r = 0.10, p = .626.

Impulsive behaviors and the proactive behavioral index

The correction ratio and the engaged errors rates did not significantly correlate with the PBI in our sample, r = -0.12 and p = .565, r = 0.22, p = .297, respectively. There was a close-to-significance correlation between the k-value and the PBI, ρ = -0.34, p = .100.

The multiple regression analysis replicated the main effect of the UPPS scores on the PBI, β = -0.06, t = -2.14, SD = 0.03, p = .049. There was no main effect of the k-value on the PBI, β = -275.52, t = -1.52, SD = 180.94, p = .149. There was a close-to-significance effect of the CR on the PBI, β = -8.50, t = -1.89, SD = 4.51, p = .079. More interestingly, we observed a significant interaction effect between the correction ratio and the UPPS scores on the PBI, β = 0.08, t = 2.07, SD = 0.04, p = .057. The interaction suggests that higher the correction capacities, the lesser the association between high impulsiveness and smaller dominance of proactive control during an AX-CPT task (see Figure 5.7). However, results failed to showed a direct association between between the CR and the capacity to adapt the PBI across blocks, r = -0.20, p = .372.

Discussion

The preliminary findings of this ongoing study replicated the effect of impulsiveness on the proactive behavioral index (PBI) observed in the first study (see Chapter 5.1). High impulsive personality traits were associated with a reduction in the dominance of proactive control in the general population. This finding is consistent with the PBI calculated on

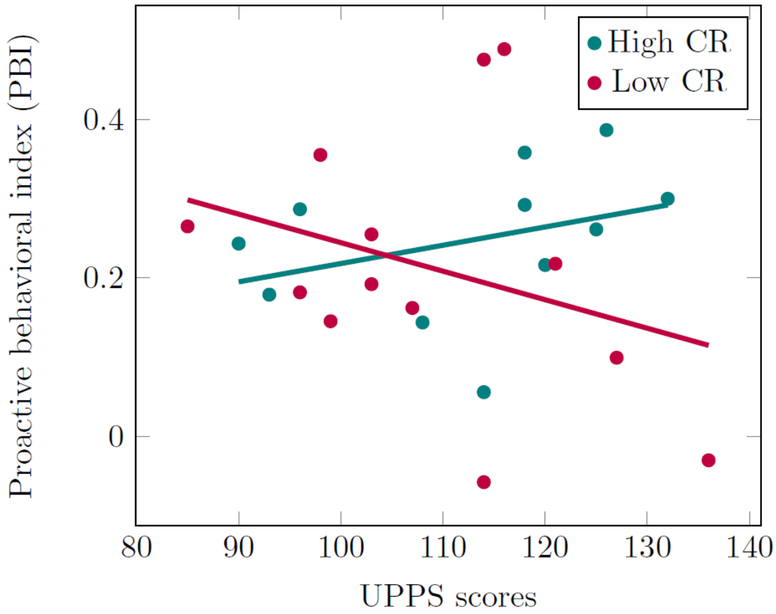

Figure 5.7 – **Proactive behavioral index as a function of the UPPS scores and the correction ratio (CR)**. High and low CR groups were created using the median-split method for visualization purposes only.

the basis of the data reported in studies in pathological populations (e.g., Smucny et al., 2019; van Dijk et al., 2014; Brambilla et al., 2007; Lesh et al., 2013; Kräplin et al., 2016) presented in the Table 3.1. Indeed, the PBI is smaller in various impulsive pathological populations than in control subjects. However, the indices of impulsive behaviors used in this study failed to predict the PBI. Finally, results showed that higher impulsiveness was associated with a higher rate of engaged errors, mostly driven by a higher occurrence of partial-errors, suggesting that the weaker dominance of proactive control in high impulsive individuals leads to a higher sensitivity to interference.

More interestingly, the preliminary results of this study suggest that the relationship between impulsiveness and the PBI is moderated by behavioral inhibition capacities. Greater the behavioral inhibition capacities in impulsive individuals, as assessed through the correction ratio (CR), higher the dominance of proactive control. As the first study showed that participants were able to increase the dominance of proactive control over time (see Chapter 5.1), the analyzed PBI in this study may result from the adaptation of the dominance of proactive control over the four AX-CPT blocks. The moderation effect of inhibition capacities on the relationship between impulsiveness and PBI suggested that efficient inhibition capacities may improve the capacity to adapt, but the results failed to show such an association. Nonetheless, in this study, only four AX-CPT blocks were performed in order to reduce the participant's fatigue, a methodological choice that could have limited the analysis of the adaptation of control mechanisms.

Conclusion of the first axis

The first axis of my PhD project investigates the dual mechanisms of control in the general population with high or low impulsiveness. More precisely, I explored impulsive-related inter-individual differences in the dominance of the proactive control and its adaptation to external demands. Here, the external demands were the experimental paradigm itself: proactive control is more optimal than reactive control to perform the AX-CPT task.

In the first study, I observed a less dominant proactive control (i.e., a smaller PBI) in high impulsive individuals compared to that observed in low impulsive individuals. The preliminary results of an ongoing study replicated this finding, and suggested that behavioral inhibition capacities moderate this relationship. Greater the behavioral inhibition capacities, smaller the association between impulsiveness and the PBI. Also, it is important to emphasize that, in the first study, the effect of impulsiveness on the proactive behavioral index was mostly driven by the slower adaptation of control mechanisms to task demands in the high impulsiveness group. High impulsive individuals slowly (or did not) adapted the dominance of proactive control over time, as they relied longer on reactive control compared to low impulsive individuals. Moreover, as impulsive behaviors did not predict smaller PBI, I postulated that an impairment in the capacity to adapt control mechanisms to external demands better explains the emergence of impulsive behaviors than the weaker dominance of proactive control itself.

Overall, these findings suggested that impulsiveness (i.e., the personality component of impulsivity, see Chapter 1) could be defined as a less proactive cognitive control system, driven by a difficulty in adapting control mechanisms to external demands. The impairment in the capacity to adapt control mechanisms to external demands might underlie how impulsiveness predicts impulsive behaviors, and thus how it is a vulnerability factor for psychiatric disorders.

Chapter 6

Adaptation of cognitive control mechanisms to external demands in a pathological population

Foreword

The findings from the first axis of my PhD research project suggested that impulsiveness in the general population was associated with a less-dominant proactive cognitive control system. As this effect was mostly driven by a slower adaptation of control mechanisms to external demands, I hypothesized that impairments in the capacity to adapt control mechanisms to external demands might underlie how impulsiveness predicts impulsive behaviors, and thus how it is a vulnerability factor for psychiatric disorders.

Therefore, I conducted a second study in patients with alcohol-dependence disorder. The onset and the severity of alcohol-dependence are indeed strongly associated with impulsivity (e.g., Khemiri, Kuja-Halkola, Larsson, & Jayaram-Lindström, 2016; Liu et al., 2020). Similarly to the Study I, alcohol-dependent patients (AD) and matched control subjects (HC) performed an AX-CPT task and fulfilled the UPPS questionnaire. They also fulfilled the AUDIT questionnaire to analyze the relationship between the severity of the consumption and the capacity to adapt control mechanisms.

6.1 Study II: Adaptation of control mechanisms in an alcohol-dependent population

Preliminary results of a larger study

Introduction

Literature shows a strong association between impulsivity and addictive disorders (e.g., Verdejo-García et al., 2007; Bjork, Hommer, Grant, & Danube, 2004). In the case of alcohol-dependence, impulsivity is a vulnerability factor for the development of alcohol use disorder (AUD, de Wit, 2009), but also for relapses after periods of abstinence (Stevens et al., 2014). Moreover, impulsivity is also associated with an increased quantity and frequency in consumption (Weafer, Milich, & Fillmore, 2011; Moody et al., 2016). Interestingly, some authors suggest that different facets of impulsivity are involved in different stages of the AUD.

Impulsive decision-making, as assessed using delayed gratification and risk-taking tasks, is particularly targeted in the investigation of AUD. Fernie, Cole, Goudie, and Field (2010) showed that risk-taking, but not delay gratification, predicted alcohol use in young social drinkers. However, several studies observed a larger k-value during the Delay Discounting task (i.e., index of higher impulsive decision-making) in heavy drinkers and in dependent alcohol users compared to control populations (e.g., Kollins, 2003; Gowin, Sloan, Swan, Momenan, & Ramchandani, 2019; Bobova, Finn, Rickert, & Lucas, 2009; Petry, 2001). Also, performances at the Stop Signal task (i.e., index of impulsive motor action through behavioral inhibition capacities) in heavy drinkers is one of the significant predictor of the development of a dependence at a 4-year follow-up (Rubio et al., 2008). According to Aragues, Jurado, Quinto, and Rubio (2011)'s review, the two impulsive behavioral components come into play at different stages of the AUD. Impulsive decision-making is a vulnerability factor for the development of AUD whereas impulsive motor action maintains the consumption and therefore, predicts the onset of an alcohol dependence (Rubio et al., 2008; Aragues et al., 2011).

To explain the role of impulsivity in the AUD, literature have largely focused on reactive control, through the capacities to inhibit and stop ongoing actions. However, this over-simplistic perspective of AUDs (Baines, 2019) conceals the potential role of the other control mechanism, namely proactive control, that is thought to provide better explanation of substance use disorder (Aron, 2011). In non-dependent drinkers, Baines, Field, Christiansen, and Jones (2020) showed that inter-individual differences in proactive and reactive control capacities during an AX-CPT task did not predict alcohol consumption. However, Sharma (2017) observed less conflict adaptation (i.e., reduced Gratton effect, a proactive control index) after alcohol exposure in heavy drinkers. The author thus suggested that heavy drinkers relied more on reactive processing compared to light drinkers, as they were more sensitive to irrelevant contextual information. Interestingly, Hu, Ide, Zhang, Sinha, and Li (2015) in alcohol-dependent patients and Brevers et al. (2018) in cannabis users observed that patients did not adjust proactive control (i.e., slowing RTs in Go trials) as a function of the probability of the occurrence of the Stop Signal compared to control subjects, suggesting that patients were impaired in proactive control. Overall, the studies seem to suggest that proactive behavioral adjustments are smaller in addictive populations compared to control subjects. However, results from Hu et al. (2015) and Brevers et al. (2018) could indicate that substance use is associated with less adaptation of the involvement of proactive control when the context requires to use proactive control. In the current study, we therefore investigated the capacity to adapt control mechanisms to external demands in an alcohol-dependent population with the AX-CPT task (Braver et al., 2009; Servan-Schreiber et al., 1996; Cohen & Servan-Schreiber, 1992). We compared the proactive behavioral index (PBI) calculated in the AX-CPT task and its evolution across blocks between alcohol-dependent patients (AD) and in matched controls (HC). According to previous findings (Sharma, 2017; Brevers et al., 2018; Hu et al., 2015; Grisetto, Delevoye-Turrell, & Roger, n.d.), we expected that the PBI would be smaller in AD patients compared to HC. Moreover, we hypothesized that the adaptation of the PBI across blocks will be negatively correlated with the AUD severity, as assessed through the AUDIT scores (Gache et al., 2005).

Method

Participants

Fifteen alcohol-dependent (AD) patients recruited at the Robert Debré Institute in La Réunion, France, (13 men) and 15 matched controls (HC) recruited at the University of Lille (14 men) participated in the study. One participant declared a head trauma, and was therefore excluded for the study. Technical issues led to remove two participants (one AD and one HC, $N = 28$). AD and HC participants were carefully matched on age and on social-educational level (Table 6.1). The ethics committee of the University of Lille approved this protocol (2019-359-S74, see Appendix VI).

Procedure

A standardized room was set in each experimental location. The participant was invited into two experimental sessions. In the first session, the participant was required to answer a demographic questionnaire on the history of addiction, and fulfilled the UPPS questionnaire. A brief cognitive evaluation was also performed using the MoCa, to control for the cognitive efficiency in our sample. In the second session, he/she performed the AX-CPT task. A debriefing time was proposed at the end of the second session.

AX-CPT task

The participant performed the AX-continuous performance task in a closed room (AX-CPT, Braver et al., 2009; Servan-Schreiber et al., 1996; Cohen & Servan-Schreiber, 1992) implemented using E-Prime experimental software (Psychology Software Tools, Inc.). He/she was invited to respond as fast and as accurate as possible as a function of pairs of letters composed with a cue-letter (i.e., the first letter) and a probe-letter (i.e., the second letter, see Figure 6.1). He/she had to press the right response button with the right hand if he/she saw a cue-A followed by a probe-X only. When the cue-letter was not an A (i.e., generic name “B”) or when the probe-letter was not an X (i.e., generic name “Y”), he/she had to press the left response button with the left hand. All letters were used for the cue-B and the probe-Y letters, excepted the K and the Y because of their visual similarities with the X. To ensure that the response to the cue-A and the probe-X was prepotent, 70% of the trials were “AX” trials. The other three types of trial (i.e., AY, BX and BY) were each presented 10% of the trials.

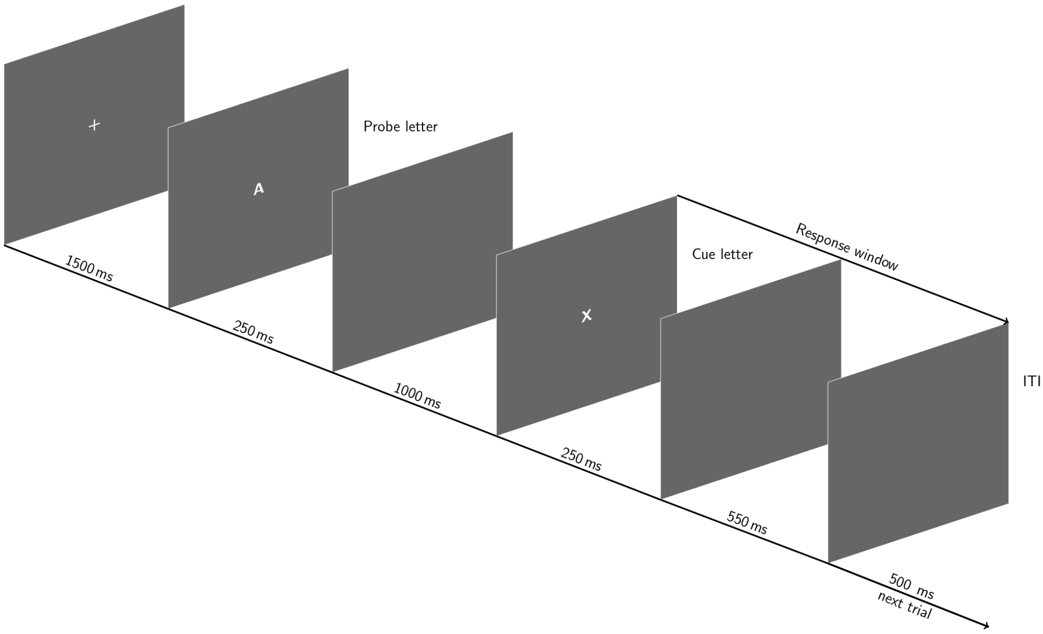

Figure 6.1 – **Procedure of the AX-CPT paradigm used in the current study.** The figure represents an "AX" trial, which appears in 70% of the trials, and that requires a right response for half the sample. The participant had 800 ms after the presentation of the probe to respond.

Each trial begun with the presentation of a fixation cross at the center of the screen during 1500 ms. The letters (i.e., both cue and probe letters) were displayed on the center of the screen during 250 ms and were separated by an empty screen for 1000 ms. The participant had 800 ms after the onset of the probe-letter to respond. Then, an empty screen was presented during 500 ms before the start of the next trial. The experiment begun with a training block of 20 trials. During this training, visual feedback appeared for 500 ms after each response providing information about the accuracy of the current trial ("*Bonne réponse*" for a correct response, "*Mauvaise réponse*" for an error, "*Aucune réponse enregistrée*" for anticipated responses or responses slower than 800 ms). If at least 90% of training trials were correct, then the experimental part begun. The participant performed six blocks of 70 trials (i.e., a total of 420 trials). A pause was implemented between each block. The experiment lasted about 30 minutes.

Questionnaires

UPPS. The UPPS is a 45-item questionnaire assessing impulsiveness through four subscales: *Urgency*, *Premeditation* (lack of), *Perseverance* (lack of) and *Sensation Seeking* (Whiteside & Lynam, 2001; Van der Linden et al., 2006).

AUDIT. The Alcohol Use Disorders Identification test (AUDIT, Barbor, de la Fuente, Saunders, & Grant, 1989; Saunders, Aasland, Babor, Fuente, & Grant, 1993; Gache et al., 2005) is a 10-item questionnaire assessing the severity of the alcohol consumption (see Appendix .3). According to Gache et al. (2005), a score superior to 13 both in men and women indicates an alcohol dependence. Alcohol abuse (i.e., a risk factor for dependence) is indicated by a score above 6 for men and 5 for women (Gache et al., 2005).

Statistical analysis

Two participants were removed due to a high rate of omissions in AY or BX trials (> 50%). Therefore, the statistical analysis were performed on 26 participants (13 HC and 13 AD). The classical effects of the AX-CPT task on the RTs and error rates, and their interaction with the experimental groups were analyzed with a two-factor ANOVA with Trial Type (AX, AY, BX and BY) as a within-subject factor and Group (HC and AD) as a between-subject factor. We performed a linear regression analysis with Blocks and Group (HC and AD) as predictive variables and PBI as dependent variable, to analyze the adaptation of PBI during the task between the two experimental groups. Finally, we extracted the coefficient of the regression model fitting PBI with Blocks for each individual (see Appendix .1) to analyze inter-individual difference in the PBI adaptation across blocks. We performed Pearson's correlation analyses between the adaptation index and the UPPS and AUDIT scores.

Table 6.1 – Means (*M*) and standard deviations (*SD*) of demographic variables, MoCa, AUDIT and UPPS scores in matched controls and alcohol-dependent patients.

Variables	Matched controls (N = 13)		Alcohol-dependent (N = 13)		*t/W*	*p*	*Cohen's d*
	M	*SD*	*M*	*SD*			
Age	41.92	1.035	44.00	8.79	0.55	.587	0.22
Socio-educational level	1.83	0.83	1.46	0.78	57.5	.225	0.46
MoCa	27.69	1.70	25.15	2.82	36	**.013***	1.09
AUDIT	4.85	3.67	31.15	5.8	169	**<.001 *****	5.42
UPPS	91.69	16.44	105.31	17.2	2.06	**.050***	0.81

Note. Socio-educational, MoCa and AUDIT scores were not normally distributed. Non-parametric Wilcoxon test has been applied.

Results

Table 6.1 presents the differences in the demographic variables and in questionnaires scores between the matched control group (HC) and the alcohol-dependent group (AD). As expected, the AD group scored higher on both the AUDIT and the UPPS than the HC group (see Table 6.1 for the statistical tests). Considering the AUDIT cut-offs, four HC participants among the 13 showed "alcohol abuse" scores (the nine others scored lower than 6). In the AD group, all AUDIT were superior to 13 confirming the alcohol dependence (N = 13). The global cognitive efficiency assessed by the MoCa was significantly smaller in the AD group compared to the HC group (see Table 6.1 for the statistical test).

Global analysis: reaction times and error rates

Table 6.2 presents the mean RTs and error rates in the whole sample, in the matched controls group and in the alcohol-dependent group. ANOVA results revealed a main effect of Trial Type on RTs in correct trials, $F(3, 92) = 41.28$, $p = < .001$, $\eta^2 = 0.57$, and on error rates, $F(3, 92) = 9.40$, $p < .001$, $\eta^2 = 0.23$, confirming the dominant use of proactive control in the whole sample. Indeed, the RTs in correct AY trials were longer than the RTs in correct AX, BX and BY trials. The error rates in correct AY trials were larger than the error rates in correct AX, BX and BY trials. There was no effect of the Group on global RTs, $F(1, 92) = 0.02$, $p = .875$, $\eta^2 < 0.01$, nor on global error rates, $F(1, 92) = 1.34$, $p = .250$, $\eta^2 = 0.01$. Finally, there was no interaction effect between Trial Type and Group on RTs, $F(3, 92) = 0.07$, $p = .978$, $\eta^2 < 0.01$, nor on error rates $F(3,$

92) = 1.69, p = .174, η^2 = 0.05, respectively.

Table 6.2 – Means (M) and standard deviations (SD) of global and by-trials error rates (%) and reaction times (RTs, ms) and the proactive behavioral index (PBI) in the all sample, in matched controls and alcohol-dependent patients.

	All sample (N = 26)		Matched controls (N = 13)		Alcohol-dependent (N = 13)	
	M	*SD*	*M*	*SD*	*M*	*SD*
Global error rate (%)	1.34	3.15	1.68	3.52	1.03	2.77
AX (%)	0.42	0.44	0.37	0.4	0.47	0.49
AY (%)	3.81	3.70	3.57	4.12	4.03	3.42
BX (%)	1.14	3.96	2.58	4.92	0.00	2.27
BY (%)	0.00	1.54	0.20	1.59	0.00	1.53
Global RTs (ms)	420.00	100.56	421.12	105.7	418.97	96.6
AX (ms)	421.33	55.97	419.51	61.42	423.01	52.92
AY (ms)	543.26	47.84	549.71	50.56	537.3	46.41
BX (ms)	358.15	82.78	358.29	86.51	358.02	82.73
BY (ms)	357.28	74.39	356.97	84.2	357.56	67.59
PBI	0.21	0.09	0.21	0.09	0.21	0.09

Comparison of the PBI and its adaptation across blocks

The linear regression analysis revealed no main effect of Blocks or Groups on the PBI, β = 0.003, t = 0.38, p = .708 and β = 0.002 and t = 0.06, p = .952, respectively. In our sample, there was no increase in the PBI across blocks and the global PBI did not differ between HC and AD groups (see Table 6.2). Moreover, there was no significant interaction effect between Blocks and Groups on the PBI, β = 0.0003, t = 0.03, p = .973.

To go further, we used the individual coefficients of the regression model to investigate individual differences in the adaptation of the PBI. The AUDIT scores and the UPPS scores did not correlate with the adaptation index, ρ = -0.27, p = 0.182 (see the black line in Figure 6.2A) and r = -0.26, p = .205 (see the black line in Figure 6.2B), respectively. In the AD group (see the red lines in Figure 6.2), the AUDIT and the UPPS scores did not correlate with the index of adaptation, r = -0.43, p = 0.138 and r = -0.43, p = 0.147, respectively. In the HC group (see the green lines in Figure 6.2), the AUDIT and the UPPS scores did not correlate with the index of adaptation, r = -0.35, p = 0.238 and r = -0.18, p = 0.564, respectively.

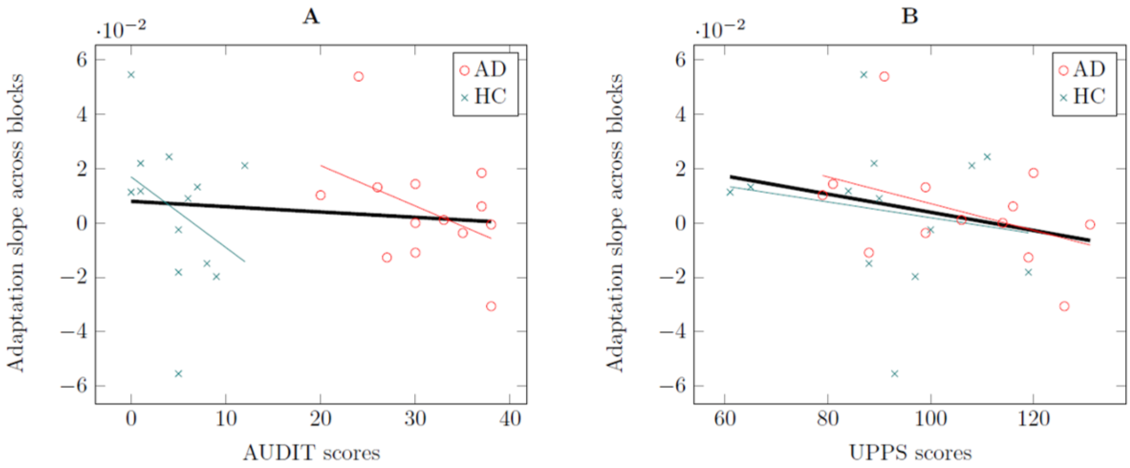

Figure 6.2 – **Correlations between AUDIT (A) and UPPS scores (B) with the PBI adaptation slope across blocks during the AX-CPT task in the entire sample** (N = 26, black lines). Red circles represent the alcohol-dependent patients group (AD) and the green crosses represent the matched controls group (HC).

Finally, we created groups as a function of the presence or the absence of adaptation of the PBI. A negative index of adaptation reflected no adaptation of PBI across blocks, whereas a positive index of adaptation reflected PBI adaptation across blocks. Ten participants (i.e., five AD and five HC) had a negative index of PBI adaptation. The absence of PBI adaptation was therefore unrelated to the pathological status. However, the participants that did not adapt tended to have greater UPPS scores (M = 106.00, SD = 16.15) than the group that did adapt (M = 93.81, SD = 17.77), $F(1,24) = 3.10$, p = .091, $\eta^2 = 0.11$ (cf. Figure 6.3). The adaptation groups did not differ on AUDIT scores, $F(1,24) = 0.31$, p = .582, $\eta^2 = 0.01$, nor on MoCa scores, $F(1,24) = 0.11$, p = .740, $\eta^2 < 0.01$.

Discussion

The current study aimed to explore cognitive control mechanisms in an alcohol-dependent population (AD), which is an impulsive-related pathological population. We expected to observe higher impulsiveness and thus, according to previous findings (see Chapter 5.1), a smaller proactive behavioral index (PBI) in AD patients compared to HC. Moreover based on previous findings from Hu et al. (2015) and Brevers et al. (2018), we hypothesized that the adaptation of the PBI over time would be impaired in AD patients compared to HC.

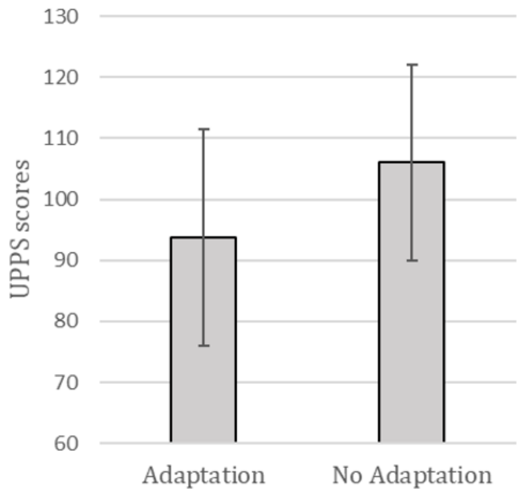

Figure 6.3 – **Comparison of UPPS scores between the group that adapted and the group that did not adapt to task demands**. Horizontal lines represent mean UPPS scores. Vertical bars represent standard deviations.

At the whole sample level, we replicated the classical pattern of AX-CPT results (i.e., larger RTs in AY trials compared to the other trials), confirming the dominant use of proactive control mechanisms during the task. However surprisingly, we did not replicate the effect of blocks on the PBI that we observed in the first study. In the current sample, participants did not increase the use of proactive control mechanisms over time. The lack of replication can be explained by the findings of Janowich and Cavanagh (2018)'s meta-analysis. Indeed, Janowich and Cavanagh (2018) showed that the increase in the proactive control index was not observed in older adults. Therefore, the mean age difference between the Study I and the Study II (i.e., 22 and 43 years, respectively) could explain the lack of replication of the effect of block on the PBI in the current study.

Comparing the AD and the HC groups, one hypothesis only was confirmed by the results. As expected, we observed higher impulsiveness in AD group than in HC group. However, there was no difference in the global PBI nor a difference in its adaptation over time between the AD and the HC groups. These findings suggested that impulsivity is not associated with a change in the dominant control mechanism, nor with a weaker adaptation of control mechanisms to external demands. Nonetheless in this sample, we found that the absence of adaptation of control mechanisms is associated with higher impulsiveness consistent with the findings of the first study (see Chapter 5.1). However, a difference in instructions might explain the absence of difference between AD and HC participants in this study.

The specific instructions of the AX-CPT in the Study I were to press right (or left) only if the letter X *was preceded by* the letter A. In the current study, the instructions given to participants were to press right (or left) only if the letter A *was followed by* the letter X. The "AX" trials are the target trials in both instructions. However, the Study I instructions emphasized the processing of the probe-letter to respond, whereas the current instructions emphasized the processing of the cue-letter to respond. Translated into cognitive control mechanisms terms, the Study I instructions might have set the participant in a reactive control situation. Therefore over time, the cognitive control system adjusted control mechanisms to be adapted to external demands. The current study's instructions might have already set the cognitive control system to a proactive control "mode". Therefore, no adaptation was required supporting the absence of an effect of blocks on the PBI. Results from Gonthier, Macnamara, Chow, Conway, and Braver (2016)'s study supports the hypothetical effect of the instructions on the control mechanisms. In their study, they induced an increase in the PBI by a "strategy training". During the training, participants were asked to prepare for a response when a cue-letter A appeared on the screen, and to prepare a non-response otherwise. The training explicitly set the participant to use proactive control mechanisms. The instructions in the current study were less explicit, but might still have set the cognitive control system into a proactive control mode, not allowing us to distinguish the capacity to adjust control mechanisms to external demands between the AD and the HC groups. The question of the effect of instructions leads to interesting lines of research. Indeed, if implicit and explicit instructions are associated with different performances, it would lead to differentiate between spontaneous and prompted adaptation of control mechanisms.

Overall considering inter-individual differences in the adaptation of control mechanisms, we did not observe an effect of the pathological status on the adaptation capacity. However, consistently with the first study, we observed an association between high impulsiveness and the capacity to adapt. In both studies, participants that did not adapt were more impulsive than participants that adapted control mechanisms to external constraints.

Conclusion of the second experimental axis

The second study of this thesis aimed at exploring cognitive control mechanisms in a pathological population, characterized by high levels of impulsiveness. Contrary to our expectations, the alcohol-dependent patients did not differ from matched controls on the proactive behavioral index, nor on the adaptation rate of the control mechanisms to external demands. In this study, we failed to show that impulsive-related pathological behaviors were associated with an impairment of the adaptation of control mechanisms as a function of external demands. However, the change in the instructions might explain the lack of results, but opened to an interesting line of research differentiating prompted from spontaneous adaptation of control mechanisms. Consistently with previous findings (see Chapter 5.1), high impulsiveness, independently from the pathological status, was associated with the lack of adaptation of control mechanisms to external demands.

Chapter 7

Adaptation of cognitive control mechanisms to internal demands in the general population

Foreword

Both studies I and II (see Chapters 5.1 and 6.1, respectively) revealed that high impulsiveness was associated with a slow, or even an absence, of control mechanisms adaptation to external demands. However in the dual mechanisms of control (Braver, 2012), adaptive behaviors do not only rely on the flexible shift between control mechanisms as a function of external demands, but also internal demands. Previous studies showed that the implementation of cognitive control mechanisms is driven by contextual characteristics (i.e., external demands), such as the task load (Mäki-Marttunen et al., 2019a) and stressful or motivational situations (Hefer & Dreisbach, 2016; Yang et al., 2018), but also by inter-individual characteristics (i.e., internal demands), such as the age (Paxton et al., 2008) or the working memory capacities (Richmond et al., 2015; Redick, 2014). Therefore in a third study, I investigated the ability to adjust proactive control involvement through the analysis of the post-error slowing as a function of behavioral inhibition capacities. These capacities are thought to participate to the reactive control mechanism as they encompass the ability to refrain or to stop an ongoing inappropriate action. In normal functioning, poor behavioral inhibition capacities would be counterbalanced with higher involvement of proactive control to ensure the efficiency of the cognitive control system. I therefore postulated that as the adaptation of control mechanisms is reduced in high impulsiveness, such counterbalance would not be observed in high impulsive individuals.

This study was realized in the context of a collaboration between SCALab and the ECCA-Conduite company. The collaboration aimed at updating a battery of neuropsychological tests for the evaluation of driving aptitudes, in the case of the loss of the driving license. In this industrial partnership, I was especially charged to review the concept of risk-taking and to choose the methodology to objectively assess this impulsive behavior. The experimental sessions were performed by trained psychologists employed by the ECCA-Conduite company.

7.1 Study III: The broken proactive-reactive control balance in high risk-takers

Grisetto, F., Le Denmat, P., Delevoye-Turrell, Y. N., Vantrepotte, Q., Davin, T., Dinca, A., Desenclos-El Ghoulti, I. & Roger, C. (submitted). The broken proactive-reactive control balance in high risk-takers.

Abstract

According to the dual mechanisms of control (DMC), both reactive and proactive control are involved in adjusting behaviors when those are not appropriate to the environment. These control mechanisms have different costs and benefits, orienting the implementation of one or the other control mechanisms as a function of contextual and inter-individual factors. However, to our knowledge, no studies have investigated whether reactive control capacities modulate the use of proactive control. According to the DMC, poor reactive control capacities should be counterbalanced by greater proactive control involvement to efficiently adjust behaviors. We expected that maladaptive behaviors, such as risk-taking, would be characterized by an absence of such compensation. A total of 176 healthy adults performed two reaction time tasks (the Simon and the Stop Signal tasks) and a risk-taking assessment (the Balloon Analog Risk Taking, BART). For each individual, the Stop Signal Reaction Time (SSRT) was used to assess reactive inhibition capacities and the mean duration of the button press in the BART was used as an index of risk-taking propensity. The post-error slowing (PES) in the Simon task reflected the individuals' tendency to proactively adjust behaviors after an error. Our results showed that smaller SSRT, revealing better reactive inhibition capacities, were associated with shorter PES, suggesting less involvement of proactive adjustments. Moreover, higher the risk-taking propensity, lesser was the proactive control counterbalance for poor reactive inhibition capacities. Risky behaviors, and more broadly maladaptive behaviors, could emerge from the absence of proactive control counterbalance for reactive control deficits.

Keywords: cognitive control; risk-taking; reactive inhibition; post-error slowing

Introduction

In everyday life situations, one must constantly integrate multiple sources of information in order to achieve his/her goals. When driving to the grocery store keeping in mind the shopping list and remembering the route, one must focus on the road and monitor other drivers' behaviors to stay safe. This is even more necessary in complex and unpredictable environments, such as crowded areas. In such a situation, one can be cautious and slow down the car to anticipate a pedestrian who could suddenly cross the road. On the contrary, one can choose to wait and react only if a pedestrian crosses. Although both strategies lead to the same goal, namely to avoid an accident, they differ in the way this goal is achieved. Investigating the implementation and adaptation of these control strategies is the key to gain a better understanding of adaptive behaviors (Braver, 2012).

Cognitive control is a set of basic executive functions that guides and adjusts goal-directed actions according to internal and external demands (Nigg, 2017; Ridderinkhof et al., 2011). According to the dual mechanisms of control framework (Braver, 2012), two distinct and complementary mechanisms are involved in cognitive control. On the one hand, proactive control refers to a costly and sustained activation of attention leading to an early selection of goal-relevant information (Braver, 2012; Braver et al., 2007). Proactive control is illustrated by the individual who chooses to slow down near a crowded area. On the other hand, reactive control mechanisms correspond to a late correction of the action by the retrieval of the goal-relevant information when an interference is detected and needs to be resolved (Braver, 2012; Braver et al., 2007). Reactive control is illustrated by the individual who chooses to maintain speed and brake if a pedestrian crosses. Proactive and reactive mechanisms rely on different temporal dynamics, but both use goal-relevant information in order to adjust goal-directed behaviors to external and internal demands (e.g., contextual or inter-individual characteristics).

Proactive and reactive control mechanisms are complementary but independent processes (Braver, 2012). They can be independently and simultaneously engaged during a cognitive control task (Mäki-Marttunen et al., 2019a). However, some contextual and inter-individual characteristics favor one control mechanism over the other. This dominance of one control mechanism over the other reduces the cost of the cognitive control system. Indeed, proactive and reactive control mechanisms have specific costs and benefits that are modulated by contextual and inter-individual characteristics (Braver, 2012; Del Giudice & Crespi, 2018). Proactive mechanisms rely on sustained attention on goal-relevant information and is therefore robust against distractors. However, proactive control is also more costly and resource-consuming than reactive control. Indeed, reactive control, relying on inhibitory capacities, is more flexible and is able to respond to fast changes in the environment, but it is more sensitive to disturbances and leads to slower reaction times (Del Giudice & Crespi, 2018). Therefore, the implementation of one control mechanism over the other (i.e., the balance between the weights on proactive and reactive control) depends on the proactive and reactive mechanisms costs.

The proactive and reactive mechanisms costs are known to be sensitive to several factors, which thus indirectly result in the preferential implementation of one type of control over the other. At the situation level, the environmental context can punctually orient the choice towards proactive control or reactive control. High task-context load decreases the use of proactive control (Mäki-Marttunen et al., 2019b). At the individual level, proactive processes are favored by individuals with a high working memory capacity, as the cost induced by sustained attention is lighter for them compared to that experienced by individuals with a low working memory capacity (Redick, 2014; Richmond et al., 2015). Consistently, older adults showing impairments in goal maintenance shift to reactive control processes (Paxton et al., 2008). Therefore, the implementation of control mechanisms seems to mostly depend on the cost of proactive control mechanisms, which varies as a function of contextual and inter-individual characteristics (e.g., Mäki-Marttunen et al., 2019b; Richmond et al., 2015). However, to our knowledge, no studies have investigated whether reactive control capacities can modulate the use of proactive control at an individual level. If reactive control is efficient, one can easily resolve the current interference. Therefore, one should not have to engage strong proactive control resources to facilitate the resolution of a future interference, in order to reduce the cost of the cognitive control system while preserving efficiency. On the contrary, if reactive control is less efficient, proactive control resources should be engaged to improve the efficiency of the cognitive control system. We thus hypothesized that individuals with effective reactive inhibition capacities (i.e., the capacity to inhibit an ongoing but no longer appropriate response) would put smaller weight on proactive control and thus have smaller proactive behavioral adjustments. Conversely, individuals with poor reactive inhibition capacities should rely more on proactive behavioral adjustments to adapt behaviors to increase the efficiency of the cognitive control system (H1).

Adaptive behaviors rely on the flexible balance between proactive and reactive control mechanisms to adjust goal-directed behaviors while reducing the costs of the cognitive control mechanisms (Braver, 2012). Therefore, one can consider that a broken balance in the implementation of the two control mechanisms could underlie maladaptive behaviors. In the current study, we tested this second hypothesis by investigating the effect of risk-taking propensity on the balance between proactive and reactive control mechanisms. Risk-taking is a component of the impulsivity construct (e.g., Lane et al., 2003; Reynolds et al., 2006), largely associated with maladaptive behaviors such as substance abuse (e.g., Granö et al., 2004; Stautz et al., 2016), eating disorders (e.g., Evans et al., 2019; Meule et al., 2017; Meule & Platte, 2015) and aggression (e.g., Bousardt, Hoogendoorn, Noorthoorn, Hummelen, & Nijman, 2016; MacDonell & Willoughby, 2020). We therefore expected that the effect described in H1 would not be observed in individuals with high risk-taking propensity. In other words, we hypothesized that higher risk-taking propensity would be associated with less proactive counterbalance as a function of reactive inhibition capacities (H2).

Method

Participants

A total of 571 healthy participants (300 males) were recruited on several sites in France. Ages ranged from 18 to 92 years ($M = 36.79$, $SD = 16.91$). Data were collected from May to July 2018, then from August 2018 to September 2019. Participants were evaluated with psychometric tests followed by an on-road driving test assessed by professional driving instructors. The results of the driving test were not used for the current analysis. The ethics committee of the University of Lille (2017-9-S55) approved the experiment.

Experimental tasks

Stop Signal task. In this task, the participant was instructed to respond right or left according to the direction of a white arrow, which was presented at the center of a screen (Go trials). Each trial began with the presentation of a fixation cross for 300 ms. Then, the left or right pointing arrow appeared at the center of the screen until a response was given by the participant. In the absence of a response, the arrow disappeared after time intervals of 1500 ms. Trials were separated by an empty screen lasting 500 ms. In 25% of the trials (the Stop trials) and after a certain delay (the Stop Signal Delay, SSD), a stop signal appeared, which instructed the participant to withhold the response by inhibiting the engaged motor command. In our study, this stop signal was illustrated by the white arrow becoming red. The SSD, initially set to 200 ms, was adjusted trial-by-trial according to each participant's performance. In a Stop trial, if the participant succeeded to inhibit in time his/her response, the SSD was increased by 50 ms. If the participant did respond despite the Stop signal, the SSD decreased by 50 ms. A short training phase of 20 trials was implemented in order to familiarize participants with the task instructions and the response device. During training only, a feedback was provided at the end of each trial for 500 ms (i.e., "Well done, correct response" - *"Bravo, bonne réponse"* for a correct response, "Incorrect response" - *"Réponse incorrecte"* for an error, "Try to be faster" - *"Essayez d'être plus rapide"* for an omission during a Go trial and "Try to stop" – *"Essayez de vous arrêter"* for a response despite the Stop Signal). The experimental phase of the Stop Signal task was composed of two blocks of 129 trials without any feedback and lasted approximatively six minutes.

The Stop Signal indicates that the current action is no longer adapted to the task demands; thus, it triggers reactive control mechanisms to resolve the interference. Therefore, the Stop Signal reaction time (SSRT) was used as an index of the reactive inhibition capacity, which refers to the cessation of an ongoing motor response (Logan et al., 1984;

Meyer & Bucci, 2016). The SSRT was calculated with the integration method detailed by Verbruggen et al. (2019). The longer the SSRT, the more time is needed for the participant to stop the ongoing action and thus, the less efficient the reactive inhibition is.

Simon task. The participant had to perform a modified version of the classic Simon task (Simon, 1990). In this variant, he/she was required to respond as fast and accurately as possible to the shape of the stimuli (a white square or a white circle) that could appear on the right or left side of the fixation cross. Each trial began with a fixation cross presented for 300 ms. Then, the stimulus was displayed until a response was given. In the absence of a response, the stimulus disappeared after time intervals of 1500 ms. Trials were separated by an empty screen lasting 500 ms. The stimulus-response mapping created 50% of incongruent trials and 50% of congruent trials. A short training phase of 20 trials was implemented in order to familiarize participants with task instructions and response device. During training only, a feedback was provided at the end of each trial for 500 ms (i.e., "Well done, correct response" - *"Bravo, bonne réponse"* for a correct response, "Incorrect response" - *"Réponse incorrecte"* for an error and "Try to be faster" - *"Essayez d'être plus rapide"* for an omission). The experimental phase of the Simon task was composed of two blocks of 129 trials each, without any feedback, and lasted approximatively six minutes.

The Simon task was used to calculate the post-error slowing (PES), which refers to the lengthening of reaction times after the commission of an error compared to after a correct response (Rabbitt, 1966). The PES was calculated as the difference between the mean reaction times in correct trials after an error and the mean reaction times in correct trials after a correct response. The post-error slowing effect has been largely replicated in several studies using different paradigms and was interpreted as a reallocation of executive attention towards goal-relevant information for the next trial to avoid a new error (e.g., Verguts, Notebaert, Kunde, & Wühr, 2011). Thus, this measure was used as an index of the strength of proactive behavioral adjustments (Danielmeier & Ullsperger, 2011). Indeed, the PES indicates the presence of control processes that anticipates and facilitates the execution of the correct response in the subsequent trial.

Balloon Analog Risk Taking task. In the Balloon Analog Risk Taking task (Lejuez et al., 2002), the participant was asked to virtually inflate 30 balloons by pressing a button. The more inflated the balloon, the more a participant earned points. Each 500 ms of pumping gave one point. However, the balloons could explode at any time: the longer the participant pressed the button at a given trial, the greater risk the balloon had to explode. The predefined time before explosion ranged between 7 and 14 seconds (M = 10.0 s, SD = 1.8 s). If it exploded, the participant lost the cumulated points in the current trial. Therefore, the participant had a choice: keep inflating the balloon to gain points but risking explosion or stop inflating, earn less and keep the cumulated points. To challenge participants and to promote risk-taking, the instructions set a goal score to exceed (400 points). The mean duration time of the button press for the unexploded balloons was used as an index of risk-taking propensity (Risk Taking Index – RTI; Lejuez et al., 2002). A longer duration of the button press revealed a higher risk-taking propensity.

Statistical method

Inclusion criteria. We used several inclusion criteria to limit our sample to participants that respected the instructions. In the Simon task, only participants with an error rate superior to 5% were selected. This strategy was adopted to remove participants that did not complete the task as fast as they could have and thus, did not make enough errors to calculate a reliable post-error slowing index. In the Stop Signal paradigm, we followed the recommendations by Verbruggen et al. (2019) for the calculation of reliable SSRT. Only participants with a positive SSRT were included with in addition: less than 10% of incorrect responses, less than 40% of omissions in Go trials, and a proportion of successfully stopped trials between 25% and 75%. Following the application of these criteria, a total of 178 participants were included for further statistical analysis. The large majority of exclusion was due to a too few number of errors in the Simon task. In addition in this remaining sample, two participants had outliers SSRT (inferior to 100 and superior to 600) and therefore, were removed from further analysis. In the sample included for the current analysis (N = 176, 98 men), the age ranged from 18 to 90 years (M = 33.68, SD = 15.77).

Statistical analysis. There were two aims in the current study. In the one hand, we aimed to explore the predictive value of reactive inhibition capacities, indexed by the Stop Signal reaction time (SSRT, ms), on the implementation of proactive behavioral adjustments, indexed by the post-error slowing (PES, ms). In the other hand, we wanted to investigate its potential modulation by the risk-taking propensity (RTI, s). To do so, we used a mixed effect linear model (lme4 and lmertest packages on RStudio, Bates, Maechler, Bolker, & Walker, 2015; Kuznetsova, Brockhoff, & Christensen, 2017) to analyze the PES as a function of SSRT and RTI, both considered as fixed effects. To complete the model, we considered sex and age as random effects, since these variables are known to impact the variables of interest. The effects of sex and age on the three variables of interest were therefore individually analyzed using t-test and linear regression analysis, respectively, to decide the structure of random effects.

Results

Global analysis

In the Simon task, the mean correct reaction time was 501.25 ms (SD = 76.15) and the global error rate was 7.63% (SD = 2.67, ranging from 5.04 to 18.22). Error rates for incongruent trials (M = 9.39%, SD = 4.39) were larger than for congruent trials (M = 5.73%, SD = 3.41), t = -8.72, $p < .001$. There was also a significant effect of congruency on RTs (M = 25.67 ms, SD = 26.30), one-sample t-test $t(175) = 12.95$, $p < .001$, Cohen's $d = 0.98$. Reaction times in incongruent trials were longer (M = 530.82 ms, SD = 82.65) than in congruent trials (M = 505.15 ms, SD = 81.72), $t(175) = 12.95$, $p < .001$, Cohen's $d = 0.31$. There was a significant slowing of RTs after errors (M = 54.12 ms, SD = 41.17), one-sample t-test $t(175) = 17.46$, $p < .001$, Cohen's $d = 1.31$. In the Stop Signal task, the mean reaction time in correct Go trials was 575.26 ms (SD = 149.83) and the mean SSRT was 271.93 ms (SD = 53.5). Finally, the mean duration time of the button press to pump balloons in the BART was 7.78 s (SD = 0.71). The mean of cumulated points was 355.41 (SD = 38.42, range from 206 to 431).

Analysis of the confounded variables

The effect of sex on the three variables of interest was analyzed using Student's t-test (see Table 7.1). There were no significant effect of sex on PES, SSRT or on RTI, all p-values > .050.

Table 7.1 – Means and standard deviations of the post-error slowing (ms), the stop signal reaction time (ms) and the press duration (s) in the BART.

Variables of interest	All sample (N = 176)		Men (N = 98)		Women (N = 78)		t	p	*Cohen's d*
	M	SD	M	SD	M	SD			
PES (ms)	54.12	41.17	57.31	40.4	50.23	42.04	1.13	.260	0.17
SSRT (ms)	271.93	53.5	269.18	48.72	275.38	59.1	0.75	.456	0.12
RTI (s)	7.78	0.71	7.71	0.67	7.88	0.74	1.56	.122	0.24

The effect of age on the three variables of interest was analyzed using simple linear regression. Results showed a significant effect of age both on the PES and on the SSRT, $\beta = 0.47$, $t(174) = 2.43$, $SE = 0.19$, $p = .016$, adjusted $R^2 = 0.03$ and $\beta = 1.54$, $t(174) = 6.71$, $SE = 0.23$, $p < .001$, adjusted $R^2 = 0.20$, respectively (see Figures 7.1A and 7.1B). However, there were no significant effect of age on the RTI, $\beta = 0.00$, $t(174) = -0.70$, $SE < 0.01$, $p = .483$, adjusted $R^2 < 0.01$ (see Figure 7.1C).

As age had an effect on both PES and SSRT (see Figure 7.1), Age was set in the model as a random effect to control for its confounded effect. As sex had no effect on the variables of interest (see Table 7.1), sex was not added to the model.

Modulation of proactive adjustments as a function of reactive inhibition and risk-taking propensity

The model revealed a significant main effect of SSRT on the PES, $\beta = 1.36$, $t(77.94) = 2.16$, $SE = 0.63$, $p = .034$. Our first hypothesis was confirmed as longer SSRT predicted greater post-error slowing. The main effect of RTI was not significant on the PES, $\beta = 37.35$, $t(96.37) = 1.58$, $SE = 23.62$, $p = .117$. Interestingly, results showed a significant

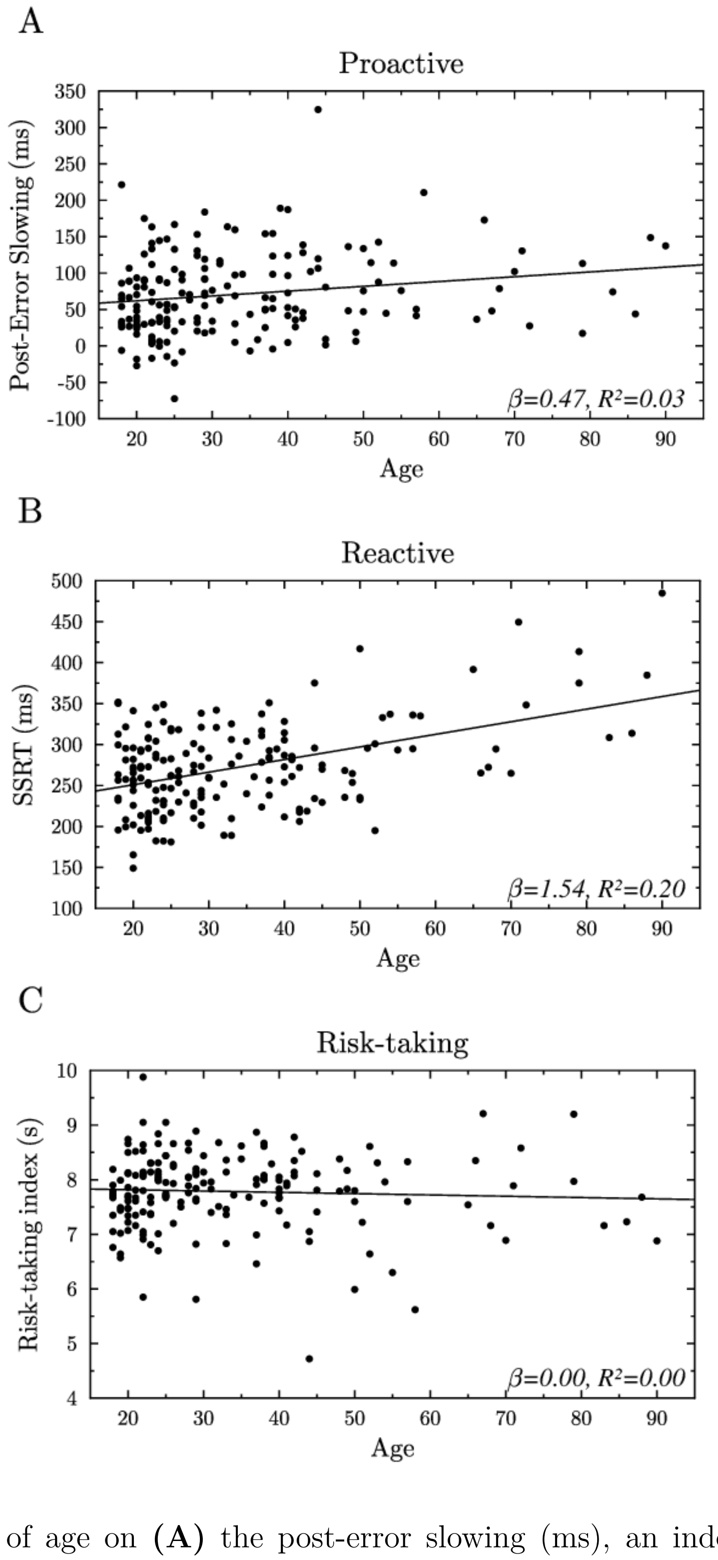

Figure 7.1 – Effects of age on **(A)** the post-error slowing (ms), an index of proactive behavioral adjustments, **(B)** the Stop Signal reaction time (ms), an index of reactive inhibition capacity and on **(C)** the mean button press duration (s), the risk-taking index in the BART task.

interaction effect between SSRT and RTI on the PES, β = -0.17, $t(82.17)$ = -2.08, SE = 0.08, p = .040. Higher the risk-taking propensity in our sample, lesser the counterbalance of reactive inhibition capacities with greater proactive behavioral adjustments (cf. Figure 7.2).

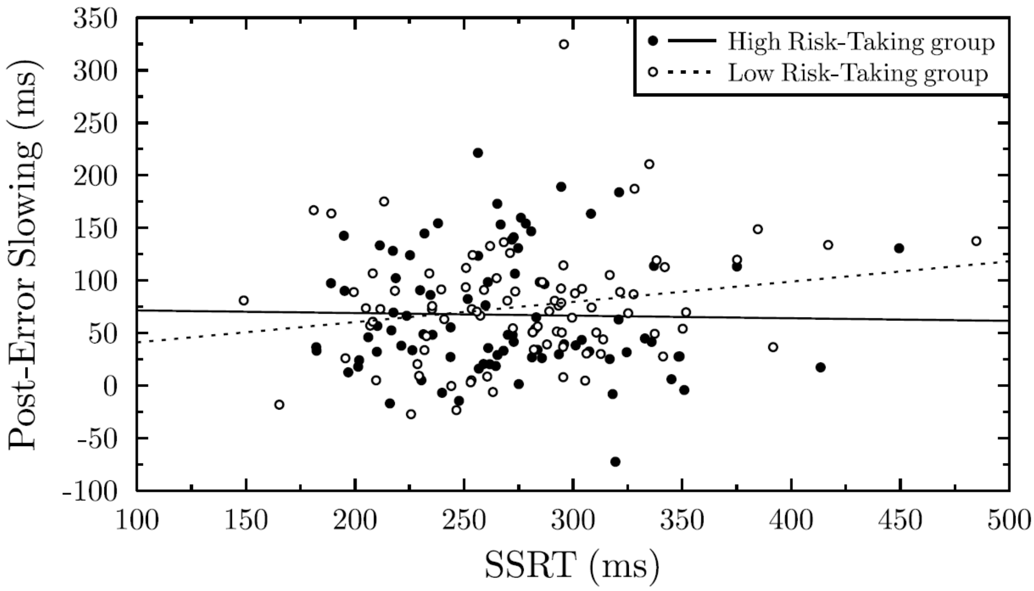

Figure 7.2 – **Proactive behavioral adjustments as a function of reactive inhibition capacity and risk-taking propensity.** (N = 176). The SSRT (Stop Signal Reaction Time) was used as an index of reactive inhibition capacities. The PES (Post-Error Slowing) was used as an index of proactive behavioral adjustments. The risk-taking groups were created for visualization purpose only. We used the median of the RTI (Risk-Taking Index, the mean duration of the button press at the BART task) distribution to categorize participants as high (N = 87) or low risk-takers (N = 86).

Discussion

The aim of our study was to test whether reactive inhibition capacities could modulate the use of proactive control. We hypothesized that an individual with efficient reactive control capacities would limit the use of proactive mechanisms to minimize the cost for the cognitive control system. Furthermore, we explored the influence of risk-taking propensity on this observed balance between the two control mechanisms. The reported findings indicated that reactive inhibition capacities predicted proactive behavioral adjustments after an error. However, higher an individual's tendency to take risks, smaller was the shift towards proactive control as a function of reactive inhibition capacities.

Reactive and proactive control mechanisms can be independently engaged to resolve interferences (Braver, 2012). However, certain inter-individual factors increase or decrease the cost of proactive control and thus, indirectly favor the use of one mechanism over the other (e.g., Paxton et al., 2008; Redick, 2014; Richmond et al., 2015). As proactive control is resource-consuming compared to reactive control (Del Giudice & Crespi, 2018), we expected that the involvement of proactive behavioral adjustments would be reduced in individuals with efficient reactive inhibition capacities. Our results confirmed our first hypothesis. Indeed, the stop signal reaction time (SSRT) predicted the post-error slowing effect (PES): larger SSRT (i.e., poorer reactive inhibition capacities) were associated with larger PES (i.e., stronger proactive behavioral adjustments after an error). To our knowledge, this study is the first to empirically demonstrate the shift towards proactive control as a function of poor reactive control capacities. The opposite shift was already demonstrated by Redick (2014) and Richmond et al. (2015). Indeed investigating working memory capacities as a proactive-related capacity, both studies showed a shift towards reactive control with poor proactive control capacities.

The second aim of our study was to investigate the influence of risk-taking propensity on the observed balance between proactive and reactive control. Risk-taking refers to the adaptive or maladaptive selection of an action potentially harmful, but associated with an opportunity to obtain immediate rewards Lejuez et al. (2002); Nigg (2017). In our sample and in accordance with previous result (Kertzman, Lidogoster, Aizer, Kotler, & Dannon, 2011), reactive inhibition capacities alone did not differentiate high and low risk-takers. However, our results showed that higher risk-taking propensity was associated with a smaller balance between proactive control and reactive control. More precisely, higher risk-taking propensity was associated with smaller proactive behavioral adjustments to counterbalance poor reactive inhibition capacities. High risk-taking individuals make less use of proactive behavioral adjustments to compensate for poor reactive inhibition capacities. The weaker balance between the two control mechanisms with high risk-taking propensity reduces the cost of control mechanisms, but it also reduces performance levels, especially when reactive inhibition capacities are inefficient. These findings have therefore direct applicability in the general population. Indeed, the evaluation of the balance between reactive and proactive control mechanisms could be useful to create a finer-grained index of an individual's tendency to adopt maladaptive behaviors rather than the investigation of inhibition capacities only. Maladaptive behaviors may emerge directly from the unbalance between reactive and proactive control in individuals suffering from weak reactive inhibition mechanisms.

Overall, the present study demonstrated that reactive inhibition capacities predict proactive behavioral adjustments, but this effect is reduced with high risk-taking propensity. Poor inhibition capacities are not sufficient to index the tendency to adopt maladaptive behaviors, but the absence of control mechanisms counterbalancing could be a finer-grained index to identify at-risk individuals.

Conclusion of the third experimental axis

According to the dual mechanisms of control (DMC, Braver, 2012; Braver et al., 2007), adaptive behaviors rely on the shift between reactive and proactive control mechanisms according to external and internal demands. Study I and Study II (see Chapters 5.1 and 6.1) showed that impulsiveness was associated with a smaller (or a lack of) adaptation of control mechanisms to external demands (i.e., the AX-CPT task demands). The aim of the third study was to investigate the capacity to adapt control mechanisms to internal demands.

The internal demand in the study III was the efficiency of behavioral inhibition. In the same way that higher working memory capacities favor the use of proactive control (Redick, 2014; Richmond et al., 2015), I hypothesized that poor behavioral inhibition capacities would drive the use of proactive control. Indeed poor behavioral inhibition capacities limit the efficiency of reactive control. Moreover, considering the difficulty in adapting control mechanisms with high impulsiveness, I expected that the relationship between behavioral inhibition capacities and proactive behavioral adjustments would not be observed in high impulsive individuals. The findings of the third study confirmed the hypothesis. Indeed, higher risk-taking was associated with a smaller counterbalancing of poor behavioral inhibition capacities with stronger proactive behavioral adjustments.

Overall, the results suggest that impulsivity (i.e., both impulsiveness and impulsive behaviors) in the general population is associated with smaller adaptation of the use of proactive control as a function of both external and internal demands (Study I and Study III, respectively). The lack of adaptation of control mechanisms, and in particular towards the use of proactive control mechanisms, might explain the emergence of impulsive behaviors in high impulsive individuals under some situations and contexts.

Chapter 8

The monitoring system and impulsivity in the general population

Foreword

The previous three studies aimed to explore the adaptation of control mechanisms to external and internal demands in both general and pathological populations. Overall, the findings consistently showed that higher impulsivity, assessed with a self-reported questionnaire or a behavioral measure, was associated with a weaker (or an absence of) adaptation of control mechanisms to external (i.e., the AX-CPT task demands) and internal demands (i.e., poor behavioral inhibition capacities). Following Dickman (1990)'s perspective on impulsivity, the weaker adaptation of control mechanisms could be an impulsivity-related vulnerability for psychiatric disorders. The lack of adaptation of control mechanism to external and internal demands may lead to the emergence of impulsive behaviors under some situations and contexts, and in the long-term to the development of psychiatric disorders.

Across these studies, I investigated at a behavioral level the adaptation between reactive and proactive control mechanisms, two components of the cognitive control system as described in the Chapter 2.2. However, one main component of the cognitive control system has not been yet investigated in the PhD project. The conflict monitoring is indeed central in the cognitive system as it triggers proactive and reactive behavioral adjustments (Botvinick et al., 2001; De Pisapia & Braver, 2006). Therefore, in order to have a more complete approach of the cognitive control system in impulsivity, I conducted a fourth study using the EEG technique to explore the monitoring system activity through the ERN/Ne component (Falkenstein et al., 1991; Gehring et al., 1993) in a general population.

8.1 Study IV: Efficient but less active monitoring system in individuals with high aggressive predispositions

Grisetto, F., Delevoye-Turrell, Y. N., & Roger, C. (2019). Efficient but less active monitoring system in individuals with high aggressive predispositions. *International Journal of Psychophysiology, 146*, 125-132.

Abstract

Aggressive behaviors in pathological and healthy populations have been largely related to poor cognitive control functioning. However, few studies have investigated the influence of aggressive traits (i.e., aggressiveness) on cognitive control. In the current study, we investigated the effects of aggressiveness on cognitive control abilities and particularly, on performance monitoring. Thirty-two participants performed a Simon task while electroencephalography (EEG) and electromyography (EMG) were recorded. Participants were classified as having high and low levels of aggressiveness using the BPAQ questionnaire (Buss & Perry, 1992). EMG recordings were used to reveal three response types by uncovering small incorrect muscular activations in 15% of correct trials (i.e., partial-errors) that must be distinguished from full-error and pure-correct responses. For these three response types, EEG recordings were used to extract fronto-central negativities indicative of performance monitoring, the error and correct (-related) negativities (ERN/Ne and CRN/Nc). Behavioral results indicated that the high aggressiveness group had a larger congruency effect compared to the low aggressiveness group, but there were no differences in accuracy. EEG results revealed a global reduction in performance-related negativity amplitudes in all the response types in the high aggressiveness group compared to the low aggressiveness group. Interestingly, the distinction between the ERN/Ne and the CRN/Nc components was preserved both in high and low aggressiveness groups. In sum, high aggressive traits do not affect the capacity to self-evaluate erroneous from correct actions but are associated with a decrease in the importance given to one's own performance. The implication of these findings are discussed in relation to pathological

aggressiveness.

Keywords: aggressiveness; cognitive control; EEG; ERN/Ne; CRN/Nc; performance monitoring

Introduction

Aggressiveness is defined as an individual's predispositions to respond aggressively, to experience negative emotions and to hold hostile thoughts (Buss & Perry, 1992). Previous studies in pathological and healthy individuals have demonstrated that aggressive tendencies are linked to poor executive capacities. In maladapted populations, for example, violent offenders, Hancock, Tapscott, and Hoaken (2010) showed that deficits in executive functioning predicted the frequency and severity of intentional acts in physical aggression. Even in a normal population, higher aggressive traits have been associated with low inhibitory control capacities (Pawliczek et al., 2013; Zajenkowski & Zajenkowska, 2015). Conversely, higher cognitive control abilities predicted less aggressive behaviors in response to provocation (Wilkowski, Robinson, & Troop-Gordon, 2010). These evidences indicate that executive functioning and in particular cognitive control, may be valuable research targets to gain a better understanding of aggressiveness.

Cognitive control is a set of executive functions that are orchestrated to adjust behaviors, according to internal goals and environmental constraints (Ridderinkhof et al., 2011). Among cognitive control mechanisms, some of them are mobilized proactively and others reactively, according to when a risk of making an error is detected (Braver et al., 2007; Braver, 2012). Indeed, the risk of making an error must be monitored efficiently in order to involve the appropriate proactive or reactive adjustment mechanism (Nieuwenhuis et al., 2001). Monitoring capacities are often investigated using electroencephalography (EEG) in participants performing choice reaction time tasks in which the stimulus-response congruency is manipulated, such as the Flanker or the Simon tasks. Falkenstein et al. (1991) and Gehring et al. (1993) reported a negative fronto-central activity emerging at the time of the response and peaking around 100 ms after the response, but only when participants were making errors. This event-related potential (ERP) has been called the error (-related) negativity (ERN/Ne) and is predominantly considered to reflect the involvement of the error detection mechanisms (e.g. Hajcak, Moser, Yeung, & Simons, 2005; Maier, Scarpazza, Starita, Filogamo, & Làdavas, 2016). Indeed, when the situation emphasizes accuracy over speed (e.g., financial penalties for errors), it is important not to make errors and the ERN/Ne is increased, whereas the ERN/Ne is reduced in situations for which the errors are not meaningful because the instructions emphasize speed over accuracy (e.g. Gehring et al., 1993; Hajcak et al., 2005). Another ERP component linked to the performance monitoring system was also reported by Falkenstein et al. (1991) and Falkenstein et al. (1995). This parameter referred as the error positivity (Pe) is a later centro-parietal component that peaks between 200 and 400 ms after the response. It is only observable during trials for which participants consciously detected their errors (Nieuwenhuis et al., 2001); its magnitude varies according to the degree of error consciousness (Leuthold & Sommer, 1999). Therefore, whereas the ERN/Ne indicates automatic internal performance feedback, the Pe is considered to reflect the conscious detection and evaluation of errors (Falkenstein et al., 2000).

The error-specificity of the ERN/Ne has been challenged by the findings of Vidal et al. (2000) who observed an ERN/Ne-like in non-error trials thanks to the use of electromyography (EMG) and a methodology to increase the spatial resolution of EEG recordings. More specifically, the EMG was recorded to reveal partial-errors that are engaged erroneous actions that are successfully detected, inhibited and corrected (Eriksen et al., 1985; Hasbroucq et al., 1999). Furthermore, in their work, the low spatial resolution of EEG was improved using the Laplacian transform technique (Babiloni et al., 2001; Burle et al., 2015). Vidal et al. (2000) reported the classical ERN/Ne in errors, but also described an ERN/Ne-like following both partial-errors and correct responses, which differed by their magnitudes. Indeed, the ERN/Ne-like observed in correct responses, also called the correct-related negativity (CRN/Nc), is largely smaller in amplitude than the ERN/Ne observed after a partial-error, which is in turn smaller than the ERN/Ne in full-error responses. Despite these differences in amplitude, the three ERPs have similar temporal dynamics, topographies and are generated by the same cerebral regions: the supplementary motor area and/or the dorsal anterior cingulate cortex (Bonini et al., 2014; Fu et al., 2019; Roger et al., 2010). Therefore, these components are thought to reflect an identical process varying in degrees according to performance (Weinberg et al., 2015). Even though the debates remain around the question of the functional significance of these brain activities, the observed differences in magnitudes between full-error ERN/Ne, partial-error ERN/Ne and CRN/Nc negativities confirm the capacity of the brain to monitor behavioral motor performances. Additionally, the combined analysis of the performance-related negativities (i.e., ERN/Ne and CRN/Nc) enables the precise distinction between the ability to self-evaluate one's own performance from the strength of the monitoring processes that is mobilized during the task. On the one hand, a reduced ERN/Ne in error trials along with an increased CRN/Nc in correct trials indicates a loss in the ability to self-evaluate the ongoing performance with less differentiation between erroneous and correct actions. This is the case for example in schizophrenic patients, in de novo patients with Parkinson disease and in patients with frontal lesions (Mathalon et al., 2002; Turken & Swick, 2008; Willemssen, Müller, Schwarz, Falkenstein, & Beste, 2009). On the other hand, a reduced ERN/Ne combined to a reduced CRN/Nc indicates a global reduction of the importance given to the evaluation of the motor performance. Such a pattern suggests that the monitoring system is less activated throughout the task, but that the ability to self-evaluate an ongoing performance is preserved. Consequently, investigating the CRN/Nc component appears to be relevant since it enables to decide between several interpretations that could be drawn from the reduction in ERN/Ne. Using the same methodology as Vidal et al. (2000), the current study combined the analysis of the negativities of all response types to highlight the monitoring processes in high and low aggressive individuals.

Numerous factors differentially modulate the magnitude of the ERN/Ne and the Pe (for a review, see Overbeek et al., 2005). In particular, a reduction in ERN/Ne is often associated with psychiatric disorders such as borderline personality disorders (de Bruijn et al., 2006) and schizophrenia (Charles et al., 2017; Mathalon et al., 2002). These studies suggest that a reduced ERN/Ne is a marker of psychopathology (Olvet & Hajcak, 2008). However, reduced ERN/Ne are also observed in externalizing populations in a broader sense such as conduct disorders and substance dependences (Hall, Bernat, & Patrick, 2007; Pasion & Barbosa, 2019) and in juvenile offenders (Vilà-Balló et al., 2014). Aggressive behaviors, a common factor between psychiatric populations, externalizing behaviors and offenders (e.g. Mancke, Herpertz, & Bertsch, 2015; Zhou et al., 2016), thus seem to be associated with a reduction in ERN/Ne. Fewer studies investigated the effect of aggressiveness on the Pe amplitudes. Moreover, their results are less consistent. Comparing offenders and controls, Brazil et al. (2009) showed reduced Pe amplitudes in the offenders whereas Vilà-Balló et al. (2014) did not find any difference between the two groups. This inconsistency might be explained by the presence of psychopathic traits in the population of the Brazil et al. (2009) study compared to Vilà-Balló et al. (2014). Indeed, Steele, Maurer, Bernat, Calhoun, and Kiehl (2016) found larger Pe amplitudes in offenders scoring high in psychopathic traits compared to those scoring low. Psychopathic traits rather than aggressiveness itself may affect Pe amplitudes in these aggressive populations.

In the current study, the main goal was to investigate the effect of aggressiveness on performance monitoring. Considering the inconsistency of the findings relative to the Pe component, we did not set a hypothesis of the effect of aggressiveness on its amplitude. However, based upon previous studies (e.g., Charles et al., 2017; Hall et al., 2007; Vilà-Balló et al., 2014), we expected that the reduction in ERN/Ne in full-errors would be revealed in individuals showing high aggressive traits compared to those with low aggressive traits. Moreover, because our participants were well-adapted non-clinical adults, we hypothesized that the monitoring system in our sample would remain as efficient in distinguishing between erroneous and correct actions unlike what it is found in pathological populations (Mathalon et al., 2002; Turken & Swick, 2008; Willemssen et al., 2009). However, if the reduction in the ERN/Ne in erroneous trials is confirmed, then we should observe a similar reduction in the other ERPs to preserve the distinction between each ERN/Ne in the three response types. Consequently, in addition of the reduction in the ERN/Ne in full-error trials, we should observe a reduction both in the ERN/Ne in partial-error trials, and in the CRN/Nc in pure-correct responses.

Method

Participants

Thirty-two right-handed volunteers recruited at the University of Lille participated in the study (18 women, mean age = 22.40 years, range from 19 to 28). Handedness was assessed with the Edinburgh Handedness Inventory (Oldfield, 1971). Exclusion criteria included motor and/or sensory disorders and a current medical treatment. They all gave written informed consent for taking part in this study. The ethics committee of the University of Lille (2015-9-S35, see Appendix VI) approved the experiment.

Procedure and task

Experimental task

The participant sat in a closed room facing a computer screen. She/he performed a modified version of the Simon task (Simon, 1990). Visual stimuli were created in the shape of a circle and of a square. Each participant was invited to respond as quickly and accurately as possible as a function of the shape of the stimulus. For example, holding a response button in each hand, the participant was required to press with the right hand if the stimulus was a circle and with the left hand if it was a square. Shape-to-response mapping rules were counterbalanced across participants. Importantly, the shapes were displayed on the right or on the left part of the screen. Although this dimension of the stimuli was salient, it was irrelevant for the task. Hence, 50% of the trials were labeled as “congruent” since the expected response was ipsilateral to the position of the stimulus (e.g., when a circle requiring a left response was presented on the left side of the display). Inversely, 50% of the trials were labeled as “incongruent” since the expected response was contralateral to the position of the stimulus (e.g., when a circle requiring a left response was presented on the right side of the display).

Each trial begun with the presentation of a fixation cross at the center of the screen during 300 ms. The stimulus appeared and remained displayed until a response was given or after a 1000 ms time lapse. Then, a black screen was presented during 1000 ms before the start of the next trial.

The experiment begun with a training block of 20 trials. During this training, visual feedback appeared for 500 ms after each response providing information about the accuracy of the current trial ("Bonne réponse" for a correct response, "Mauvaise réponse" for an error, "Essayez d’aller plus vite" for responses longer than 1000 ms). Then, the participant performed 10 blocks of 129 trials. A pause of 15 seconds was implemented between each block. The experiment lasted about 30 min.

Aggressiveness indices

Participants responded to the BPAQ Aggression Questionnaire (Buss & Perry, 1992; Pham, Ducro, & Saloppé, 2011) after the end of the Simon task to avoid potential influences of the questionnaire on behaviors (see Appendix .3). The BPAQ reveals traits in aggression and contains four subscales. The subscales *Physical Aggression* and *Verbal Aggression* evaluate the external forms of aggression (i.e., the tendency to act with the focus to hurt someone). The subscale *Anger* evaluates the affective aspect of aggression and is defined as the physiological arousal associated with the preparation for aggression. This subscale assesses the individual differences in the frequency of experiencing the urge to act and the behavioral reactivity towards angry feelings (Poland, Monks, & Tsermentseli, 2016). Finally, the subscale *Hostility* relates to a more cognitive aspect of aggression and is defined as the tendency to evaluate negatively other people, which is often accompanied by a desire to harm others (Poland et al., 2016). Internal consistency was adequate in our sample for the total BPAQ scores, α = .86, 95% CI [.79, .93] as well as for the four subscores: *Anger*, α = .68, 95% CI [.51, .85], *Hostility*, α = .76, 95% CI [.63, .89], *Physical Aggression*, α = .86, 95% CI [.80, .93] and *Verbal Aggression*, α = .55, 95% CI [.30, .79]. These internal consistency values correspond to those found by Pham et al. (2011) with Cronbach's α below .70 both for the *Anger* and for the *Verbal Aggression* subscales.

Data acquisition and processing

All electrophysiological data were recorded simultaneously using Ag/AgCl electrodes with the BioSemi© system (BioSemi ActiveTwo electrodes, Amsterdam). EEG signals were collected with 64 electrodes (10-20 system positions) mounted on an elastic cap. The vertical electro-oculogram (EOG) was recorded by means of two external electrodes placed below and above the left eye. The horizontal EOG was recorded by means of two external electrodes placed on the temples. The EOGs measurements were recorded to control for eye movement artefacts. The left and the right electromyographic activities (EMG) were recorded by means of two pairs of electrodes placed on the surface of the skin above the thumb-flexor pollicis brevis of each hand. These EMG measurements were recorded to detect partial-errors and the onset of all the muscular activities. The sampling rate was set to 1024 Hz. Electrophysiological data were collected during the experimental blocks of the Simon task only.

Electrophysiological data pre-processing

All the electrophysiological data pre-processing steps were done using BrainVision Analyzer 2.1© software (Brain Products, Munich, Germany).

The EMG data were filtered with a 10 Hz high-pass filter. Onsets of EMG activities were manually marked after visual inspection as it remained more precise than automatic algorithms (Staude et al., 2001). Experimenters were not aware of the nature of the trial being inspected. Based on the manual markers, all trials were classified as (1) pure-correct trials (i.e., trials with only one muscular burst on the correct side), (2) full-error trials (i.e., trials with only one muscular burst on the incorrect side), and (3) partial-error trials (i.e., trials containing two EMG activations, one on the incorrect side preceding the correct response).

The raw EEG data were filtered with a 0.16 Hz high-pass filter only and were referenced offline to the left mastoid. The EOGs were used to perform the ocular corrections on the EEG signals following the statistical method by Gratton, Coles, and Donchin (1983). All other artifacts were manually rejected after visual inspection of individual traces. To improve the spatial and the temporal resolutions of the EEG signals, the Laplacian transform was applied to the monopolar data (Babiloni et al., 2001; Burle et al., 2015). To perform this operation, signals were interpolated with the spherical spline interpolation procedure using 3 as the degree of spline and 15 degrees, for the Legendre polynomial (Perrin, Bertrand, & Pernier, 1987; Perrin, Pernier, Bertrand, & Echallier, 1989). Then, the second derivatives in two dimensions of space were computed. Thus, electrical brain activities are expressed in μV/cm^2.

EEG data processing

Information related to EMG onsets was superimposed upon the EEG signals. EEG data were segmented with respect to the EMG onsets of pure-correct, full-error, and partial-error EMG bursts. EEG segments ranging from 500 ms before and 500 ms after EMG onsets were baseline corrected (100 ms pre-EMG window). Time courses were averaged as a function of the response type. Previous studies showed that the ERN/Ne is maximal at the FCz electrode (e.g. Bates, Kiehl, Laurens, & Liddle, 2002; Ladouceur et al., 2018; Taylor et al., 2018; Weinberg et al., 2016). Therefore, the magnitudes of the central negativities were measured at the FCz electrode. A peak-to-peak method (i.e., baseline-free method, Falkenstein et al., 2000; Meckler, Carbonnell, Ramdani, Hasbroucq, & Vidal, 2017; Olvet, Hatchwell, & Hajcak, 2010) was applied in the time window between 50 ms and 250 ms after EMG onsets. However, as a peak-to-peak method to measure Pe amplitudes would have been contaminated by the variability of the ERN/Ne amplitudes, the mean positivity in a window frame between 200 ms and 400 ms after EMG onsets was used as an index of Pe amplitudes.

Experimental groups and statistical analyses

The aim of this study was to evaluate the relation between cognitive control capacities and aggressiveness. In the present study, ERN/Ne amplitudes in all response types were used as an indicator of the performance monitoring capacities. Partial-error rates were used as an indicator of the efficiency in reactive control. Finally, the post-error slowing and the Gratton effects (Gratton et al., 1992; Rabbitt, 1966) were used as indicators of the efficiency in proactive control.

The BPAQ median score was used to categorize participants as possessing high/low aggressiveness trait personalities. In our sample, the BPAQ scores ranged from 44 to 101, with 67 as the median score. The median-split method categorized 15 participants as low aggressive (i.e., they scored strictly less than 67 in the BPAQ) and 14 participants as highly aggressive (i.e., they scored strictly more than 67 in the BPAQ). Three participants were excluded from ANOVA analyses because their BPAQ scores were equal to the median score. ANOVAs were performed using the R *aov* function available in the stats package (Team, 2018). The behavioral performances (i.e., reaction times – RTs, accuracy, reactive and proactive control indices) were submitted to a one-level ANOVA with Aggressiveness as between-group factor. Performance monitoring indices were submitted to a two-level ANOVA with Aggressiveness (2) as between-group factor and Response-Type (3) as within-group factor. Post hoc Scheffé were applied when required and the effect sizes were calculated as eta-squared and partial eta-squared (η^2 and ηp^2, respectively) using the R *etaSquared* function available in the *lsr* package (Navarro, 2015). The alpha level was set to .05 for all analyses.

Results

The following results present the findings obtained during the Simon task in the total sample of 32 participants. We then report the results obtained in the sub-groups after categorizing participants with high and low aggressiveness traits using the total BPAQ score.

Global analyses

Accuracy and reaction times Among the exploitable EMG recordings, a total of 72.6 %, 23.2 % and 4.1 % of trials were classified as pure-correct, partial-error and full-error, respectively. As classically found, incongruent RTs (478 ms) were longer than congruent RTs (453 ms), $t(31)$ = -12.41, $p < .001$, Cohen's d = 2.19. The RTs in full-error trials were shorter (416 ms) than the RTs measured when correct responses were observed (i.e., combined pure-correct and partial-error trials, 465 ms), $t(31)$ = 10.65, $p < .001$, Cohen's d = 1.88. The post-error slowing was significant: RTs in correct trials following an error were longer (511 ms) than the RTs in correct trials following a correct response (463 ms), $t(31)$ = -6.96, $p < .001$, Cohen's d = 1.23. The Gratton effect was significant: the congruency effect was smaller after incompatible trials (-17 ms) compared to the congruency effect observed after compatible trials (69 ms), $F(1,124) = 26.88$, $p < .001$, $\eta p^2 = .18$. Overall,

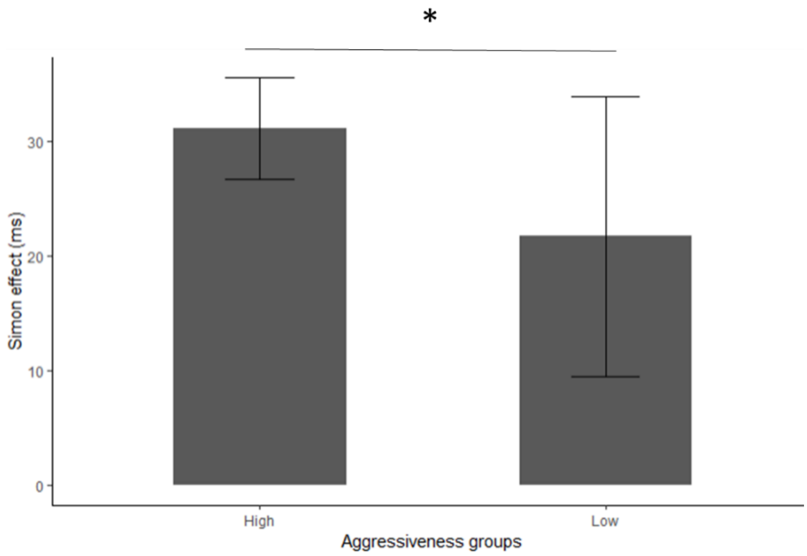

Figure 8.1 – **Mean Simon effect (ms) in the high and the low aggressiveness groups.** Error bars represent standard deviations. *: $p < .05$.

the classical effects of the Simon task were replicated.

Performance monitoring The ANOVA revealed the classical main effect of Response Type on ERN/Ne amplitudes, $F(2,93) = 23.52$, **p** $< .001$, $\eta^2 = .34$. The post hoc Scheffé test confirmed that ERN/Ne was larger in full-error trials than both in partial-error trials ($p < .001$) and in pure-correct trials ($p < .001$). ERN/Ne amplitudes were smaller in pure-correct trials than in partial-error trials ($p < .001$).

Task performance, cognitive control as a function of aggressiveness

Table 8.1 – Means (*M*) and standard deviations (*SD*) for the task performance indices in the high and the low aggressiveness groups.

Behavioral indices	Low aggressiveness		High aggressiveness		F	p	η^2
	M	*SD*	*M*	*SD*			
Full-error rates (%)	3.55	1.52	3.77	1.97	0.12	.737	<.01
Partial-error rates (%)	21.88	10.14	20.95	11.12	0.06	.816	<.01
RTs in full-error trials (ms)	382.51	44.32	369.69	49.11	0.55	.466	.02
RTs in correct trials (ms)	417.87	40.10	408.34	47.98	0.34	.565	.01

ANOVA revealed no main effects of Aggressiveness on error rates, on RTs in full-error trials and on RTs in correct trials $F(1,27) = 0.12$, $p = .737$, $\eta^2 < .01$, $F(1,27) = 0.55$, $p = .466$, $\eta^2 = .02$ and $F(1,27) = 0.34$, $p = .565$, $\eta^2 = .01$, respectively. These results are presented in Table 8.1. There was a main effect of Aggressiveness on the Simon effect,

Table 8.2 – ANOVA results for mean performance-related negativities and Pe amplitudes.

Factors	Performance-related negativities			Pe		
	F	p	ηp^2	F	p	ηp^2
Aggressiveness	10.53	**.002** **	.12	1.00	.326	.04
Response type	23.21	**<.001** ***	.36			
Aggressiveness x Response type	0.18	.832	<.01			

$F(1{,}27) = 7.35$, $p = .012$, $\eta^2 = .21$ (cf. Figure 8.1). The high aggressiveness group had a larger Simon effect (31.13 ms) than the low aggressiveness group (21.74 ms). When considering the partial-error rates reflecting reactive control, results revealed no main effects of Aggressiveness, $F(1{,}27) = 0.06$, $p = .816$, $\eta^2 < .01$. When considering proactive control, the ANOVA revealed no main effects of Aggressiveness on neither the post-error slowing nor the Gratton effect, $F(1{,}27) = 1.45$, $p = .239$, $\eta^2 = .05$ and $F(1{,}27) = 0.38$, $p = .545$, $\eta^2 = .01$, respectively.

Performance monitoring and aggressiveness

The EEG traces are represented in Figure 8.2 as a function of aggressiveness groups and responses types. The analyses revealed a main effect of Aggressiveness on ERN/Ne amplitudes, $F(1{,}81) = 10.53$, $p = .002$, $\eta p^2 = .12$. The ERN/Ne amplitudes were smaller in the high aggressiveness group (-0.56 μV/cm^2) than in the low aggressiveness group (-0.77 μV/cm^2). Reductions in ERN/Ne amplitudes in the high aggressiveness group were not modulated by Response Type, $F(1{,}81) = 0.18$, $p = .833$, $\eta p^2 < .01$. Concerning the Pe observed in full-error trials, there were no differences in amplitudes between the high and the low aggressiveness groups, $F(1, 27) = 1.00$, $p = .326$, $\eta p^2 = .04$. Table 8.2 presents the ANOVA results for the performance-related negativities (i.e., both ERN/Ne and CRN/Nc) and the Pe amplitudes.

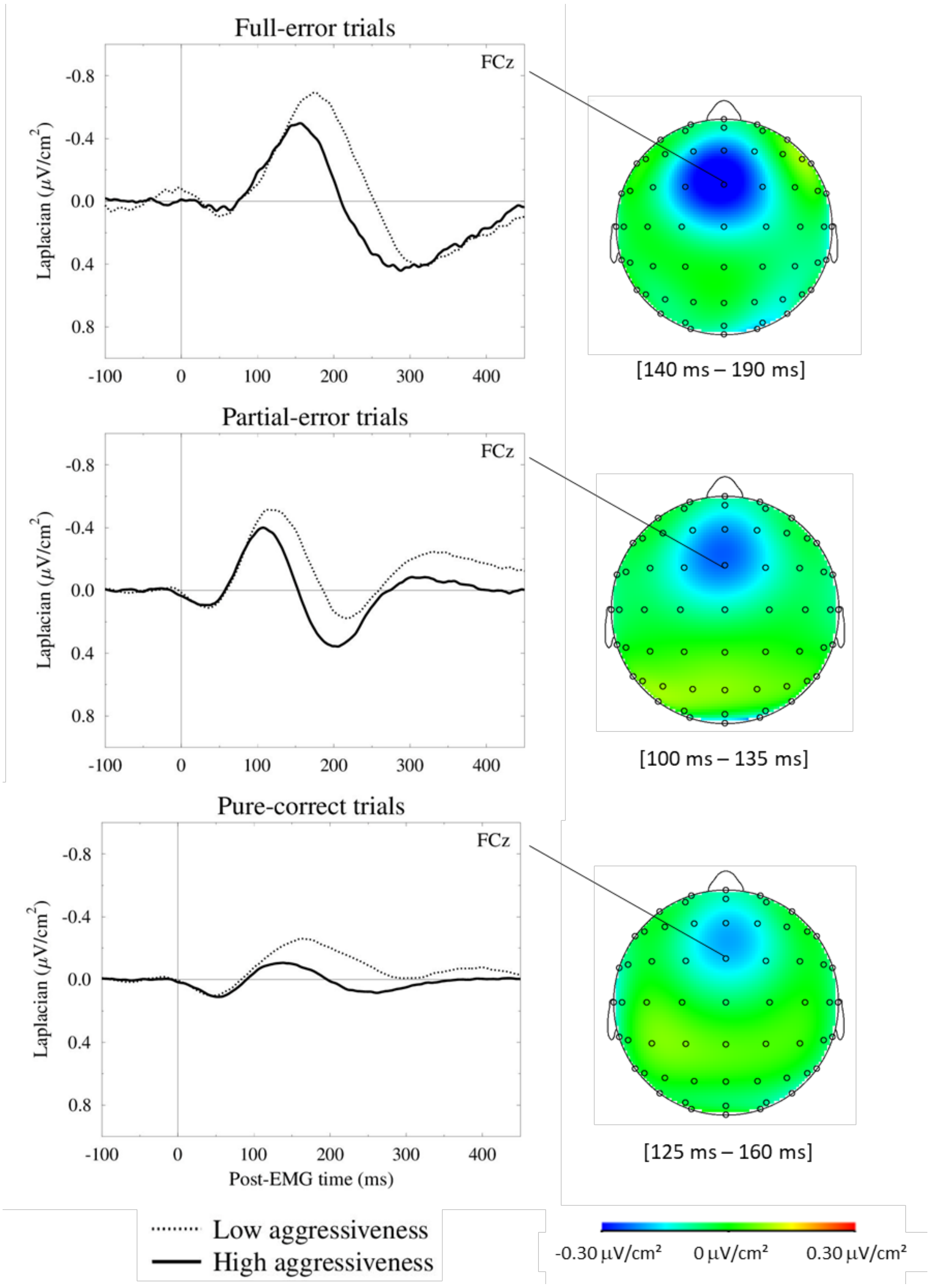

Figure 8.2 – **The Laplacian transformed performance related negativities (both ERN/Ne and CRN/Nc) and Pe (FCz electrode) and the corresponding Laplacian topographies measured in the full-error (top panel), in the partial-error (middle panel) and in the pure-correct responses (bottom panel)**. Continuous lines and dotted lines represent the results obtained in the high and the low aggressiveness groups, respectively. Signals were locked to the EMG onset of the motor responses. The topographical maps (right column) show a top/ horizontal view of the scalp (nose up) with the actual distribution of the Laplacian-transformed EEG data, separately for each response type, at the time of the negativity peak maximum.

Discussion

Aggressiveness is often associated with poor executive functioning and reduced performance monitoring in pathological and maladapted populations (e.g., Hancock et al., 2010; Vilà-Balló et al., 2014; Zajenkowski & Zajenkowska, 2015). The aim of the current study was to explore cognitive control capacities, and in particular performance monitoring, in a non-clinical population characterized with low and high aggressiveness personality traits. At the behavioral level, the findings showed that the high aggressiveness group globally performed as well as the low aggressiveness group in terms of accuracy and RTs. However, individuals with high aggressive traits were characterized by a greater congruency effect compared to those with low aggressive traits. At the brain level, the current study confirmed the expected reduction in ERN/Ne amplitudes in full-error trials in the high aggressiveness group compared to the low aggressiveness group. Interestingly, the results extended this finding by also revealing a reduction in performance-related negativities after both partial-errors and pure-correct responses. Additionally, the global reduction that was observed in all performance-related negativities amplitudes in the high aggressiveness group did not interact with the response types. Overall, the present results showed a reduction in the global activation of the performance monitoring system, and not a decrease in its efficiency.

Aggressiveness effects on cognitive control at behavioral level

Aggressive behaviors are known to be related to disturbed cognitive control abilities. Indeed, several studies investigating aggressiveness in tasks manipulating the stimulus-response congruency have reported worse performances in pathological and populations with problematic behaviors than in healthy controls (e.g., Gastaldo, Umiltà, Bianchin, & Prior, 2002; Hancock et al., 2010). In the current study, the performances of the participants in a choice RT task requiring cognitive control mechanisms were considered through the prism of their predispositions to act aggressively. We selected the BPAQ to assess the levels of aggressiveness through a 35-item questionnaire (Buss & Perry, 1992; Pham et al., 2011). A modified version of the Simon task manipulating the stimulus-response congruency was used to reveal cognitive control functioning. Results showed no differences in the global performance in the Simon task between groups of individuals categorized as having high and low traits in aggressiveness (i.e., RTs and error rates). Additionally, there were no differences neither in partial-error rates nor in behavioral adjustments indicating no effects of aggressive traits, both on reactive and proactive control mechanisms, respectively. However, the high aggressiveness group showed a larger congruency effect than the low aggressiveness group, revealing higher difficulty in inhibiting irrelevant information with higher aggressive tendencies. This result is consistent with a previous study showing longer reaction times in incongruent trials in schizophrenic patients compared to control participants (Gastaldo et al., 2002). While the few differences at the behavioral level between the two groups in our study may seem disconcerting at first sight, they might not be so surprising. Firstly, our participants were young individuals, recruited at the University, without maladapted behaviors. Secondly, the experimental setup was made to not induce aggressive behaviors, like it has been done in some previous studies (e.g., Krämer, Kopyciok, Richter, Rodriguez-Fornells, & Münte, 2011; Pawliczek et al., 2013). Therefore, the traits in aggressiveness were not amplified, and consequently the impact of such a trait may be too weak to be observable within the global indices of behavioral performances (i.e., RTs and error rates). Even if the global performances were not sensitive enough to the trait of aggressiveness in our study, the brain responses revealed a different pattern.

Aggressiveness effects on cognitive control at the brain level

Electroencephalographic recordings were used to assess performance monitoring abilities through the analysis of a specific response-locked ERP that is the error(-related) negativity (ERN/Ne) and its equivalent in pure-correct trials (CRN/Nc). These EEG components are fronto-central negativities peaking rapidly after the response. The amplitude of the ERN/Ne is known to vary as a function of the need to self-evaluate behavioral performances. The more the error is meaningful, the larger is the ERN/Ne amplitude (Gehring et al., 1993; Hajcak et al., 2005). In the current study, we choose to use the Laplacian transform to improve the temporal and spatial resolutions of the EEG (Babiloni et al., 2001; Burle et al., 2015) and especially to uncover the CRN/Nc, usually masked by a large parietal positivity (Roger et al., 2010; Vidal et al., 2000, 2003). We conducted a combined analysis of the negativities in full-errors, in partial-errors and in pure-correct trials. This joint analysis provides the means to specify how a variable can affect patterns of performance monitoring abilities (e.g., task instructions, disorders). In our opinion, only investigating the effect of a variable on the amplitude of the ERN/Ne can mislead interpretations. A reduced ERN/Ne cannot be a marker of error monitoring deficit if the CRN/Nc is also reduced: the monitoring system still distinguishes erroneous and correct actions. This pattern of results should be interpreted as a global decrease in monitoring engagement (i.e., reduction in the value placed on the performance). On the contrary, if a reduced ERN/Ne goes along with a large CRN/Nc, this pattern should be interpreted as a specific difficulty in the evaluation of one's own performance: the monitoring system becomes less discriminant.

In the current study, the performance-related negativities peaks were observed within a time window of 100 to 200 ms after the onset of the muscular responses recorded using EMG. Its amplitude was the highest in full-error, intermediate in partial-error and the smallest in pure-correct responses. This pattern of results replicated previously reported findings (e.g. Meckler et al., 2011; Roger et al., 2014, 2010; Vidal et al., 2003, 2000). Considering the aggressiveness effect, the ERN/Ne in full-errors was reported to be decreased in individuals showing high traits in aggressiveness compared to those with low aggressive traits. The current study replicated the findings by Vilà-Balló et al. (2014) in an adapted population and without manipulating the aggressive states of the participants. Interestingly, thanks to the Laplacian transform and the use of EMG, the current study extended these findings by revealing a reduction in the ERN/Ne in partial-errors and in CRN/Nc in pure-correct trials in the high aggressiveness group compared to the low aggressiveness group. Since all the negativities were affected in the same way by aggressiveness, the current findings suggest that aggressiveness does not affect the ability to self-evaluate actions, but instead reduces the importance attached to one's own performance. This global reduction in negativities amplitudes is consistent with several previous studies. Indeed, aggressiveness has already been linked to reduced prefrontal activities in an emotion-manipulated context (Pawliczek et al., 2013) and after exposure to violent video games (Hummer, Kronenberger, Wang, & Mathews, 2019). Nevertheless, the study showed that high aggressive predispositions are characterized by a less active, but still efficient monitoring system even in a neutral situation. It seems that high aggressive individuals care less about their performance than low aggressive individuals do, but are still able to clearly evaluate it. Further studies should consider the functioning of the monitoring system in high aggressive individuals in motivational situations to understand whether the global reduction observed here, in a neutral environment, is due to a genuine inability to mobilize the monitoring system.

Aggressive behaviors are characteristic of psychiatric populations (e.g. Mancke et al., 2015; Zhou et al., 2016) and these disorders are also associated with a reduction in the ERN/Ne amplitude (e.g. Charles et al., 2017; de Bruijn et al., 2006). Olvet and Hajcak (2008) even proposed that the ERN/Ne should be considered as an endophenotype of psychopathology. In the current study, we did not carry out precise psychiatric screenings for ethical reasons and, thus, it might be possible that in our sample, especially in the high aggressiveness group, some may meet criteria of psychiatric disorders. Moreover, aggressive predispositions are risk factors for psychiatric disorders (e.g. Mula et al., 2015). Considering the high aggressiveness group as at risk to develop psychiatric disorders, the current results suggest that the global reduction in performance monitoring activities reflects a neurophysiological marker for psychiatric vulnerability. However, this decrease in involvement of the monitoring resources itself is not sufficient to suggest the existence of a psychopathological state. In contrast, a difficulty in distinguishing between erroneous and correct actions may be a more accurate marker of maladapted behaviors. Accordingly to this hypothesis, Hall et al. (2007) and Mathalon et al. (2002) both showed weaker differences between ERN/Ne and CRN/Nc amplitudes in externalizing disorders and in schizophrenia, respectively, than in healthy individuals. The interpretation of the reduction in ERN/Ne as a marker of psychopathology (Olvet & Hajcak, 2008) should also take into account the modulation of the CRN/Nc to confirm the presence of disturbed self-evaluation capacities and to specify the true nature of abnormal cognitive control functioning of the monitoring system.

Conclusion

This study used the BPAQ questionnaire in order to evaluate aggressive tendencies in a non-clinical and adapted population to compare cognitive control capacities between individuals with low and high aggressive personality traits. At the behavioral level, the high aggressiveness group was associated with a larger congruency effect compared to the low aggressiveness group. However, this difficulty in inhibiting irrelevant information was not reflected in performance: the high and low aggressiveness groups differed neither on error rates nor on reaction times. More particularly, the aim of the current research was to study the influence of these personality traits on the performance monitoring system, which plays a crucial role in cognitive control. Individuals with high aggressive traits showed a reduction in performance-related negativities amplitudes independent of the response type compared to those in the low aggressiveness group. This reduction reveals a decrease in the value placed on performance, but an intact capacity to self-evaluate one's own performance in high aggressiveness. Further studies should be conducted in order to disentangle the influence of aggressive personality traits from the influence of a psychiatric diagnosis on performance monitoring capacities.

8.2 Supplementary analysis: Impulsiveness and the monitoring system

During the Study IV, participants also fulfilled the UPPS questionnaire (Whiteside & Lynam, 2001; Van der Linden et al., 2006) assessing impulsiveness. The global UPPS score showed interesting results in previous studies by correlating with the proactive behavioral index (see Chapter 5.1), and by revealing associations with the adaptation of control mechanisms both in the general and in a pathological populations (see Chapters 5.1 and 6.1, respectively). We therefore investigated the relationship between the UPPS scores and the monitoring system activity.

Method

We performed a two-factor ANOVA on the performance-related negativities amplitudes with Response Type (Full-error, Partial-error and Pure-correct) as within-subject factor and UPPS Groups as between-subject factor (HI and LI). The UPPS groups were created with the median-split method (median score = 97). The analysis was performed on 29 participants (i.e., 14 high impulsive and 15 low impulsive).

Results

Table 8.3 – Distribution of the high and low UPPS and BPAQ groups created with the median-split method.

	Low UPPS	High UPPS
Low BPAQ	5	8
High BPAQ	9	4

The UPPS scores did not correlate with the BPAQ scores, r = -0.20, p = .276. Contrary to what could be expected, high aggressiveness was not associated with high impulsiveness in our sample, $\chi^2 = 1.39$, $p = .238$ (see Table 8.3). The main effect of Response Type on the performance-related negativities was observed, $F(2, 81) = 20.35$, $p < .001$, $\eta^2 = 0.33$. However, there was no main effect of UPPS Groups, $F(1, 81) = 0.06$, $p = 0.815$,

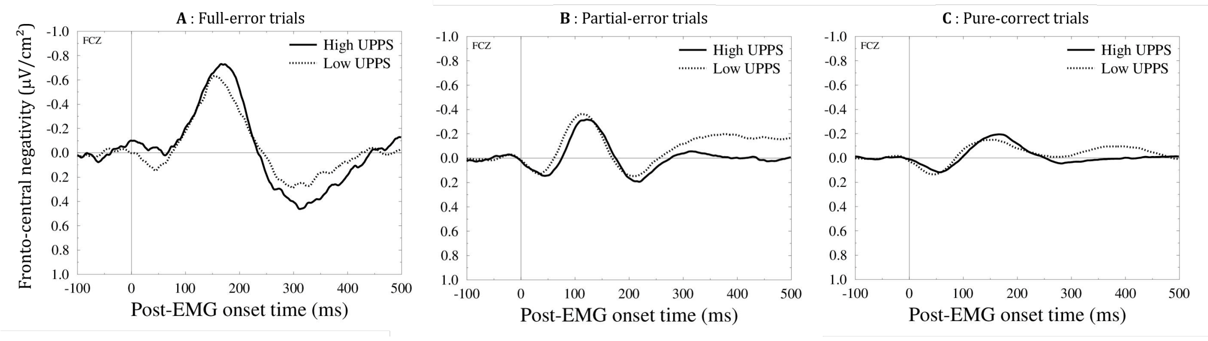

Figure 8.3 – **Amplitudes of the fronto-central negativities (μV/cm^2) recorded at the FCz electrode as a function of the UPPS groups and the Response Type**: full-error trials **(A)**, partial-error trials **(B)** and pure-correct trials **(C)**. The high (N = 14, bold lines) and low UPPS (N = 15, dashed lines) groups were created with the median-split method. The ERP signals were filtered at 30Hz (low pass filter) for visualization purpose only.

$\eta^2 < 0.01$, nor an interaction effect between Response Type and UPPS Groups, $F(2, 81) = 0.13$, $p = 0.881$, $\eta^2 < 0.01$. The Figure 8.3 represents the EMG-locked negativities traces as a function of the UPPS groups and the Response Type.

Discussion

As reported in the introduction of the manuscript (see Chapter 3.1.1), impulsive-related pathological populations are often associated with a reduction in the ERN/Ne amplitude whereas researchers often failed to observe an impact of impulsiveness on the activity of the monitoring system in the general population. The absence of an effect of impulsiveness on the ERN/Ne amplitudes in all the three performances trials in our sample is therefore not surprising and consistent with the literature. However, one could wonder why the monitoring system is reduced in high aggressive individuals, but not in high impulsive individuals. Indeed, impulsiveness and aggression are thought to be closely related (e.g., Archer & Webb, 2006; O'Connor, Archer, Hair, & Wu, 2002; Stanford, Houston, Villemarette-Pittman, & Greve, 2003). However, in our sample, impulsiveness and aggressiveness were not correlated: the high impulsive individuals were not the more aggressive ones. To explain the discrepancy of the ERN/Ne amplitudes pattern between impulsiveness and aggressiveness in the general population, it can be hypothesized that the reduction in the activity of the monitoring system is a marker of impulsive-related behaviors, and not a marker of impulsiveness. Indeed, a reduced ERN/Ne is consistently observed in pathological populations (e.g., Mathalon et al., 2002; de Bruijn et al., 2006; Liotti et al., 2005), or in the general population with impulsive behaviors (Ruchsow et al., 2005). Aggressiveness as assessed through the BPAQ questions more behavioral components (e.g., "*I have become so mad that I have broken things*", "*I have threatened people I know*", "*I get into fights a little more than the average person*", see Appendix .3) than impulsiveness as assessed through the UPPS questionnaire (e.g., "*I am a cautious person*", "*It is hard for me to resist acting on my feelings*", "*I tend to give up easily*", see Appendix .3). The reduction in activity of the monitoring system may result in impulsive behaviors. Also within the postulate that impulsive behaviors result from the inadequacy of control mechanism as a function of external and internal demands, then we can hypothesize that the activity of the monitoring system is associated with the adaptation of control mechanisms. This hypothesis was tested, and the results are presented in the following chapter.

8.3 ERN/Ne and adaptation of control mechanisms

Reduction in the ERN/Ne amplitudes is often observed in impulsive-related pathological populations such as schizophrenia (Mathalon et al., 2002), borderline personality disorder (de Bruijn et al., 2006) or ADHD patients (Liotti et al., 2005). As reported in Chapter 3.1.1 and as our analysis between impulsiveness and ERN/Ne amplitudes suggests, the pattern of results is not always reported in impulsive individuals from the general population (e.g., Luu et al., 2000; Potts et al., 2006). However, in the general population, aggressiveness and error speed were associated with reduced monitoring activities (Grisetto, Delevoye-Turrell, & Roger, 2019; Ruchsow et al., 2005, respectively). According to these findings, we hypothesized that a reduced ERN/Ne may only be observed in individuals expressing impulsive behaviors at a normal or a pathological level. Also, as suggested by the results of the Study I and the Study III, impulsive behaviors might emerge when the control mechanism at play is not adapted to external and internal demands (see Chapters 5.1 and 7.1). Therefore, a link between the amplitudes of the ERN/Ne and the capacity to adapt control mechanisms may be postulated. More particularly, I hypothesized that smaller the ERN/Ne amplitudes, weaker the adaptation of control mechanisms. To investigate this research question, I used the EEG data previously collected in the Study I during the AX-CPT experimental blocks.

Method

The EEG data used in this analysis were collected during the AX-CPT task presented in Chapter 5.1. The EEG data were recorded with the BioSemi© system (BioSemi ActiveTwo electrodes, Amsterdam) using 64 Ag/AgCl electrodes (10–20 system positions) mounted on an elastic cap. The sampling rate was 1024 Hz (filters: DC to 208Hz, 3dB per octave). The vertical electro-oculogram (EOG) was recorded by means of two external electrodes placed below and above the left eye. The horizontal EOG was recorded by means of two external electrodes placed on the temples. The EOGs measurements were recorded to control for eye movement artifacts.

All the electrophysiological data processing was realized using BrainVision Analyzer

2.1© software (Brain Products, Munich, Germany). The raw EEG data were filtered with a 0.16 Hz high-pass filter only and were referenced offline to the left mastoid. The EOGs were used to perform the ocular corrections on the EEG signals following the statistical method by Gratton et al. (1983). All other artifacts were manually rejected after visual inspection of individual traces. To improve the spatial resolution of the EEG signals, the Laplacian transform was applied to the monopolar data (Babiloni et al., 2001; Burle et al., 2015). To perform this operation, signals were interpolated with the spherical spline interpolation procedure using 3 as the degree of spline and 15 degrees for the Legendre polynomial (Perrin et al., 1987, 1989). Then, the second derivatives in two dimensions of space were computed. Thus, electrical brain activities are expressed in μV/cm^2.

The pre-processed EEG data were segmented to the error triggers. EEG segments ranging from 500 ms before and 500 ms after response-onset were baseline corrected (100 ms pre-response window) and averaged by participants. The magnitudes of the ERN/Ne component were measured at the FCz electrode. A peak-to-peak method (i.e., baseline-free method, Falkenstein et al., 2000; Meckler et al., 2017; Olvet et al., 2010) was applied in the time window between -100 ms and 100 ms around the onset of the error.

Signals from 34 participants were used in this analysis. We performed Pearson's correlations to analyze the relationship between (1) the ERN/Ne amplitudes and the adaptation index (i.e., individual coefficients of the linear regression model fitting the PBI with Blocks, see Appendix .1) and (2) the ERN/Ne amplitudes and the PBI calculated in last block of the AX-CPT task.

Results

The Figure 8.4 represents the response-locked ERN/Ne and CRN/Nc recorded at the FCz electrode, and the corresponding topography consistent with previous literature during the AX-CPT task in the whole sample. The ERN/Ne amplitudes were significantly larger (M = -0.77 μV/cm^2, SD = 0.61) than the CRN/Nc amplitudes (M = -0.31 μV/cm^2, SD = 0.24), V = 20, $p < .001$, Cohen's d = 0.94. There was no significant correlation between the ERN/Ne amplitudes and the index of PBI adaptation over time, $\rho = 0.14$,

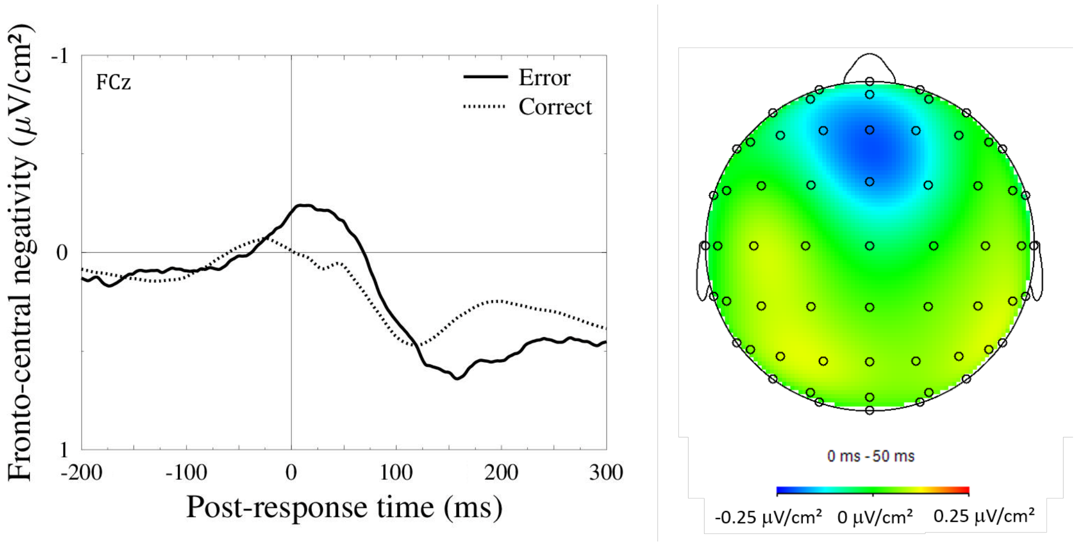

Figure 8.4 – **Amplitudes of the fronto-central negativities recorded during the AX-CPT task after an error (ERN/Ne, bold line) and after a correct response (CRN/Nc, dashed line).** Time 0 refers to the response occurrence. The signals were filtered at 30Hz (low pass filter) for visualization purpose only. The topography represents the EEG activity between 0 ms and 50 ms after the onset of the error.

p = .447 (see Figure 8.5A). However, we observed a significant correlation between the ERN/Ne amplitudes and the PBI in the last block $\rho = 0.37$, $p = .039$ (see Figure 8.5B). Smaller the ERN/Ne amplitudes, higher the proactive behavioral index was in the last block.

Discussion

Using data from the Study I (see Chapter 5.1), we aimed at exploring the relationship between the ERN/Ne amplitudes and the adaptation of the use of proactive control as a function of external demands for two main reasons. Firstly, according to the models of cognitive control (Botvinick et al., 2001; De Pisapia & Braver, 2006), the activation of the conflict monitoring layer triggers proactive and reactive behavioral adjustments. The average level of conflict (computed by the long time-scale conflict unit) reinforces the involvement of proactive control, by increasing the active maintenance of goal-relevant information (see Chapter 2.2.3). For this theoretical reason, one can easily argue that the efficiency of the monitoring system is associated with the capacity to adjust control mechanisms. Secondly, previous results on the relationship between impulsivity and the

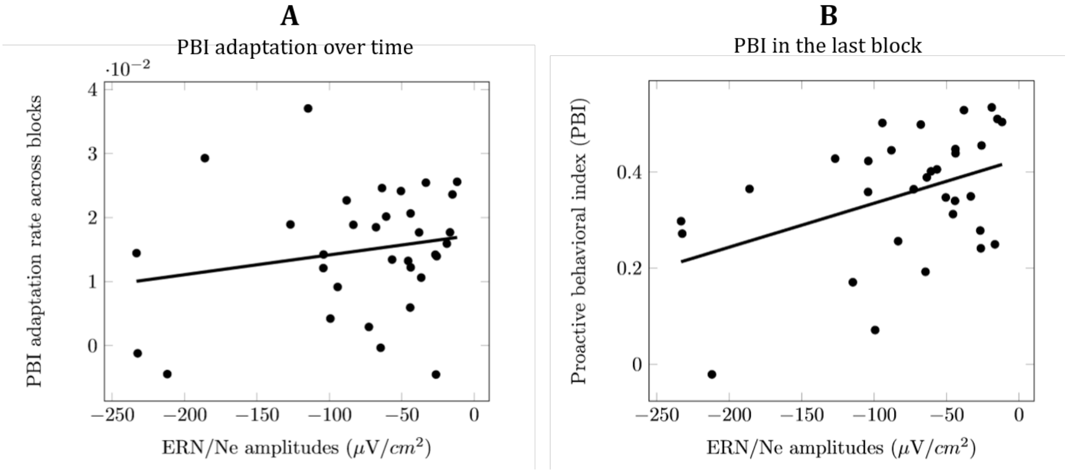

Figure 8.5 – **Correlations between the the ERN/Ne amplitudes (μV/cm^2) and (A) the adaptation of the proactive behavioral index (PBI) across blocks and (B) the PBI in the last block.**

ERN/Ne component suggested that reduced ERN/Ne amplitudes could only be observed in individuals with impulsive behaviors both in the general and pathological populations (e.g., de Bruijn et al., 2006; Liotti et al., 2005; Mathalon et al., 2002; Ruchsow et al., 2005). Moreover, behavioral findings from the current thesis suggest that impulsive behaviors may be associated with a smaller adaptation of control mechanisms. Impulsive behaviors are thus associated with both a lack of adaptation between reactive and proactive control mechanisms and a reduction in the activity of the monitoring system. With these empirical arguments, a reduction in the activity of the monitoring system could be associated with a weaker adaptation capacity. For these reasons, we investigated the relationship between the ERN/Ne amplitudes and the adaptation of control mechanisms in the current study.

The adaptation of control mechanisms was indexed by the individual coefficients of the regression model fitting the proactive behavioral index (PBI) with blocks (see Appendix .1). We expected that reduced ERN/Ne amplitudes will be associated with weaker adaptation to task demands (i.e., smaller adaptation index), but our results failed to show such a relationship. However, the ERN/Ne amplitudes correlated with the PBI in the last block (cf. Figure 8.5). Higher the PBI in the last block, smaller the ERN/Ne amplitudes throughout the task. This finding is consistent with the perspective of Burle et al. (2008) on the interpretation of the ERN/Ne component as an "alarm signal" that persists until control processes are in play. The participants with a high PBI need less to be informed of the need to trigger remediation processes, as they are already adapted to external demands. However, when the control mechanism at play is not sufficiently adapted to external demands, the alarm signal is still strongly activated: smaller the PBI at the end of the AX-CPT task, higher the ERN/Ne amplitudes throughout the task. The ERN/Ne amplitudes could reflect the need to adapt control mechanisms, rather than the adaptation of control mechanisms itself. However, further studies are needed to investigate the link between the monitoring system and the capacity to adapt control mechanisms. Indeed, in the current study, the ERN/Ne component was extracted from the same experimental paradigm than the index of adaptation. It would be interesting to measure the ERN/Ne component in a distinct experimental paradigm that do not involve the need to adapt control mechanisms (i.e., a simple reaction time task) and investigate its predictive value on the adaptation in the AX-CPT task.

Conclusion of the fourth experimental axis

In Botvinick et al. (2001) and De Pisapia and Braver (2006)'s models, the detection of a conflict (i.e., the co-activation between competitive responses) triggers reactive and proactive behavioral adjustments. The ERN/Ne component, originally interpreted as an index of error detection, is largely used to investigate the capacity to monitor conflicts (see Chapter 3.1.1). However, Burle et al. (2008) showed that the ERN/Ne amplitudes was not correlated with the strength of the conflict, and therefore the ERN/Ne could rather be interpreted as an "alarm signal" that informs the system of the need of control processes as a function of several factors (e.g., presence of a conflict, commission of an error, motivational contexts).

The results from the fourth experimental axis suggest that the efficiency of the "alarm system", assessed through the ERN/Ne signal, relates to the capacity to adapt control mechanisms. Indeed, impulsive behaviors, potentially emerging when the control mechanism in play is not adapted to external and/or internal demands, are often associated with a reduction in the ERN/Ne amplitudes. However, the current results failed to show a direct association between small ERN/Ne amplitudes and weaker adaptation of control mechanisms.

Chapter 9

Providing food for thoughts on the role of HRV in the adaptation of control mechanisms

Foreword

So far, my PhD findings suggest that impulsivity in a general population is associated with a less proactive and less flexible cognitive control system. Impulsive individuals less exert proactive control when external and internal demands (i.e., the AX-CPT task demands and the efficiency of reactive inhibition capacities, see Chapters 5.1 and 7.1) promote its use. This weaker adaptation of control mechanisms might lead to impulsive behaviors when the control mechanism is not sufficiently adapted (i.e., not optimal) to the context. Targeting the capacity to adapt control mechanisms could be an interesting therapeutic pathway to reduce impulsive manifestations in high impulsive individuals.

At a physiological level, the heart rate variability (HRV) is thought to reflect the activity of the autonomic nervous system (ANS), also known as the stress axis, responsible of the fight or flight response (e.g., Dobrek, Friediger, Furgała, & Thor, 2006; Sztajzel, 2004; Xhyheri, Manfrini, Mazzolini, Pizzi, & Bugiardini, 2012; Miyawaki & Salzman, 1991). The HRV refers to the variability of the heartbeat intervals, revealing the parasympathetic ANS activities on the heart (Appelhans & Luecken, 2006). Accordingly, the HRV indicates the psychophysiological flexibility of the system to adjust cardiac rhythm as a function of the situation. Consistently, this physiological index is associated with self-regulation capacities at behavioral, cognitive and emotional level (Beauchaine, Gartner, & Hagen, 2000; Thayer & Lane, 2000; Gillie, Vasey, & Thayer, 2015; Thayer, Hansen, Saus-Rose, & Johnsen, 2009). Interestingly, more and more authors suggest that higher HRV moderates the effect of several risk factors on the emergence of maladaptive behaviors and psychiatric disorders (e.g., personality traits, traumatic experiences Oshri, Liu, Duprey, & MacKillop, 2018; Ramírez, Ortega, & Reyes Del Paso, 2015; Baik et al., 2019). Similarly, Scarpa, Tanaka, and Haden (2008) observed that traumatic experiences, such as violence exposure during childhood, was associated with aggressive behaviors but only in low HRV participants. Finally, impulsive-related psychiatric disorders, such as schizophrenia, borderline personality disorders and substance use, are characterized by low HRV (e.g., Clamor, Lincoln, Thayer, & Koenig, 2016; Koenig, Kemp, Feeling, Thayer, & Kaess, 2016; D'Souza et al., 2019).

During my PhD, I thus became interested in the potential link between HRV and the capacity to adapt control mechanisms to external and internal demands. Indeed, both low HRV and the lack of adaptation of control mechanisms seem to be associated with impulsive behaviors. Therefore, in order to provide some preliminary results on this research question, I used the signals initially recorded for the EMG data during the Study I and the Study IV to extract electrocardiographic (ECG) signals (see Appendix .2). An algorithm was used to automatically detect the heartbeats in the ECG signal and to measure an HRV index (i.e., SDNN which refers to the standard deviations of the heartbeat intervals). Within the dataset collected in the Study I (see Chapter 5.1), I investigated the relationship between HRV and the adaptation of the proactive behavioral index over time during the AX-CPT task. Within the dataset collected in the Study IV (see Chapter 8.1), I investigated the relationship betwen HRV and the activity of the monitoring system. The results are presented hereafter.

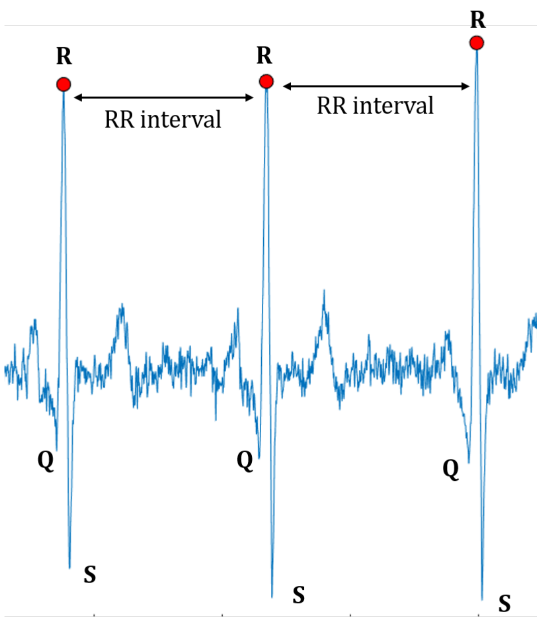

Figure 9.1 – **Decomposition of heartbeats into QRS complexes.** The ECG signal was extracted from the EMG recordings. An algorithm was used to automatically detect the R peaks of the QRS complex (red dots) to calculate the RR intervals (double-head arrows). The SDNN, the HRV-index used in the following analyses, refers to the variability in the RR intervals. The represented data were collected during the Study I.

9.1 Heart rate variability and adaptation to external demands

In the first study (see Chapter 5.1), the ECG information, extracted from the EMG signal, was recorded before and after the ten experimental blocks of the AX-CPT task. Firstly, as the HRV is a physiological index of adaptation, we expected that HRV should be greater after the task compared to the HRV measured as baseline. Moreover, we expected that the pre and post-HRV difference should be weaker in the high impulsive group and near to 0 for the participants that did not adapt PBI during the task, supporting the behavioral observation index (H1). Secondly, as the HRV is a moderator of the relationship between risk factors and impulsive behaviors, we investigated the HRV as a potential moderator of the relationship between impulsiveness and adaptation capacities. We expected that higher HRV could reduce the impact of impulsiveness on the adaptation of control mechanisms (H2).

Method

ECG data acquisition and processing

The ECG recording was performed using one external electrode placed on the *flexor pollicis brevis* on the left hand of the participant. The sampling rate was 1024 Hz (filters: DC to 208Hz, 3dB per octave). The participant was asked to stay still, with his/her eyes closed, for a five-minutes period before and after the ten AX-CPT blocks (i.e., pre-HRV and post-HRV, respectively). The raw ECG was first filtered at 10Hz (low-pass filter) and segmented as "Pre-task" and "Post-task". An algorithm was used to automatically detect the R peaks of the QRS complex within these segmentations (see red dots in Figure 9.1). A visual inspection of the peak detection was performed to ensure the quality of the detection, and to correct potential artefacts due to muscular activities. The algorithm calculated the time difference between two consecutive R peaks (i.e., RR intervals) and compiled the list of RR intervals for each participant at the two time periods. Finally, to index HRV, the standard deviation of the RR intervals (i.e., SDNN) was calculated for each individual and for the two time periods.

Statistical analysis

To investigate H1, the HRV was analyzed with a two-factor ANOVA with Time (Pre, Post) as within-subject factor and Impulsiveness (High, Low) as between-subject factor ($N = 40$). Impulsiveness groups were created with the median-split method (18 high and 22 low). We also performed a two-factor ANOVA with Time (Pre, Post) as within-subject factor and Adaptation (Adaptation, No adaptation) as between-subject factor ($N = 38$). The Adaptation groups were created as a function of the positive or negative sign of the index of adaptation (No adaptation, $N = 7$, Adaptation, $N = 31$). To investigate H2, multiple linear regression analysis was performed with the pre-task HRV and the UPPS scores as predictors and the index of the PBI adaptation as the dependent variable ($N = 38$).

Results

The ANOVA revealed a main effect of Time on the HRV, $F(1{,}38) = 44.07$, $p < .001$, $\eta^2 = 0.54$. The HRV was smaller before the task ($M = 58.82$, $SD = 21.99$) than after the task ($M = 81.44$, $SD = 33.62$), revealing the adaptation at a physiological level. There was no main effect of Impulsiveness on HRV, $F(1{,}38) = 0.55$, $p = .462$, $\eta^2 = 0.01$. There was no difference in HRV between high and low impulsive groups. The interaction effect between Time and Impulsiveness did not reach significance, $F(1{,}38) = 1.13$, $p = .294$, $\eta^2 = 0.03$. Therefore, there was no difference in the increase in HRV between high and low impulsive groups. However, we also investigated the difference in HRV increase between the group that adapted to task demands (i.e., positive index of adaptation) and the group that did not adapt to task demands (i.e., negative index of adaptation). The ANOVA revealed no main effect of the Adaptation groups on the HRV, $F(1{,}36) = 0.08$, $p = .778$, $\eta^2 < 0.01$. However, there was a close-to-significant interaction effect between Adaptation groups and Time on HRV, $F(1{,}36) = 3.39$, $p = .074$, $\eta^2 = 0.09$. The Figure 9.2 represents the interaction effect. The mean difference between pre and post HRV was larger in the group that did adapt (M = 26.51, SD = 22.13) compared to the group that did not adapt (M = 10.47, SD = 12.16).

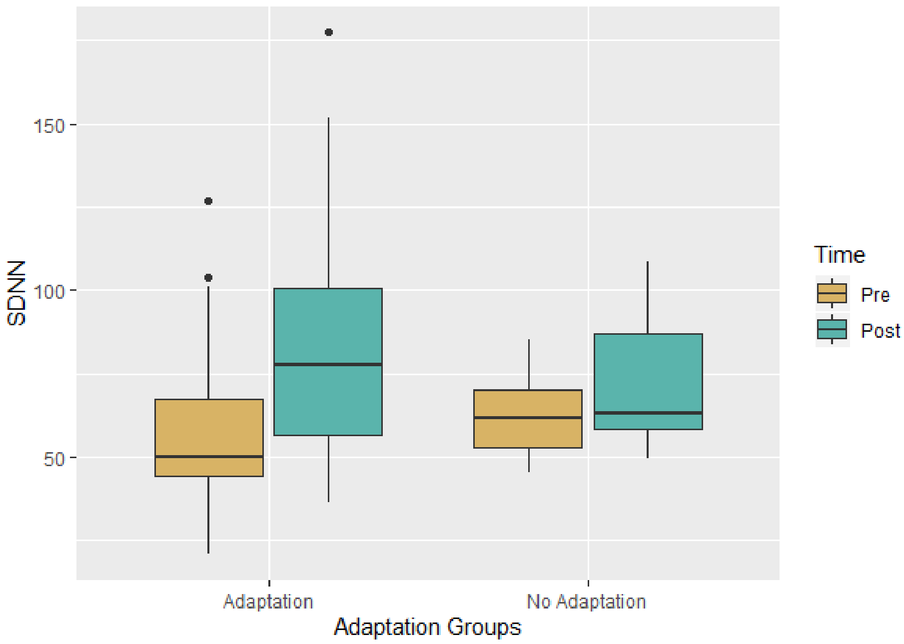

Figure 9.2 – **Interaction effect between Time (Pre and Post task) and Adaptation groups on the SDNN, an index of HRV.** Adaptation groups were created as a function of the positive or negative sign of the index of PBI adaptation.

The multiple linear regression showed a significant main effect of the UPPS scores on the adaptation rate, β = -6.91$^{10\text{-}4}$, t = -2.32, p = .026. Higher UPPS scores were significantly associated with smaller PBI index of adaptation. Also, results reveal a significant main effect of the pre-task HRV on the adaptation rate, β = -9.33$^{10\text{-}4}$, t = -2.14, p = .040. Surprisingly, this result suggested that higher HRV was associated with smaller adaptation of control mechanisms over time. More interestingly, the interaction between the UPPS scores and the pre-task HRV significantly predicted the adaptation rate in the AX-CPT task, β = 8.39$^{10\text{-}6}$, t = 2.13, p = .041 (cf. Figure 9.3). Higher the HRV, smaller the association between impulsiveness and the adaptation rate. However, one observation was significantly considered as an outlier by the model (p = .014). This outlier observation drove the significance of the model.

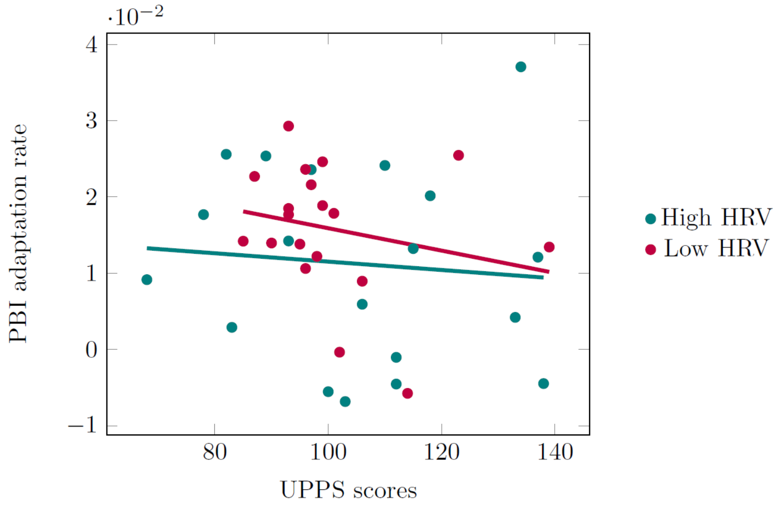

Figure 9.3 – **Interaction effect between the UPPS scores and the HRV on the adaptation rate in the AX-CPT task.** The high and low HRV groups were created with the median-split (median = 53.5) as visualization purpose only.

Discussion

On the one hand, the study aimed at exploring heart rate variability (HRV) as a physiological index of the adaptation of control mechanisms. We expected an increase in the HRV after the task compared to pre-HRV. Moreover, to support the behavioral data, we expected a smaller pre-post HRV difference in high impulsive individuals compared to low impulsive individuals. As expected, the HRV was higher after the experimental blocks, but we failed to show an effect of impulsiveness on this increase. However, the increase in HRV was smaller for participants that did not adapt to task demands compared to that observed in participants that did adapt. On the other hand, the study aimed at exploring HRV as a moderator factor on the relationship between impulsiveness and the adaptation of control mechanisms during an AX-CPT task. According to previous literature showing that higher HRV reduces impulsive manifestations in impulsive individuals, we expected that higher HRV would be associated with better adaptation of control mechanisms in high impulsive individuals. Result from our sample confirmed this hypothesis.

As expected, the HRV increased after the experimental session. The adaptation observed at the behavioral level was confirmed with a physiological index of adaptation. However, contrary to our expectations, high impulsiveness was not associated with a difference in the increase in HRV after the task. The slower adaptation in high impulsive individuals was not reflected at a physiological level, but the absence of adaptation (i.e., negative index of adaptation) was associated with a smaller increase in HRV.

The heart rate variability (HRV) moderates the relation between impulsiveness and the adaptation of control mechanisms to external demands. In our sample, the higher the HRV, the less the UPPS scores were negatively associated with the adaptation of control mechanisms. This result suggests that the moderation effect of the HRV on the relationship between several risk factors and impulsive behaviors or psychiatric disorders (e.g., personality traits, traumatic experiences, neuronal differences, Oshri et al., 2018; Ramírez et al., 2015; Baik et al., 2019) could be explained through the improvement of the capacity to flexibly adapt control mechanisms to external and internal demands. However, in our sample, one observation (i.e., a high impulsive individual with a high HRV) was pointed as a statistical outlier in the multiple linear regression model and drove the significance of the model. It may be possible that the association between high impulsiveness and high HRV is rare (i.e., low HRV characterizes several impulsive-related pathological populations, e.g., Clamor et al., 2016; Koenig et al., 2016; Cannon, 2014), statistically explaining the outlier participant. The result reported in this study is therefore to take with caution. However, our finding is consistent with literature viewing HRV as a moderator between several risk factors and maladaptive behaviors or psychiatric disorders (Oshri et al., 2018; Ramírez et al., 2015; Baik et al., 2019). Although this result has statistical limitations and has to be taken with caution, it opens to interesting lines of research. Further studies are needed to try to replicate this finding in a larger sample, and using other HRV index.

9.2 Heart rate variability and the monitoring system

My PhD findings suggest that impulsivity is associated with a less proactive and less flexible cognitive control system. Following Dickman (1990)'s footsteps, I postulated that impulsive behaviors emerge when the control mechanism at play is not sufficiently adapted to the context. Moreover, in the fourth study of the present thesis (see Chapter 8.1), we showed that the activity of the monitoring system assessed through the ERN/Ne amplitudes was globally reduced in individuals with high aggressive tendencies, but not in high impulsive individuals. Based on this finding and on previous literature, I postulated that the reduction of the activity of the monitoring system could be associated with inappropriate behaviors and therefore, that the monitoring system is an "alarm system" informing when adaptation of control mechanisms is needed. A reduced activity in the monitoring system is therefore associated to a weaker alarm signal to adapt, resulting in inappropriate behaviors.

In the previous section (see Chapter 9.1), the reported results suggested that the adaptation of control mechanisms was improved in high impulsive individuals with high HRV. High HRV may protect at-risk individuals (e.g., with high impulsiveness) to impulsively behave or to develop psychiatric disorders (e.g., Oshri et al., 2018; Ramírez et al., 2015; Baik et al., 2019; Scarpa et al., 2008). This effect might be explained by the moderation of the relationship between impulsiveness and adaptation of control mechanisms to external demands, potentially reducing the emergence of inappropriate behaviors.

Impulsive behaviors might result from the absence of control mechanisms adaptation, potentially explained by a weaker alarm signal that informs of the need to adapt. As higher HRV improves the adaptation of control mechanisms in high impulsive individuals (see Chapter 9.1), I hypothesized that high HRV might increase the activity of the monitoring system (i.e., the alarm system). Using the data collected during the Study IV, I hypothesized that high aggressive individuals with high HRV would have higher ERN/Ne amplitudes than low aggressive individuals with low HRV.

Method

The EEG data processed for the study IV (see Chapter 8.1) was used for this analysis. The only novelty in the method relates to the ECG processing to measure heart rate variability (HRV). A homemade algorithm was used to detect visually R peak of the QRS complex within each heartbeat time series obtained with the best of the electrical signal recorded from the two electrodes placed on the left hand (see Appendix .2). The heartbeat period was then calculated as the time difference between consecutive R peaks, known as the RR interval. The standard deviations of the RR intervals was calculated (i.e., SDNN) and used as an index of HRV. Personality groups were created using the median-split method on the global BPAQ scores. The HRV groups were created using the median-split of the SDNN distribution. An ANOVA was performed on the negativities amplitudes with Personality and HRV as between-subject factors and Response Type (Pure-correct, Partial-error and Full-error) and Congruency (Congruent and Incongruent) as within-subject factors.

Results

Table 9.1 – Sample sizes of groups crossing the BPAQ scores and the HRV.

	Low HRV	High HRV
Low BPAQ	6	6
High BPAQ	7	5

The main effects of Personality and Response Type already reported in the Study IV (see Chapter 8.1) were replicated in this analysis. The ANOVA revealed no main effect of HRV on the ERN/Ne amplitudes, $F(1{,}126) = 0.24$, $p = .627$, $\eta^2 < 0.01$. However, the ANOVA revealed a close-to-significant interaction effect between Aggressiveness and HRV on ERN/Ne amplitudes, $F(1{,}126) = 2.78$, $p = .098$, $\eta^2 = 0.02$. Figure 9.4 represents the EEG traces and their corresponding topographies.

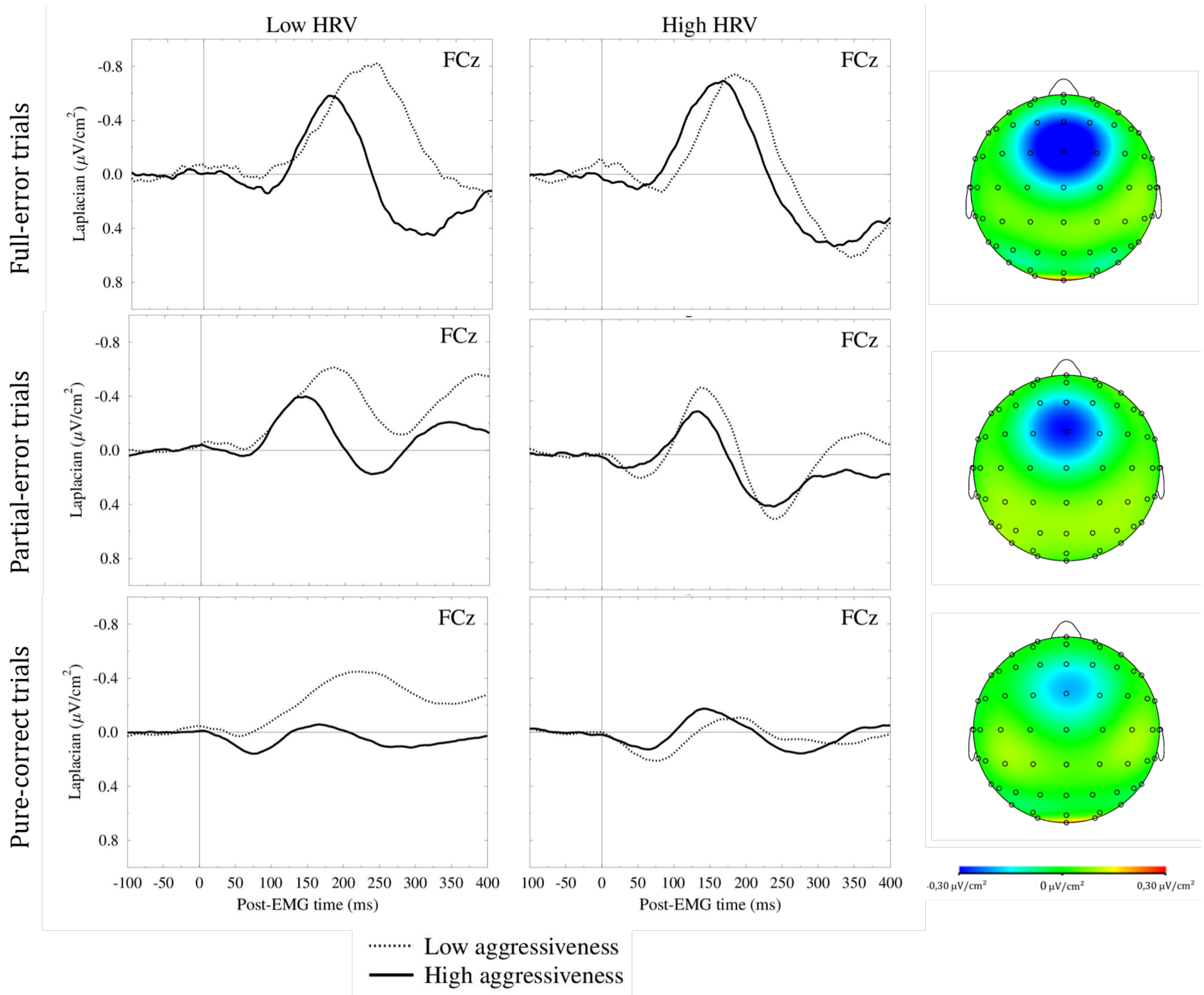

Figure 9.4 – **The Laplacian transformed ERN/Ne (FCz electrode) and the corresponding Laplacian topographies** measured in the full-error (top panel), in the partial-error (middle panel) and in the pure-correct responses (bottom panel) observed in the low HRV group (left column) and in the high HRV group (middle column). Continuous lines and dotted lines represent the results obtained in the high and the low aggressiveness groups, respectively. Signals were locked to the EMG onset of the motor response. The topographical maps (right column) show a top/horizontal view of the scalp (nose up) with the actual distribution of the Laplacian-transformed EEG data, separately for each response type.

Discussion

The activity of the monitoring system is reduced in individuals with aggressive tendencies (e.g., Grisetto et al., 2019) and these aggressive tendencies are decreased in individuals with high HRV (Scarpa, Haden, & Tanaka, 2010; Scarpa et al., 2008). However, little is known about the interaction of these two individual characteristics on the activity of the monitoring system. The current analysis aimed to fill this gap by investigating the interaction of aggressiveness and HRV on the activity of the monitoring system.

Higher HRV did not systematically and directly improve the activity of the monitoring system, but seems to moderated the effects of high self-reported aggressiveness. The aggressiveness-related reduction in ERN/Ne amplitudes may only be visible in the low HRV group. High HRV seems to normalize the activity of the monitoring system by reducing the amplitude difference between high and low aggressive individuals. To our knowledge, this is the first study that shows a moderating influence of heart rate variability on cognitive monitoring abilities. However, these results have to be taken with caution. Sample sizes were small in our sample when crossing the BPAQ and the HRV groups (see Table 9.1) and the result failed to reach statistical significance threshold.

Conclusion of the fifth experimental axis

Several studies showed that at-risk individuals with high HRV show less impulsive behaviors and psychiatric symptoms than at-risk individuals with low HRV (e.g., Scarpa et al., 2008; Oshri et al., 2018; Ramírez et al., 2015; Baik et al., 2019). The current findings bring food for thoughts to explain the moderation effect of high HRV on the relationship between impulsive-related personality traits and impulsive behaviors. Indeed, high impulsiveness was less associated with smaller adaptation of control mechanisms when the HRV was high (see Chapter 9.1). Also, the effect of aggressiveness on the activity of the monitoring system was reduced in individuals with high HRV (see Chapter 9.2). Postulating that impulsive behaviors result from maladaptive control mechanisms, these findings suggest that higher HRV reduces the emergence of impulsive behaviors in at-risk individuals through the improvement of the capacity to adapt control mechanisms, potentially explained by the normalization of the "alarm system" (i.e., the activity of the monitoring system). These findings are discussed in Chapter 13.2 in regards to existing HRV-based therapeutic interventions. Indeed, increasing HRV in impulsive individuals is an interesting therapeutic target to reduce, or even prevent, impulsive manifestations, and to reduce the social negative outcomes associated with these behaviors. However, it is important to note that the reported findings are only preliminary results and has to be taken with caution as some statistical limitations can be raised. Further studies are needed to confirm the relationship between HRV and the capacity to adapt control mechanisms, in larger sample and with other indices of HRV (e.g., RMSSD, HF-HRV, see Shaffer & Ginsberg, 2017, for different metrics).

Part IV

General discussion

Chapter 10

Main findings of my thesis

Impulsivity encompasses different behavioral patterns (i.e., impulsive behaviors) and a large range of personality traits (i.e., impulsiveness) that can be observed in the general population. Impulsivity is also an important concept in clinical work as it is a key component of several psychiatric disorders. Impulsive manifestations among other criterion support the diagnosis of several psychiatric disorders (e.g., ADHD, substance use, personality disorders), and high impulsivity is a vulnerability factor for the emergence of such disorders. Several studies have indeed reported that high impulsive individuals had more risk of developing psychiatric disorders, such as substance use (e.g., Granö et al., 2004; Stautz et al., 2016; Rømer Thomsen et al., 2018), depression (e.g., Granö et al., 2007) and personality disorders (e.g., Fossati et al., 2004). My PhD project is anchored in the field that searches to gain a better understanding of this vulnerability aspect of impulsivity. Previous research focused on inhibition to understand the lack of control over impulses. However, "*impulsivity consists of more than one dimension of control*" (Buss & Plomin, 1975) and inhibition is only one of the many dimensions. Therefore, during my PhD I investigated impulsivity through the angle of the cognitive control system, and more particularly through the dual-mechanisms of control framework (Braver, 2012).

The cognitive control system adjusts behaviors to a constantly changing environment, to avoid the emergence of inappropriate behaviors and to reduce their potentially negative outcomes. An efficient cognitive control system has been reported to moderate the relationship between impulsiveness and impulsive behaviors (e.g., Youssef et al., 2016; Robinson et al., 2009). Broadly viewed, the efficiency in cognitive control seems to prevent impulsive-related behaviors from emerging in high impulsive individuals. In the above cited studies, the efficiency was assessed through behavioral indices that are thought to reflect efficient control processes (e.g., congruency effect, error rates, post-error slowing). However, these indices do not provide information on the functioning of the cognitive control system. As discussed in Chapter 3, the efficiency of the cognitive control system can be investigating at the capacity level, but also at the mechanism level.

Two complementary but independent control mechanisms are implemented to adjust behaviors: the proactive and the reactive control (see Chapter 2.2). One mechanism dominates over the other as a function of external and internal demands, to reduce cost while preserving the efficiency of the cognitive control system. Therefore, the implementation of the optimal control mechanism for the current situation is crucial for adaptive behaviors. However, to the best of my knowledge, the capacity to adapt control mechanisms to external and internal demands has not been investigated in relation to impulsivity. Therefore, during my PhD I used the dual mechanisms of control framework proposed by Braver (2012) to gain a better understanding of control mechanisms that provides the possibility to adapt behavior to external and internal demands in impulsive individuals from the general population. I postulated that high impulsivity would be associated with weaker adaptation to external demands (see Studies I and II, Chapters 5.1 and 6.1, respectively) or to internal demands (see Study III, Chapter 7.1). As proactive and reactive control mechanisms involvement are triggered through the detection of a conflict (De Pisapia & Braver, 2006), I studied the efficiency in the monitoring system through the investigation of the ERN/Ne component (see Study IV, Chapter 8.1).

At behavioral level, the findings of the present thesis revealed that impulsivity was associated with difficulty in adapting control mechanisms to external and internal demands. More specifically, high impulsive individuals did not rely on proactive control as much as low impulsive individuals when this control mechanism was optimal for the current task demands (see Study I, Chapter 5.1) and for compensating poor reactive cognitive capacities (see Study III, Chapter 7.1). High impulsive individuals were less proactive than low impulsive individuals during an AX-CPT task (see Study I, Chapter 5.1) consistently with previous results in pathological populations (see Table 3.1). However, this effect was driven by the slow (or the absence of) adaptation of control mechanisms to task demands. Also, high impulsive individuals did not adjust proactive behavioral adjustments as a function of an internal demand, assessed by their behavioral inhibition capacities (see Study III, Chapter 7.1). This first set of findings suggests that impulsiveness could be defined as a less-dominant proactive control system that may lead to impulsive behaviors when the use of control mechanisms is no longer adapted to context demands. These results are discussed in Chapter 11.

Electroencephalographic (EEG) activities were recorded both in Studies I and IV. Results showed that the activity of the monitoring system was globally reduced in high aggressive individuals, but not in high impulsive individuals (see Study IV, Chapter 8.1). These findings are consistent with the interpretation of previous literature results: the decrease in the activity of the monitoring system is observed in relation to impulsive behaviors only (see Chapter 3.1.1). Therefore, I postulated that the decrease in the monitoring activity could correlate with the adaptation of control mechanism. Smaller ERN/Ne amplitudes failed to predict weaker adaptation during the AX-CPT, but were associated with larger proactive behavioral index in the last block (see Chapter 8.3). These results are discussed in Chapter 12.2.

Finally, electrocardiographic (ECG) signals were analyzed in Study I and Study IV to investigate the relationship between heart rate variability (HRV) and the capacity to adapt the use of control mechanisms to external and internal demands. Indeed, the HRV has previously been reported to moderate the relationship between impulsiveness and impulsive behaviors. The findings suggested that high HRV moderates the effect of impulsiveness on the adaptation of control mechanisms to external and internal demands. The higher the HRV, the smaller was the association between impulsiveness and adaptation of control during the AX-CPT task (see Chapter 9.1). Moreover, high HRV normalized the activity of the monitoring system in high aggressive individuals (see Chapter 9.2). These results are discussed in Chapter 13.

Chapter 11

Impulsivity and the adaptation of control mechanisms

The dual mechanisms of control theory (Braver, 2012) postulates the existence of two control mechanisms: reactive and proactive control. On the one hand, proactive control is defined as a goal-driven preparatory attentional bias and selection of the goal-relevant information to facilitate the resolution of future conflicts. On the other hand, reactive control refers to a stimulus-driven late correction of an ongoing interference after its onset. These mechanisms are complementary and independent as they can be both simultaneously engaged to resolve conflicts (Mäki-Marttunen et al., 2019a). However, one mechanism always dominates over the other as a function of external (e.g., motivational context or cognitive load of the task, Hefer & Dreisbach, 2016; Mäki-Marttunen et al., 2019b, respectively) and internal demands (e.g., working memory capacity or age, Richmond et al., 2015; Paxton et al., 2008, respectively). External and internal demands impact the costs of control mechanisms (e.g., high working memory capacities reduce the cost of proactive control by facilitating the active maintenance of goal-relevant information) and thus, drive the dominant use of one mechanism over the other. Though costly, proactive control is thus favored in unpredictable and complex environments to optimize behaviors (Criaud et al., 2012; Mäki-Marttunen et al., 2019b). In predictable and less complex environments, the reactive control mechanism, although more fragile (i.e., more sensitive to distractors), is favored to minimize the costs of the cognitive control system. The flexible use of proactive and reactive control mechanisms as a function of external and internal demands is a key feature for adaptive behaviors (Braver, 2012). Previously, impulsivity was studied through the capacities of reactive and proactive control mechanisms, but the flexible adaptation in the use of the two control mechanisms was less investigated. During my PhD, I investigated the adaptation of control mechanisms in relation to impulsivity. This work was conducted both in the general population (see Studies I and III, Chapters 5.1 and 7.1) and in a pathological population, namely an alcohol-dependent population (see Study II, Chapter 6.1).

Findings from the first study of this thesis revealed that impulsiveness was associated with a smaller proactive behavioral index (PBI, see Study I, Chapter 5.1). This finding is consistent with the pattern reported in pathological populations, showing a smaller PBI in various impulsive-related populations (cf. Table 3.1). Higher impulsiveness is characterized by a less proactive cognitive control system, potentially explaining the tendency to act on impulses. Indeed, a weaker dominance of proactive control makes the cognitive control system more sensitive to goal-irrelevant information. Thus, an impulsive individual more often reacts upon them resulting in impulsive behaviors (e.g., higher rates of engaged errors, see Chapter 5.2). This definition of impulsiveness as a less proactive cognitive control is consistent with Strack and Deutsch (2003) who defines it as *"an association between a stimulus and a behavioral schema, to emerge automatically and to require very little cognitive resources"*. However, a sharp analysis of the PBI showed that this interpretation is not totally straightforward. Indeed, the difference in PBI observed between high and low impulsive individuals was mostly driven by the slower (or the absence of) adaptation of control mechanisms to task demands over time (see Study I, Chapter 5.1 and Figure 5.4). The use of proactive control is optimal to perform the AX-CPT task. It is more helpful to use contextual information (i.e., the cue-letter) to prepare a response than to wait and react to the probe-letter. Indeed, the occurrence of the target (i.e., the probe-letter X) is often predicted by the cue-letter A. In the Study I (see Chapter 5.1), the observed difference between high and low impulsive individuals grew over time as high impulsive individuals adapted less their cognitive control system to task demands. More specifically, they use less proactive control when it was required by external demands. Surprisingly, these results were not replicated in the pathological population (see Study II, Chapter 6.1). Alcohol-dependent patients did not differ from the matched control group in the dominance of proactive control nor in its adaptation to task demands. However, as discussed in Chapter 6.1, this lack of result may be explained by the differences in age or by the more explicit experimental instructions. Nonetheless in the Study II, I replicated the effect of high impulsiveness on the adaptation of control mechanisms: individuals that did not adapt were more impulsive than participants who did adapt. Thus, the results of both studies suggest that impulsiveness is associated with the adaptation of the use of proactive control mechanisms to external demands.

As adaptive behaviors rely on the flexible use of proactive and reactive control as a function of both external and internal demands, I also investigated the capacity to adapt control mechanisms to internal demands (see Study III, Chapter 7.1). Redick (2014) and Richmond et al. (2015) showed that efficient working memory capacities favored the use of proactive mechanisms. Proactive control relies on the active maintenance of goal-relevant information and is thus less costly for individuals with efficient working memory. Similarly, I hypothesized in the third study that poor behavioral inhibition capacities on which relies reactive control would be associated with stronger post-error slowing, an index of the efficiency of the proactive control mechanisms (see Chapter 3.1). Similarly to the facilitation of proactive control with efficient working memory, poorer reactive control capacities should favor the use of proactive control. Also, if impulsiveness decreases the capacity to adapt control mechanisms to internal demands, I expected that this "compensation" strategy would not be observed in high impulsive individuals. The findings of the third study confirmed this hypothesis (see Study III, Chapter 7.1). Higher the risk-taking propensity, smaller were the proactive behavioral adjustments as a function of the behavioral inhibition capacities. High impulsive individuals used less proactive control, even when their reactive-related cognitive capacity is limited. Overall, impulsive individuals were characterized by a less-proactive cognitive control system and a weaker adaptation of control mechanisms to both external and internal demands.

Impulsivity is a key feature of several psychiatric disorders which compose the externalizing spectrum (Beauchaine et al., 2017), which is characterized by abnormal behaviors that are directed toward the external environment (e.g., aggression, stealing, substance abuse). It is classically opposed to the internalizing spectrum, which is characterized by negative affectivity and encompasses disorders such as depression, anxiety or obsessive-compulsive disorders. This opposition opens new avenues for research. Indeed, if a key feature of the externalizing spectrum is defined as a less-proactive cognitive control system, we can postulate that disorders in the internalizing spectrum could be defined as a too-proactive cognitive control system. On the one hand, the less-proactive control system in externalizing disorders leads to a decrease in the cognitive cost, at the expense of the efficiency of impulse control and thus, impulsive behaviors would emerge under certain situations only. On the other hand, a too-proactive control system in internalizing disorders would lead to a higher robustness over distractors at the expense of flexibility (Del Giudice & Crespi, 2018), leading to rigid and over-controlled behaviors. Recently, Hogeveen, Krug, Elliott, Carter, and Solomon (2018) reported that an increased reliance on proactive control was associated with more compulsive behaviors in children with autism spectrum disorder. Hallion, Tolin, and Diefenbach (2019) observed enhanced proactive control in generalized anxiety disorder (GAD) patients. The proactive behavioral index calculated on the basis of the reported reaction times was larger in the GAD population (PBI = 0.23) than that observed in non-GAD subjects (PBI = 0.17).

Throughout the following discussion, I will postulate that my findings revealed an effect of impulsivity on the capacity to adapt control mechanisms. However, it is important to note that other hypotheses can be drawn. First, one can argue that the differences between high and low impulsive individuals reported in my work are more associated with motivational than with capacity differences. Indeed, high impulsive individuals could be less prompt to engage costly proactive control mechanisms in a non-motivational context compared to low impulsive individuals. Investigating the performance differences between high and low motivational contexts could distinguish the capacity to adapt from the intent to do so. Secondly, it would be interesting to more specifically assess the effect of instructions on the use of control mechanisms during the AX-CPT task. Indeed as discussed in Chapter 6.1, the formulation of the instructions could more or less explicitly set the cognitive control system to the optimal mode. It was shown that a session of training with explicit instructions (e.g., participants were told to prepare a response with cue-A and not cue-B) induces an increase in the use of proactive control in young healthy adults (Gonthier et al., 2016) and in patients with schizophrenia (Edwards, Barch, & Braver, 2010). Hence, the performance differences with implicit and explicit AX-CPT instructions could distinguish impairments in prompted and spontaneous adaptation of control mechanisms in impulsive individuals. Nevertheless, my PhD findings provide empirical elements in favor of a weaker use of proactive control in high impulsive individuals when required by external and/or internal demands, that may underlie the emergence of impulsive behaviors and/or psychiatric disorders.

In the following chapter, I will consider several hypotheses to explain this lack of control mechanisms adaptation that are based on both results from my PhD research work and from previous literature.

Chapter 12

Explaining the lack of adaptation of control mechanisms

The first three studies of my PhD research suggest that high impulsivity is associated with a weaker flexible use of proactive control as a function of external and internal demands, resulting in a less adapted cognitive control system under some situations and potentially in maladaptive behaviors (see Chapter 11). Impulsive individuals showed difficulties in exerting proactive control mechanisms when required by the task or their cognitive capacities. As this lack of adaptation could explain impulsive manifestations, it is crucial to understand its causal mechanisms to orient therapeutic choices in the care of impulsive individuals. However, it is unclear how to explain the lack of adaptation of control mechanisms. Three hypotheses discussed in the following sections can be drawn based on results of the present thesis:

— **Shifting capacities hypothesis** (cf. Figure 12.1B). The lack of adaptation of control mechanisms is caused by an impairment in shifting capacities.

— **Working memory capacities hypothesis** (cf. Figure 12.1C). The lack of adaptation of control mechanisms is driven by poorer working memory capacities, limiting the use of proactive control.

— **Monitoring reduction hypothesis** (cf. Figure 12.1D). The lack of adaptation of control mechanisms is explained by a weaker alarm signal to adjust control mechanisms to the demands.

All the aforementioned hypotheses explain the lack of adaptation of control mechanisms by targeting distinct cognitive processes. I will describe and review the literature for each hypothesis, but will not argue in favor of one specific hypothesis. Indeed, I postulate that the three hypotheses might define different impulsive profiles and support inter-individual differences in treatment outcomes.

12.1 Executive functions impairments

As suggested by the results of my PhD research, the shift toward proactive control is affected by high impulsivity. A preliminary result reported in Chapter 5.2 suggested a role of behavioral inhibition capacities in this shift. Indeed, we observed that the relationship between high impulsiveness and the proactive behavioral index during the AX-CPT was moderated by the capacity to correct an engaged error in the Simon task (i.e., the correction ratio, which is the proportion of engaged errors that were successfully corrected, see Chapter 3.1.2 for a detailed description of this index). The higher the correction ratio revealing great behavioral inhibition capacities, the smaller was the association between impulsiveness and proactive behavioral index (see Chapter 5.2). Interestingly, according to Miyake and Friedman (2012), inhibition is associated with the efficiency in the other two executive functions, namely shifting and working memory. The shifting refers to the ability to flexibly shift task and mental sets (e.g. shifting between two tasks instructions - Miyake & Friedman, 2012). Working memory, referred to as "*updating*" in the Miyake and Friedman (2012)'s model, corresponds to the maintenance and processing of information in memory. Both executive functions are required in the dual mechanisms of cognitive control (Braver, 2012). Indeed, shifting capacities may be involved in the shift between reactive and proactive control mechanisms. Also, working memory capacities are involved in the active maintenance of goal-relevant information underlying proactive control. Therefore, the moderator effect of inhibition on the relationship between impulsiveness and the dominance of proactive control reported in Chapter 5.2 might be indirectly associated with working memory and/or shifting capacities. Reviews of the literature between impulsivity and these executive functions are discussed in the following sections to further explore these hypotheses (see Figures 12.1B and 12.1C).

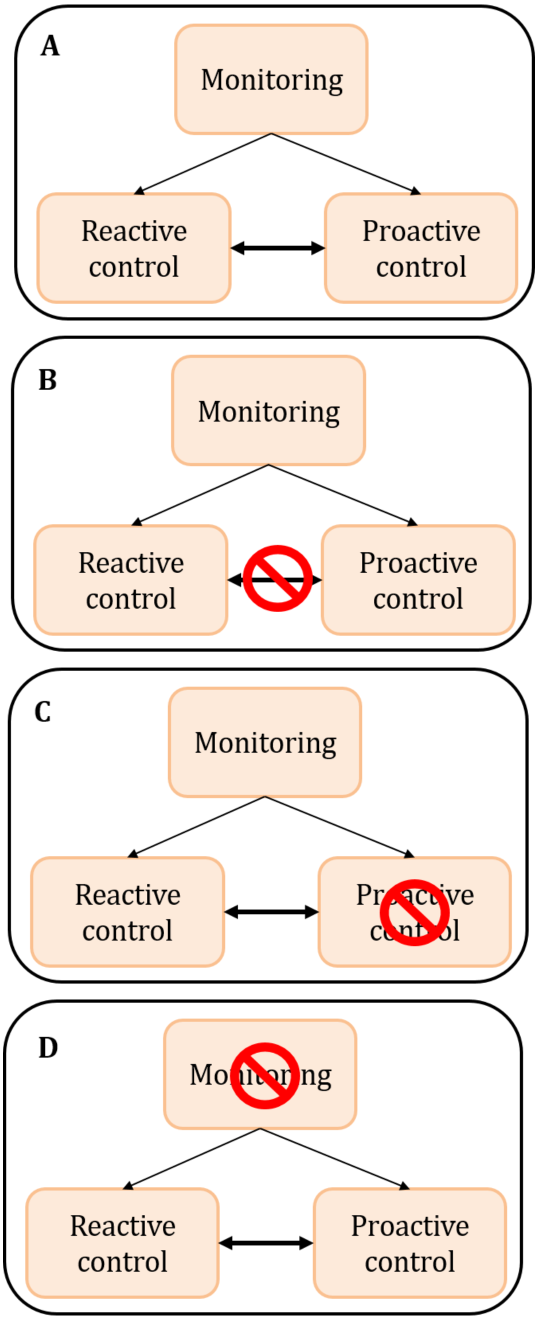

Figure 12.1 – **Schematic representations of the cognitive control system under the three hypotheses to explain the lack of adaptation of control mechanisms in impulsive individuals.** **(A)** Normal functioning of the cognitive control system. The monitoring system triggers reactive and proactive behavioral adjustments as a function of conflict levels. **(B)** Representation of the *shifting capacities hypothesis*. Within this alternative, the lack of adaptation of control mechanisms is explained by shifting impairments.**(C)** Representation of the *working memory capacities hypothesis*. Within this alternative, the lack of adaptation of control mechanisms is explained by working memory impairments. **(D)** Representation of the *monitoring reduction hypothesis*. Within this alternative, the lack of adaptation of control mechanisms is explained by a reduced alarm signal to trigger the shift toward proactive control.

The shifting capacities hypothesis

In the *shifting capacities hypothesis*, difficulties in exerting proactive control rely on a default in the adaptation of control mechanisms *per se* through an impairment in shifting (cf. Figure 12.1B). The ability to shift between task and mental sets can be assessed in paradigms such as card-sorting tasks (e.g., Wisconsin or the Delis-Kaplan Card Sorting Tests, WCST, DKCST - Grant & Berg, 1948; Delis, Kaplan, & Kramer, 2001, respectively). In these tasks, participants are asked to match a target card with four stimulus cards. Matching rules are unknown to the participants, and they must generate them. Once generated, they must shift from one mapping rule to another when the experimenter tells them the match is wrong. It is possible to infer that shifting capacities are crucial in the adaptation of control mechanisms when the environment changes (or when an error is committed).

In substance users, Colzato, Ruiz, Wildenberg, and Hommel (2011) and Dolan, Bechara, and Nathan (2008) reported shifting impairments compared to that observed in control participants (i.e., increased error rates). Impairments were more severe when there was a family history of addiction (Dolan et al., 2008). In abstinent alcohol-dependent patients, no matter the length of abstinence, patients committed more perseveration errors in the WCST compared to controls (Salgado et al., 2009). In the general population, both self-reported attentional and motor impulsiveness, but not non-planification impulsiveness (BIS-11 questionnaire, Patton et al., 1995), correlated with the performance in a shifting task when controlling for age and education (Keilp, Sackeim, & Mann, 2005). Finally, Sharma et al. (2014) suggested that shifting impairments, revealed through perseveration errors, is a distinct impulsive behavior in the factorial structure of impulsivity, like impulsive motor action or impulsive decision-making.

Not much is known about the shifting capacities in impulsive-related populations. Substance users seem to be the most studied population. Therefore, one cannot conclude whether the impaired shifting observed in these populations is a determinant or a cause of substance use. Also, one can question whether the shifting assessed through card-sorting tests or other classical shifting tasks is similar to the shifting required in the flexible adaptation between reactive and proactive control mechanisms. In the De Pisapia and Braver (2006)'s model, the increase in proactive control involvement is progressive with the increase in the computed average conflict (see Chapter 2.2) whereas the shift between two tasks instructions is more abrupt.

The working memory capacities hypothesis

In the *working memory capacities hypothesis*, I postulate that difficulties in exerting proactive control are not related to a default in the adaptation of control mechanism *per se*, but are due to poorer working memory capacities (cf. Figure 12.1C). Indeed, proactive control requires the active maintenance of goal-relevant information (Braver, 2012) and thus, is supported by cognitive capacities such as working memory. Notably, low working memory capacities are associated with a shift toward reactive control (Redick, 2014; Richmond et al., 2015). Within this hypothesis, the weaker adaptation of control mechanisms in situations requiring proactive control is due to the limitations or impairments in a cognitive function supporting proactive control.

Lazzaretti et al. (2012) observed impaired working memory (WM) capacities in borderline personality disorder patients compared to controls, suggesting that WM capacities are associated with impulsive-related psychiatric states. Similarly, the WM capacities have been reported to predict the frequency and the quantity of alcohol use (Khurana et al., 2013; Baines, 2019). Conversely, Ellingson, Fleming, Vergés, Bartholow, and Sher (2014) did not report a direct effect of WM capacities on alcohol use disorder (AUD). However, the WM capacities moderated the relationship between impulsiveness and AUD. Specifically, poor working memory reinforces the link between impulsiveness and AUD (Finn, 2002; Finn & Hall, 2004; Gunn & Finn, 2013; Ellingson et al., 2014). Moreover, when accounting for working memory capacities, Raiker, Rapport, Kofler, and Sarver (2012) observe an absence of differences in impulsive behaviors (i.e., error rates in the CPT task) when comparing ADHD children and paired-matched controls, suggesting that WM impairments accounted for the impulsive behaviors observed in ADHD patients. Additionally in methamphetamine users, a WM training improved the control of impulses (Brooks et al., 2017). However, it is important to note that other studies failed to replicate these conclusive results. Notably, Wardell, Quilty, and Hendershot (2016) failed to replicate the moderator effect of working memory capacity on the association between impulsiveness and impulsive behaviors. In the same way, Wanmaker et al. (2018) failed to report the efficiency of a 24-session of WM training on craving, substance use or impulsivity in a substance-use disorder group.

In conclusion, poor WM capacities are sometimes associated with, and account for, the emergence of impulsive behaviors (e.g., Khurana et al., 2013; Raiker et al., 2012) or mediate the relationship between impulsiveness and impulsive behaviors (Finn, 2002; Finn & Hall, 2004; Gunn & Finn, 2013; Ellingson et al., 2014). However, future studies are required to fully support the *working memory capacities hypothesis*.

12.2 Reduced activity in the monitoring system

Both in the *shifting capacities* and in the *working memory capacities* hypotheses, I postulate that the capacity to adapt control mechanisms solely relies on the efficiency of executive functioning. However, the adaptation requires a signal to inform the system that the actual setting of control mechanisms is no longer the most optimal. Prior to the triggering of the adaptation of control mechanisms, impulsive individuals may be impaired in creating and using the alarm signal.

Both in Botvinick et al. (2001) and De Pisapia and Braver (2006)'s models, the conflict layers are essential for the triggering of behavioral adjustments. More particularly, De Pisapia and Braver (2006) postulated that the conflict layer was able to anticipate the need of control (Alexander & Brown, 2010), through the activation of a long-time scale conflict unit that computes an average of all conflicts detected. Therefore, one hypothesis to explain the lack of adaptation toward proactive control mechanisms in impulsive individuals could be an impaired activation of the long-time scale conflict unit, or more broadly an impaired activation of the monitoring system (cf. Figure 12.1D). In Chapter 3.1.1, I described studies that led to the interpretation of the error(-related) negativity (ERN/Ne) less as an index of error detection (Falkenstein et al., 1991; Gehring & Fencsik,

2001) than as an index of conflict monitoring (Carter et al., 1998) and of a global alarm for the need for control (Burle et al., 2008; Vidal, Burle, & Hasbroucq, 2020). Within this view, a reduced ERN/Ne amplitude would reflect that the cognitive control system is less "aware" of the need for control behavior.

Reduced ERN/Ne amplitudes are often reported in impulsive pathological populations (e.g., borderline personality disorder, ADHD or schizophrenia, de Bruijn et al., 2006; Liotti et al., 2005; Mathalon et al., 2002, respectively). Interestingly, Gorka et al. (2019) reported a reduction in the ERN/Ne amplitudes in the current alcohol use disorder (AUD) group only (i.e., no reduction in the remission and at-risk AUD groups). Moreover, to the best of my knowledge, the reduced ERN/Ne amplitudes in impulsive individuals in the general population was only observed when impulsivity was assessed by a behavioral index (i.e., error speed - Ruchsow et al., 2005) or by the tendency to act impulsively (i.e., urgency and motor impulsiveness subscales - Hill et al., 2016; Taylor et al., 2018, respectively). Global impulsiveness failed to be correlated with ERN/Ne amplitudes (e.g., Potts et al., 2006; Luu et al., 2000). Similarly, in the Study IV (see Chapter 8.1), we failed to show an effect of global impulsiveness but observed an effect of aggressiveness. Coupled with previous literature, these findings suggest that impulsiveness is not sufficient to affect the monitoring system, whereas impulse-related behaviors are associated with a reduction in the control monitoring activity. If the cognitive control system is less aware of the need to control and/or adapt control mechanisms, then impulsive behaviors may emerge.

As our findings lead to the hypothesis that impulsive behaviors occur when the control mechanism is not adapted to external and internal demands, I hypothesized that it might exist a relationship between the capacity to adapt control mechanisms and ERN/Ne amplitudes (see Chapter 8.3). I expected that higher the ERN/Ne amplitudes (i.e., stronger the alarm signalling the need for control), stronger the adaptation of control mechanisms to task demands. We failed to observe a significant effect. However, methodological limitations were raised to explain the lack of results (see Chapter 8.3). Most importantly, I observed that the PBI in the last block was positively correlated with the ERN/Ne amplitudes. Higher the dominance of the proactive control at the end of the task, smaller the ERN/Ne amplitudes. This finding was consistent with the perspective of Burle et al. (2008) on the significance of ERN/Ne component as an alarm signal. Further studies investigating the relationship between the ERN/Ne component and the adaptation of control mechanisms, should use two separated tasks: one to compute a reliable ERN/Ne component (i.e., increased error rates) and one task to assess the capacity to shift to proactive control mechanisms (i.e. the AX-CPT).

In conclusion, there is still no clear consensus on the significance of the ERN/Ne component within the cognitive control system. It is broadly defined as an internal alarm signal for the need for control (Vidal et al., 2020) but seems to have no direct involvement in behavioral adjustments nor a role in the adaptation of the control mechanisms (see Chapter 8.3). For this latter research question, further studies are needed.

Three hypotheses were proposed to explain the lack of adaptation of control mechanisms with high impulsivity. Each one of these hypotheses should be tested individually and in different impulsive-related pathological populations. Indeed, it appears likely that different populations are characterized by different causal processes to explain the lack of adaptation. Investigating the differences in the causal processes would lead to personalized and improved treatment and open the avenue to new remediation pathways.

Chapter 13

Improving adaptive control

The main goal of my PhD was to identify in the general population the effects of impulsivity on the cognitive control system, to gain a better understanding of the impulsive-related vulnerability factor for psychiatric disorders. This PhD research demonstrated that impulsivity in individuals from the general population was associated with weaker adaptation of control mechanisms to external and internal demands. More specifically, I observed that impulsive individuals less exert proactive control when it is optimal to respond to external demands or to compensate for internal constraints. The capacity to exert proactive control when required could be clinically relevant to identify at-risk individuals, but also to think of new therapeutic interventions to reduce or even prevent the emergence of impulsive behaviors. In the preceding chapter, I hypothesized different processes underlying the lack of adaptation of control mechanisms. According to these hypotheses, both the executive functioning and the activity of the monitoring system could be targeted to improve the capacity to adapt control mechanisms.

13.1 Targeting executive functions

In the preceding chapter, I suggested that executive impairments in shifting and working memory capacities could explain the lack of adaptation of control mechanisms toward proactive control. I based these hypotheses on the effect of inhibition capacities on the relation between impulsiveness and the proactive behavioral index reported in the Chapter 5.2. Therefore, executive functions (EFs) training could improve the adaptation toward the use of proactive control in impulsive individuals. Consistently, EF training programs showed promising results in the reduction in impulsive manifestations.

Inhibition is the first targeted executive function in cognitive training in impulsive populations. Improving response inhibition capacities was reported to reduce impulsive manifestations in children (Kavianpour, Malekpour, & A'bedi, 2013), young adults (Houben & Jansen, 2011) and in binge-eating disorders (Giel, Speer, Schag, Leehr, & Zipfel, 2017). ImpulsE, a program training that focuses on inhibitory control and emotion regulation abilities, showed positive effects on the frequency of overeating periods (Preuss, Pinnow, Schnicker, & Legenbauer, 2017). However, both Preuss et al. (2017) and Giel et al. (2017) revealed an absence of effects of cognitive training on impulsiveness, food addiction and craving. As already reported in Chapter 12.1, working memory (WM) training also showed interesting results on impulsive behaviors in substance use disorders (e.g., Brooks et al., 2017; Khemiri, Brynte, Stunkel, Klingberg, & Jayaram-Lindström, 2019) and in ADHD children (e.g., Mezzacappa & Buckner, 2010; Stevens, Gaynor, Bessette, & Pearlson, 2016). Similarly, WM training reduces impulsive choices during a Delay Discounting task in substance users (Bickel, Yi, Landes, Hill, & Baxter, 2011). Other studies failed to replicate the positive effect of WM training on impulsivity in substance users (Wanmaker et al., 2018). However, as I discussed in the previous chapter, various cognitive processes can explain the absence of adaptive control and thus, the emergence of impulsive behaviors. Across populations and even across individuals, one intervention may not have similar effects. It is therefore crucial to identify the specific cognitive processes behind the lack of adaptation of control mechanisms, to personalize the interventions.

Some previous studies reported interesting and promising findings on the efficiency of EFs training on the reduction in impulsive behaviors, mostly in substance use disorder patients. Nonetheless, the last hypothesis to explain the lack of adaptive control still needs to be explored. Indeed, I hypothesized that the lack of adaptation toward proactive control could be explained by a weaker alarm signal from the monitoring system (see Chapter 12.2). Interestingly, one finding of my PhD research suggested that the heart rate variability (HRV) could be an interesting index to increase the activity of the monitoring system in impulsive-related populations.

13.2 Targeting the heart rate variability

The heart rate variability (HRV) is a physiological index of self-regulation ability of emotional, cognitive and behavioral processes (Mayer & Salovey, 1995; Thayer & Lane, 2000). Higher HRV was linked to better thought suppression (Gillie et al., 2015), better inhibition capacities (Ottaviani et al., 2018) and reduced maladaptive behaviors (e.g., Scarpa et al., 2010, 2008; Oshri et al., 2018; Ramírez et al., 2015). Consistently, low HRV is often reported in psychiatric populations (e.g., Koenig et al., 2016; Clamor et al., 2016) and is thought to be a physiological marker of psychopathology (Beauchaine & Thayer, 2015) like reduced ERN/Ne amplitudes are thought to be a neurophysiological marker for externalizing disorders (Olvet & Hajcak, 2008).

In Studies I and IV of the present thesis, I investigated the moderation role of the HRV on the relationship between impulsiveness and the cognitive control system. In these studies, I extracted ECG information (i.e., the heartbeats) from the EMG signals to calculate the SDNN (i.e., standard deviations in the RR intervals), an index of HRV. Both of these studies led me to postulate that a higher HRV may down regulate the negative impact of impulsiveness on the adaptation of control mechanisms (see Chapter 9.1), through the activity of the monitoring system activity (see Chapter 9.2). The combination of these two findings supported the hypothesis of the activity of the monitoring system as a signal of adaptation need. Indeed, high HRV increases the activity of the monitoring system (i.e., normalizes the activity of the alarm system), leading to a better adaptation of control mechanisms toward proactive control. By improving the adaptation of control mechanisms through the activity of the monitoring system, the increase in HRV may be a therapeutic target to reduce impulsive manifestations. Several interventions have already been reported to increase HRV. Indeed, a 6-week program of moderate physical activity (Davy, Desouza, Jones, & Seals, 1998) and HRV biofeedback (Lehrer, 2007; Shearer, Hunt, Chowdhury, & Nicol, 2016) were found to increase HRV. Interestingly, both physical activity and HRV biofeedback session reduced maladaptive behaviors such as aggression (e.g., Borders, Earleywine, & Jajodia, 2010; Wade, Smith, Duncan, & Lubans, 2018), craving (Eddie, Kim, Lehrer, Deneke, & Bates, 2014) and ADHD symptoms (Abramovitch, Goldzweig, & Schweiger, 2013; Verret, Guay, Berthiaume, Gardiner, & Béliveau, 2012; Smith et al., 2013). Mindfulness, another intervention that increases HRV (e.g., Mankus, Aldao, Kerns, Mayville, & Mennin, 2013; Krygier et al., 2013; Sun, Hu, Pan, Liu, & Huang, 2019), is particularly interesting for the scope of the current thesis.

Mindfulness is a meditation practice, defined as a non-judgemental attention to present-moment experiences (Tang, Hölzel, & Posner, 2015). In this practice, the attentional focus on the present moment and the increase in the awareness of all external and internal stimulation is learned. Mindfulness is associated with improved cognitive performance (Zeidan, Johnson, Diamond, David, & Goolkasian, 2010), with both better physical and psychological health (Prazak et al., 2012). Mindfulness has also positive effects on both impulsiveness and impulsive behaviors. Mindfulness training in substance users reduced their consumption, but also their psychiatric symptoms (Bowen et al., 2006). Regulation abilities in smokers were improved after a brief training in mindfulness, changes that were associated with an increase in ACC and PFC activities (Tang, Tang, & Posner, 2016). Soler et al. (2016) reported that mindfulness training can reduce impulsive choices in borderline personality disorder patients. In the general population, Mantzios and Giannou (2014) observed that impulsiveness, assessed using the BIS-11 questionnaire, decreased within six weeks with the practice of individual mindfulness sessions. In the same way, mindfulness training decreases impulsiveness and aggressiveness in adolescents with behavioral problems (Franco, Amutio, López-González, Oriol, & Martínez-Taboada, 2016).

The reduction in impulsivity with the increase in HRV in mindfulness individuals could be explained by greater adaptive control (Aguerre, Bajo, & Gómez-Ariza, 2020; Chang, Kuo, Huang, & Lin, 2018). Indeed, Chang et al. (2018) observed better reactive and proactive control performances in mindful individuals, increasing the flexibility between control mechanisms. Consistently, Aguerre et al. (2020) reported a more balanced use of proactive and reactive control in high mindfulness individuals compared to low mindfulness individuals. For these authors, learning to focus on the present moment allows to be less sensitive to contextual information and be more flexible in the way we use information (Aguerre et al., 2020). Consistent with the findings reported in the Chapter 9.1, mindfulness may improve the capacity to adapt control mechanisms through the increase in HRV.

In conclusion, the results reported in my thesis are consistent with those studies reporting positive effects on impulsivity of those interventions that induce an increase in HRV (e.g., physical activity, HRV biofeedback and mindfulness). Future studies should be developped to test directly the hypothesis that high HRV can improve the adaptive nature of the cognitive control mechanisms, potentially through the increase in the activity of the monitoring system leading to the reduction in maladaptive behaviors.

Chapter 14

General conclusion

Impulsivity is a key component in a large range of psychiatric disorders, both as a diagnostic factor and as a vulnerability factor. My PhD research aimed at providing original empirical results to gain a better understanding in the cognitive mechanisms underlying the impulsivity-related vulnerability for psychiatric disorders. In the long-term, my research work will strive to prevent the development of psychiatric disorders in the general population; it could in shorter timeline participate in improving the therapeutic interventions that intend to reduce impulsive behaviors in pathological populations.

In this aim, I investigated the relationships between impulsivity and the cognitive control system while monitoring brain activity and heart rate variability. I intended to identify the specific cognitive control process that could illustrate the moderation effect of cognitive control on impulsive behaviors, within the theoretical framework of the dual mechanisms of control (Braver, 2012).

The findings reported in this manuscript suggest that impulsivity in a general population is associated with a less-proactive cognitive control system, mostly explained by a weaker adaptation of control mechanisms to external and internal demands. In particular, my behavioral studies suggest that high impulsive individuals exert less proactive control when this control mechanism is optimal for the current situation. This weak flexibility to use proactive control when needed could explain the emergence of impulsive behaviors. The adaptation of cognitive control mechanisms to both external and internal demands mediates the relationship between impulsiveness and impulsive behaviors, and may therefore underlie the impulsivity-related vulnerability for psychiatric disorders (cf. Figure 14.1).

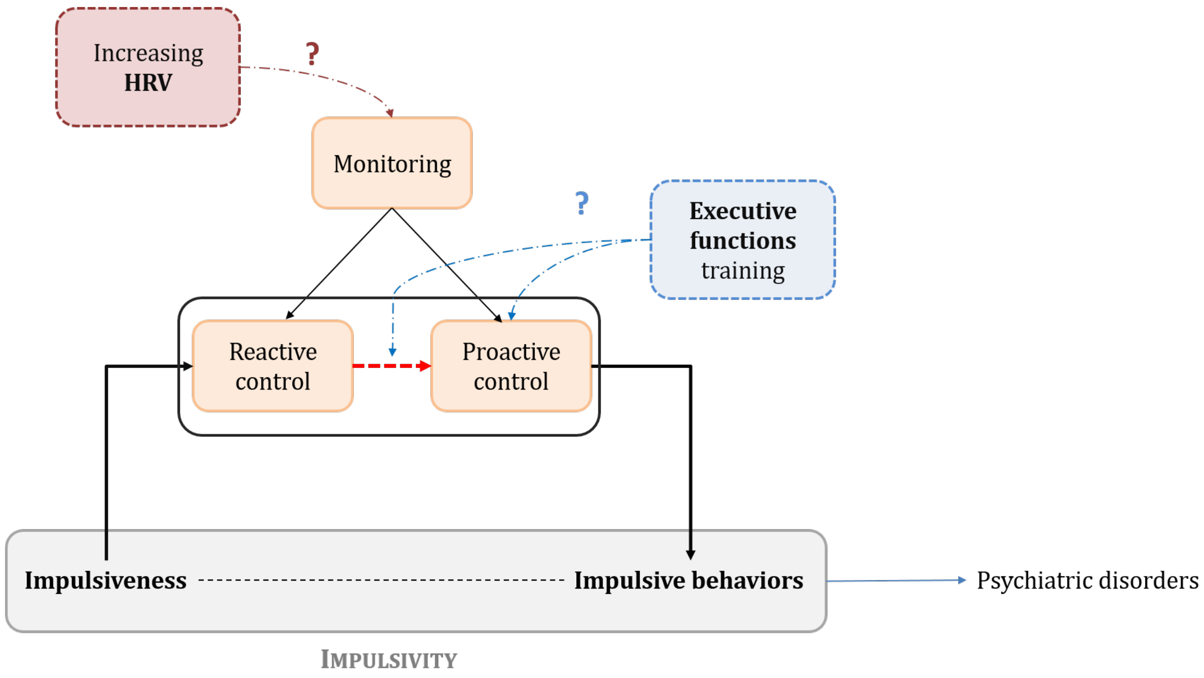

Figure 14.1 – **Schematic representation of the relationship between impulsiveness and impulsive behaviors through the capacity to adapt control mechanisms.** Impulsiveness is here defined as a less proactive-dominant cognitive control system. The lack of flexible use of proactive control when favored by external and internal demands may lead to impulsive behaviors. Executive functions training and HRV-based interventions are potential therapeutic targets to improve the deployment of proactive control when needed.

The capacity to adapt control mechanisms to external and internal demands is therefore an interesting clinical target to reduce impulsive manifestations, and potentially to prevent the development of a psychiatric disorder in the general population. However, as discussed in Chapter 12, the lack of adaptation toward the use of proactive mechanisms can be explained by different cognitive dysfunctions. In this thesis, I discussed three hypotheses for the impairment of the capacity to adapt control mechanisms. Two of them targeted the executive functioning (cf. blue part of Figure 14.1): (1) impaired shifting capacities leading to a weaker capacity to adapt control mechanisms; (2) poor working memory capacity limiting proactive control resources. Both of these hypotheses can be related to inhibitory deficits as they can impact working memory and shifting capacities (Miyake & Friedman, 2012). Finally, the third hypothesis targeted the monitoring system (cf. red part of Figure 14.1) by postulating that its activity indicates the need to adapt control mechanisms. These hypotheses tap into different cognitive dysfunctions to explain the lack of adaptation of control mechanisms.

In the long-term, determining the specific causal process behind the lack of adaptation could provide the knowledge and tools to orient and personalize therapeutic interventions. The increased-HRV interventions are promising. Indeed, several studies have shown that these interventions (e.g., physical activity, mindfulness, biofeedback) decrease impulsiveness and the occurrence of maladaptive behaviors. With my preliminary findings, I demonstrated that this decrease might be modulated by the increase in the capacity to adapt control mechanisms in impulsive individuals, potentially through the increase in the efficiency of the cognitive control alarm system.

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Chapter 14

Figures and Tables

Figures

Tables

Part V

Résumé de la thèse en français

Introduction théorique

L'impulsivité est une composante centrale de nombreux troubles psychiatriques, à la fois en tant que facteur diagnostique et facteur de vulnérabilité (cf. Partie I), faisant de ce concept une thématique de recherche majeure dans de nombreuses disciplines. En effet, les chercheurs s'intéressent aux bases neurobiologiques et cognitives de l'impulsivité, pour mieux comprendre l'émergence des comportements impulsifs afin d'améliorer la prise en charge des troubles associés.

L'impulsivité est définie globalement comme une tendance à réagir rapidement et de manière irréfléchie à des stimulations externes ou internes, sans considération pour les conséquences de ses actions pour l'individu ou son entourage (Moeller et al., 2001). Cette définition montre que le terme « impulsivité » englobe de nombreuses aspects comportementaux (par exemple, la rapidité, la non-planification). Plusieurs études ont en effet démontré la multidimensionnalité de ce concept en explorant la structure multifactorielle de l'impulsivité à travers les diverses méthodologies utilisées dans la littérature pour l'évaluer (par exemple, Reynolds et al., 2006; Lane et al., 2003; MacKillop et al., 2016). Ces méthodologies regroupent des questionnaires de personnalité auto-rapportés ainsi que des paradigmes expérimentaux, requérant aux participants d'inhiber une réponse automatique et dominante (par exemple, tâches de *Signal Stop*, de *Go/NoGo*) ou de choisir entre deux récompenses en fonction de leur délai ou de leur probabilité d'obtention (*Delay* et *Probability Discounting*), cf. Chapitre 1. Bien que les méthodologies choisies et leur nombre soient variés, la grande majorité des études indique que les traits de personnalité impulsive ne sont pas corrélés aux comportements impulsifs observés dans les paradigmes expérimentaux (par exemple, Reynolds et al., 2006; Lane et al., 2003; MacKillop et al., 2016). L'une des principales raisons évoquées pour expliquer l'absence de corrélation entre la personnalité et les comportements est la différence méthodologique. La personnalité, évaluée au travers des questionnaires, est en effet définie comme un style de réponse général et stable au cours du temps tandis que les paradigmes expérimentaux évaluent un comportement à un instant *t*. Néanmoins, on observe dans certaines populations pathologiques une corrélation entre ces scores de personnalité et les comportements impulsifs observés dans les paradigmes expérimentaux (Kirby et al., 1999; Swann et al., 2002; Lawrence et al., 2010). Ainsi, une hypothèse alternative pour expliquer cette absence de corrélation dans la population générale serait l'existence de capacités cognitives efficaces, relatives au contrôle des impulsions, qui permettraient de modérer l'impact de la personnalité impulsive sur les comportements.

Les capacités d'inhibition ont souvent été ciblées comme le facteur cognitif modérateur du lien entre personnalité et comportements impulsifs. Ainsi selon Diamond (2013), «*sans contrôle inhibiteur, nous serions à la merci des impulsions, schémas de pensée et stimuli de l'environnement qui guident nos actions* »[1]. Le comportement impulsif semble, ici, directement associé à un défaut d'inhibition. L'impulsivité était d'ailleurs définie comme l'incapacité à inhiber une réponse automatique et dominante (Barkley, 1997; Strack & Deutsch, 2003; Logan et al., 1984). Cette association est tellement importante que les termes « impulsivité » et « désinhibition » sont parfois utilisés comme étant interchangeables (Nigg, 2017). Néanmoins, à l'instar de l'impulsivité, l'inhibition, un processus cognitif visant à la réduction et/ou à la suppression d'activation, est également un concept multidimensionnel. Ce processus est en effet divisible en plusieurs fonctions : le contrôle des interférences, l'inhibition cognitive et l'inhibition comportementale (Friedman & Miyake, 2004; Rey-Mermet et al., 2017; Stahl et al., 2014), cf. Chapitre 2.1.1. À un niveau théorique, lier l'impulsivité avec l'inhibition semble donc être un raccourci entre deux concepts multidimensionnels. De plus, à un niveau empirique, les recherches portant sur les capacités d'inhibition dans l'impulsivité se sont principalement concentrées sur les capacités d'inhibition comportementale (cf. Chapitre 2.1.2). Les résultats rapportés sont, par ailleurs, mixtes et ne permettent pas de considérer seulement les déficits d'inhibition comme facteur modérateur de la relation entre personnalité impulsive et comportements inadaptés. Ces conclusions amènent donc à prendre du recul sur des capacités de contrôle des impulsions à un niveau plus global : le contrôle cognitif.

Le contrôle cognitif est un ensemble de fonctions exécutives de haut niveau qui nous permettent d'adapter nos comportements en fonction de demandes externes et de con-

1. "Without inhibitory control, we would be at the mercy of impulses, old habits of thought and action and/or stimuli that pull us this way or that."

traintes internes (Ridderinkhof et al., 2011; Nigg, 2017). Prenons l'exemple d'une situation quotidienne comme la conduite automobile pour illustrer le contrôle cognitif. Lorsque nous conduisons, notre objectif est d'atteindre notre destination tout en évitant de créer un accident afin de préserver notre intégrité corporelle et celle d'autrui. Pour ce faire, notre cerveau, en surveillant l'environnement (ici, la route) ainsi que nos propres actions, est capable d'évaluer si celles-ci sont toujours adaptées à la situation et à notre objectif. Dans le cas où une incohérence est détectée (par exemple, un pied trop lourd sur l'accélérateur ou un ballon au travers de la route), notre cerveau corrige ou modifie nos actions, voire planifie une nouvelle séquence d'actions, afin de réajuster et d'adapter le comportement (par exemple, lever le pied pour ralentir ou dévier sa trajectoire pour contourner l'obstacle). Plusieurs études ont montré que l'efficacité de ce contrôle cognitif modère la relation entre personnalité et comportements impulsifs (par exemple, Robinson et al., 2009; Youssef et al., 2016; McKewen et al., 2019). Les comportements impulsifs seraient moins fréquents chez des individus impulsifs possédant des capacités de contrôle cognitif efficaces. Cependant, le contrôle cognitif orchestre un ensemble complexe de processus cognitifs et il n'est pas encore clair quel est le composant spécifique du contrôle cognitif qui modère cette relation.

L'existence de trois composantes du contrôle cognitif est postulée dans les modèles computationnels de Botvinick et al. (2001) et De Pisapia & Braver (2006): (1) le monitoring, (2) le contrôle réactif et (3) le contrôle proactif. Le monitoring correspond à la surveillance, pouvant mener à la détection d'une erreur commise ou d'un conflit entre la réponse produite et l'environnement (cf. Chapitre 2.2.2). Selon Botvinick et al. (2001), leur détection provoque la mise en place d'ajustements comportementaux, qui ont pour but de résoudre les conflits. Selon Braver et al. (2007), repris dans le modèle de De Pisapia & Braver (2006), ces ajustements peuvent être ***réactifs***, permettant la résolution d'un conflit en cours, ou ***proactifs***, facilitant la résolution de conflits futurs. Le contrôle dit proactif est défini comme une sélection précoce et un maintien en mémoire des informations pertinentes pour la tâche en cours tandis que le contrôle dit réactif est défini comme une correction tardive de l'action (Braver, 2012). Dans notre exemple de conduite automobile, prenons une situation dans laquelle notre visibilité est réduite (par exemple, brouillard). Afin d'éviter un accident, le fait de ralentir la vitesse de la voiture illustre le contrôle proactif, puisque le ralentissement permettrait de réagir plus facilement si un événement inattendu se produit sur la route. Au contraire, le fait d'attendre et de réagir si un événement se produit (par exemple, freiner brutalement en apercevant une voiture) est illustratif du contrôle réactif. Les mécanismes de contrôle proactif et réactif ont donc le même objectif (i.e., la résolution de conflit) et co-existent dans le système cognitif. Néanmoins, leurs poids respectifs dans le système de contrôle cognitif diffèrent en fonction des demandes externes et des contraintes internes, pour réduire le coût cognitif du contrôle tout en préservant son efficacité. En effet, le contrôle proactif, requérant le maintien en mémoire des informations pertinentes, permet un contrôle global et robuste, mais est coûteux en énergie (Del Giudice & Crespi, 2018). Au contraire, le contrôle réactif est moins coûteux, car plus flexible et temporaire, mais il est également plus fragile (Del Giudice & Crespi, 2018). Ainsi, certaines caractéristiques contextuelles (par exemple, Hefer & Dreisbach, 2016) et inter-individuelles (par exemple, Paxton et al., 2008; Redick, 2014; Richmond et al., 2015), en augmentant ou diminuant le coût des mécanismes de contrôle, influencent indirectement l'implémentation des deux mécanismes de contrôle. Ainsi, les situations où la performance est récompensée (situation motivationnelle), favorisent le contrôle proactif, pour privilégier l'efficacité, par rapport au contrôle réactif (Hefer & Dreisbach, 2016). En revanche, l'augmentation de la charge cognitive (i.e., augmentation des informations en mémoire) limite les ressources proactives et favorise ainsi le contrôle réactif (Mäki-Marttunen et al., 2019b). Selon la théorie du double mécanisme de contrôle de Braver (2012), cette capacité d'adapter de manière flexible le poids des mécanismes proactifs et réactifs dans le système en fonction de demandes externes et de contraintes internes est cruciale dans l'adaptation des comportements (cf. Chapitre 2.2.3).

La relation entre contrôle cognitif et impulsivité a été largement étudiée au travers du fonctionnement de ses composantes prises individuellement, et, comme évoqué précédemment, en particulier en se concentrant sur les capacités d'inhibition comportementale. En effet, *la littérature a toujours été dominée par l'idée selon laquelle les comportements* *impulsifs sont le reflet d'une tendance inadaptée, que les chercheurs et cliniciens devraient s'efforcer à réparer pour obtenir de meilleurs résultats sur le plan comportemental*[2] (Kopetz et al., 2018). Ainsi, les recherches se sont focalisées sur l'étude des dysfonctionnements cognitifs potentiellement à l'origine des comportements impulsifs. Cependant, d'autres auteurs postulent que l'impulsivité serait utile dans certaines situations, et qu'elle ne serait donc pas le fruit de déficits cognitifs (Kopetz et al., 2018; Dickman, 1990; Stevens & Stephens, 2010). En effet, si les comportements impulsifs ont perduré au cours de l'évolution, alors l'impulsivité pourrait avoir une valeur adaptative sélective inconnue à ce jour, car négligée. Pour ces auteurs, l'impulsivité serait un style de réponse adapté dans certaines situations, mais dysfonctionnel dans d'autres (Kopetz et al., 2018; Dickman, 1990; Stevens & Stephens, 2010). Choisir une plus petite récompense disponible immédiatement plutôt qu'une plus large récompense plus tard est un choix stratégique pour survivre dans des milieux imprévisibles (Stevens & Stephens, 2010). Ce comportement est néanmoins utilisé comme indice objectif d'impulsivité et évalué notamment dans la tâche de *Delay Discounting*. Pour survivre, les chasseurs-cueilleurs agissaient donc de manière impulsive en favorisant de petites quantités de nourriture disponibles dans l'immédiat et de manière certaine, plutôt que de grandes quantités disponibles plus tard et hypothétiques. Néanmoins, dans un environnement plus prévisible (par exemple, quand tous les choix sont simultanément présentés), ce choix impulsif n'a plus rien de stratégique, ni d'adapté pour la survie. Ainsi, il me semble qu'on ne devrait pas essayer de répondre à la question « Qu'est-ce qui est dysfonctionnel dans l'impulsivité ? », mais plutôt « Qu'est-ce qui est inadapté ? ». La notion d'adaptation du style de réponse impulsif, plutôt que les dysfonctions cognitives, semble en effet cruciale dans l'étude de l'impulsivité. Comme suggéré par Dickman en 1990, l'impulsivité serait une stratégie comportementale optimale pour certaines situations, mais source d'erreur dans d'autres. Ainsi, l'impulsivité « dysfonctionnelle » (i.e., dont les conséquences sont néfastes pour l'individu et/ou son entourage) résulterait de l'incapacité de se dégager de cette stratégie comportementale dans

2. "the literature is still dominated by the notion that impulsive behavior is the reflection of a maladaptive tendancy, that researchers and practictioners should aim to "fix" it to afford better behavioral outcomes"

des situations où elle serait inadaptée. En transposant cette perspective dans le cadre du contrôle cognitif, on peut émettre l'hypothèse que des comportements inadaptés émergeraient de l'absence de modulation du poids des mécanismes réactifs et proactifs en fonction des demandes externes et des contraintes internes (Braver, 2012). À l'heure actuelle et à ma connaissance, les études explorant le contrôle cognitif en lien avec l'impulsivité n'investiguent pas cette capacité. Mon projet de thèse a ainsi porté sur l'étude des effets de l'impulsivité sur la capacité à adapter de manière flexible le poids des mécanismes de contrôle cognitif aux demandes externes et aux contraintes internes.

En se basant sur les résultats d'études précédentes dans de nombreuses populations pathologiques (par exemple, van Dijk et al., 2014; Smucny et al., 2019; Lesh et al., 2013), j'ai émis l'hypothèse que l'impulsivité serait caractérisée par une plus faible dominance du contrôle proactif. De plus, selon les perspectives de Dickman (1990) et Kopetz et al. (2018), j'ai postulé qu'une impulsivité marquée serait associée avec un défaut d'adaptation du poids des mécanismes de contrôle proactif et réactif au contexte. Ce défaut d'adaptation pourrait expliquer les manifestations comportementales de l'impulsivité, quand la configuration des mécanismes de contrôle (i.e., leurs poids respectifs) n'est plus adaptée au contexte. Mon projet de thèse se décline en trois axes expérimentaux majeurs. Le premier explore l'adaptation des mécanismes de contrôle aux demandes de l'environnement (cf. Chapitre 5). Pour ce faire, la tâche d'AX-CPT a été utilisée afin de calculer l'indice de proactivité comportementale (PBI), mesurant le poids relatif du contrôle proactif par rapport au contrôle réactif (Braver et al., 2009). Le second étudie l'adaptation des mécanismes de contrôle aux contraintes internes, en contrebalançant la force des ajustements comportementaux proactifs en fonction des capacités d'inhibition comportementale réactive (cf. Chapitre 7). Enfin, le dernier axe décrit des études explorant l'activité de surveillance (*monitoring*), considérée comme étant un signal d'alarme du système indiquant les besoins en contrôle en prévision des difficultés à venir (cf. Chapitre 8). De plus, ce manuscrit de thèse rapporte des résultats préliminaires sur le lien entre variabilité du rythme cardiaque, un indicateur d'adaptation physiologique, et le système de contrôle cognitif (cf. Chapitre 9). Dans ce résumé, seuls les résultats principaux des trois axes majeurs seront rapportés.

AXE 1 : Adaptation du poids des mécanismes de contrôle aux demandes externes dans la population générale

Etude soumise pour publication : Grisetto, F., Delevoye-Turrell, Y.N. & Roger, C. *Slower adaptation of control strategies in individuals with high impulsive tendencies.*

Le contrôle cognitif est un ensemble de fonctions cognitives nécessaires à l'adaptation de nos comportements à un environnement en constant changement. Des études précédentes ont montré que des capacités de contrôle cognitif efficaces modéraient la relation entre des traits de personnalité impulsive et des comportements impulsifs, comme des symptômes boulimiques (Robinson et al., 2009) ou des comportements de prise de risque (Youssef et al., 2016; McKewen et al., 2019). Dans ces études, le contrôle cognitif était évalué au niveau de la performance (i.e., nombre d'erreur, effet de congruence). Par conséquent, il existe peu de connaissances sur les processus de contrôle cognitif spécifiques qui expliquent la modération de la relation entre personnalité et comportement. Quel(s) est(sont) les processus de contrôle cognitif qui explique(nt) qu'un individu impulsif manifeste des comportements inadaptés ?

Pour répondre à cette question, je me suis principalement intéressée aux mécanismes de contrôle proactif et réactif, tels que définis par Braver (2012), et à leur adaptation aux demandes externes et aux contraintes internes. Les performances dans la tâche d'AX-CPT permettent l'étude des mécanismes de contrôle au travers du calcul de l'indice de proactivité comportementale (Cohen & Servan-Schreiber, 1992; Servan-Schreiber et al., 1996; Braver et al., 2009), cf. Chapitre 3.2.1. Cet indice reflète en effet le poids relatif du contrôle proactif par rapport au contrôle réactif dans la réalisation de la tâche. Plus l'indice de proactivité comportementale (PBI) est grand, plus les mécanismes proactifs prédominent dans la tâche. Le calcul de cet indice à partir des performances à la tâche d'AX-CPT a ainsi révélé une diminution du poids relatif du contrôle proactif dans de nombreuses populations pathologiques caractérisées par une forte impulsivité comparé aux PBI des groupes contrôles (cf. Table 3.1, comparaison des valeurs de PBI entre plusieurs populations). Dans ces populations, la dominance du contrôle proactif, généralement observée, semble réduite. Selon la théorie du double mécanisme de contrôle (Braver, 2012), cette réduction de la dominance du contrôle proactif engendrerait un système de contrôle moins robuste face aux distractions et plus sensible aux informations non-pertinentes de l'environnement.

Cette première étude avait pour but de (1) vérifier si la plus faible dominance du contrôle proactif était aussi observable chez des individus impulsifs de la population générale et (2) explorer le lien entre impulsivité et adaptation des mécanismes de contrôle aux demandes de la tâche. Pour ce faire, la tâche d'AX-CPT a été utilisée pour calculer le PBI. Afin d'étudier l'adaptation des mécanismes aux demandes externes, le PBI a été calculé pour chaque bloc expérimental afin d'analyser son évolution au cours du temps. La tâche d'AX-CPT favorise en effet l'utilisation des mécanismes de contrôle proactif par la présence de lettres-amorces, permettant la préparation de la réponse correcte dans 90% des essais (cf. Figure A). Nous nous attendions donc à observer une augmentation du PBI au cours des blocs, révélant une augmentation du poids des mécanismes de contrôle proactif par rapport aux mécanismes de contrôle réactif.

Quarante-huit volontaires sains recrutés à l'Université de Lille ont réalisé dix blocs de la tâche d'AX-CPT (Cohen & Servan-Schreiber, 1992; Servan-Schreiber et al., 1996; Braver et al., 2009) puis ont rempli le questionnaire de personnalité UPPS (Van der Linden et al., 2006; Whiteside & Lynam, 2001), voir Annexe .3. Durant la tâche sur ordinateur, les activités électriques cérébrales et musculaires ont été enregistrées mais ces données électrophysiologiques ne sont pas analysées pour cette étude.

La consigne donnée au participant était de répondre le plus vite possible et le plus précisément possible à une paire de lettres, composée d'une lettre-amorce (i.e., la première lettre de la paire) et d'une lettre-cible (i.e., la deuxième lettre de la paire). Une réponse droite est requise si la lettre-cible est un « X » qui a été précédé par un « A ». Une réponse gauche est requise pour toutes autres combinaisons de lettres (par exemple, les essais AY, BX et BY). Les essais AX représentent 70% des essais, tandis que les trois autres types d'essai ne sont présentés que dans 10% des cas (cf. Figure A). La prédominance des essais AX a pour conséquence de créer une forte association entre la réponse droite et les lettres A et X. Ainsi, dans les essais AY et les essais BX, la réponse droite est automatiquement activée par la lettre-amorce "A" et la lettre-cible "X", respectivement, mais doit être inhibée afin de donner la bonne réponse.

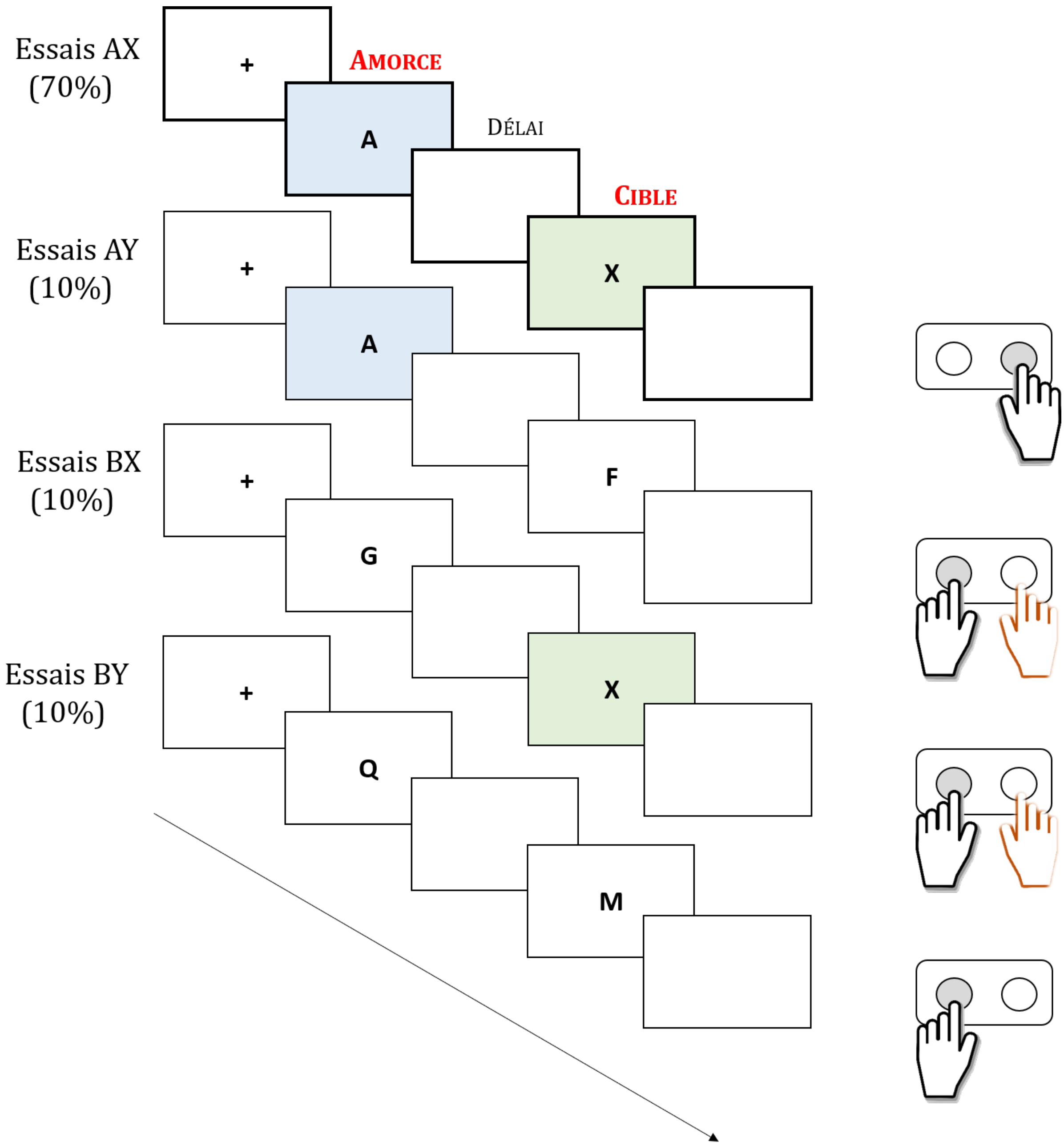

Figure A : Représentation schématique des différents essais de la tâche d'AX-CPT. Les mains dessinées en noir représentent les réponses attendues tandis que les mains dessinées en orange des essais AY et BX représentent la réponse automatique et dominante, activée par la lettre-amorce "A" et la lettre-cible "X", à inhiber.

Le taux d'erreur ainsi que les temps de réaction ont été extraits pour chaque type d'essais (i.e., AX, AY, BX, BY). De plus, l'indice de proactivité comportementale (PBI) a été calculé à partir des temps de réaction des essais corrects selon la formule suivante

$$PBI = \frac{AY - BX}{AY + BX}$$

(Braver et al., 2009) sur l'ensemble de la tâche, mais également pour chacun des 10 blocs réalisés par les participants. Un PBI positif indique ainsi un coût cognitif plus important pour résoudre le conflit AY comparé au conflit BX (i.e., TR plus longs dans les essais AY que dans les essais BX). Le participant utilise l'information de la lettre-amorce pour préparer sa réponse : le contrôle proactif est dominant. En revanche, un PBI négatif indique un coût cognitif plus important pour résoudre le conflit BX que le conflit AY (i.e., TR plus longs dans les essais BX que dans les essais AY). Le participant attend l'apparition de la lettre-cible pour réactiver l'information de la lettre-amorce : le contrôle réactif est dominant.

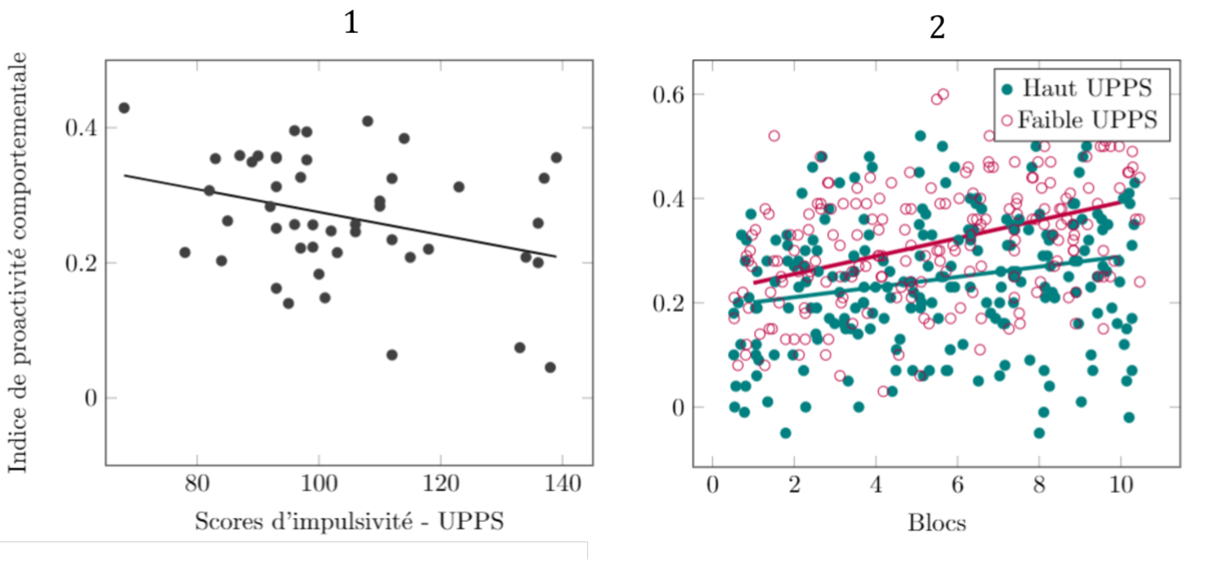

Figure B : **(1)** Corrélation entre les scores de personnalité impulsive UPPS et l'indice de proactivité comportementale. **(2)** Évolution de l'indice de proactivité comportementale au cours des blocs dans le groupe Faible UPPS (ligne et ronds roses, scores inférieurs à la médiane de la distribution) et le groupe Haut UPPS (ligne et ronds verts, scores supérieurs à la médiane de la distribution).

Les résultats de cette étude montrent que plus les scores de personnalité impulsive sont importants, moins élevé est le PBI global (i.e., calculé sur l'ensemble de la tâche), r = - .33, p = .026 (cf. Figure B.1.). De plus, en analysant l'évolution du PBI au cours des dix blocs, on observe que le PBI augmente plus lentement au cours de la tâche chez les individus les plus impulsifs comparés aux individus les moins impulsifs de l'échantillon, $F(1, 42) = 5.73$, $p = .021$, $\eta^2 = 0.12$ (cf. Figure B.2.). Enfin, en considérant un indice individuel de l'adaptation du PBI (cf. Annexe .1 pour une explication détaillée de la méthode), on remarque que huit individus (18% de l'échantillon) ne s'adaptent pas au cours de la tâche (i.e., pas d'augmentation du PBI). Par ailleurs, ces huit individus sont tous catégorisés comme hauts impulsifs dans la population étudiée, χ^2 $(2, N = 44) = 6.74$, $p = .009$. Enfin, des analyses supplémentaires et préliminaires ont montré une interaction entre les scores de personnalité impulsive et la variabilité du rythme cardiaque (i.e., *heart rate variability* - HRV; un indice physiologique d'adaptation) sur l'adaptation du PBI au cours de la tâche (cf. Chapitre 9.1). Une forte variabilité du rythme cardiaque chez un individu semblerait atténuer l'effet négatif de ses traits impulsifs sur l'adaptation des mécanismes de contrôle proactif au cours de la tâche, $\beta = 8.39^{10\text{-}6}$, $t = 2.13$, $p = .041$.

Cette première étude avait pour objectifs d'explorer la dominance du contrôle proactif et la potentielle adaptation de son poids en fonction des demandes externes chez des individus impulsifs de la population générale. Les demandes externes ont été opérationnalisées à travers la tâche d'AX-CPT. En effet, cette tâche favorise l'utilisation des mécanismes de contrôle proactif par la présence de lettres-amorces permettant la préparation des réponses à donner. L'adaptation des mécanismes de contrôle au cours de cette tâche d'AX-CPT devrait donc se traduire par une augmentation du PBI, révélant une augmentation du poids relatif du contrôle proactif par rapport au contrôle réactif.

Dans un premier temps, les résultats ont montré que l'impulsivité était négativement corrélée avec le PBI. Plus les scores d'impulsivité étaient élevés, moins le contrôle proactif était dominant. Ce résultat est cohérent avec les résultats de la littérature montrant une plus faible dominance du contrôle proactif dans de nombreuses populations psychiatriques caractérisées par une forte impulsivité. Dans un second temps, cette étude démontre que le système de contrôle cognitif adapte le poids des mécanismes de contrôle en fonction des demandes externes : le PBI augmente au cours de la tâche. On observe également que les individus les plus impulsifs adaptent moins rapidement, voire n'adaptent pas du tout, le poids des mécanismes de contrôle proactif au cours de la tâche en comparaison avec les individus les moins impulsifs de l'échantillon. Par ailleurs, les individus qui n'augmentent pas le poids du contrôle proactif au cours des blocs sont tous caractérisés par une forte impulsivité dans la population étudiée. Ce premier axe expérimental apporte des éléments empiriques associant l'impulsivité dans une population générale à une plus faible dominance du contrôle proactif dans le système de contrôle, pouvant engendrer une plus grande sensibilité aux informations non-pertinentes. De plus, lorsque l'environnement favorise l'utilisation des mécanismes de contrôle proactif, les individus impulsifs reconfigurent plus lentement (ou ne reconfigurent pas) leur système de contrôle. Dans l'ensemble, les résultats de cette étude semblent définir l'impulsivité comme un système de contrôle cognitif moins proactif et moins flexible aux demandes de l'environnement.

AXE 2 : Adaptation du poids des mécanismes de contrôle en fonction d'une contrainte interne

Etude soumise pour publication : Grisetto, F., Le Denmat, P., Delevoye-Turrell, Y.N., Vantrepotte, Q., Davin, T., Dinca, A., Desenclos-El Ghoulti, I. & Roger, C. (submitted). *The broken balance in the use of proactive and reactive control in high risk-takers.*

Les résultats de la première étude ont montré que les traits de personnalité impulsive étaient associés à une plus faible dominance du contrôle proactif, ainsi qu'à une lente (voire une absence) adaptation du poids des mécanismes de contrôle en fonction des demandes externes. Cependant, dans la théorie du double mécanisme de contrôle de Braver (2012), l'ajustement des comportements ne dépend pas seulement de l'adaptation des mécanismes de contrôle aux demandes externes, mais également aux contraintes internes. Si de précédentes études ont montré que l'implémentation des mécanismes de contrôle cognitif était influencée par des caractéristiques contextuelles (par exemple, charge cognitive de la tâche, situation motivante ou stressante, Mäki-Marttunen et al., 2019b; Hefer & Dreisbach, 2016), elle l'est également par des caractéristiques inter-individuelles telles que l'âge (Paxton et al., 2008) ou les capacités de mémoire de travail (Richmond et al., 2015; Redick, 2014). La mémoire de travail est en effet une capacité cognitive associée aux mécanismes de contrôle proactif, par le maintien des informations pertinentes en mémoire. Les individus possédant de faibles capacités de mémoire de travail favorisent ainsi moins les mécanismes de contrôle proactif lors d'une tâche d'AX-CPT comparés aux individus avec de meilleures capacités de mémoire de travail (par exemple, Redick, 2014). Les capacités de mémoire de travail semblent donc contraindre l'implémentation des mécanismes de contrôle.

Une seconde étude de cette thèse a proposé alors d'explorer si les capacités d'inhibition comportementale pouvaient également contraindre l'implémentation des mécanismes de contrôle. En effet, les capacités d'inhibition comportementale sont associées aux mécanismes réactifs, puisqu'elles correspondent à l'inhibition de l'initiation et/ou de l'exécution d'une action inappropriée. Ainsi, de faibles capacités d'inhibition comportementale (i.e., difficulté à rattraper une erreur engagée) devraient être contrebalancées par une plus forte utilisation de processus proactifs pour assurer l'efficacité du système de contrôle. Cette étude visait également à explorer cette adaptation de l'implémentation des mécanismes de contrôle à une contrainte interne chez des individus impulsifs. L'hypothèse était que la balance entre capacités d'inhibition comportementale et engagement de mécanismes proactifs ne serait pas, ou moins, observée chez les individus les plus impulsifs, participant à leur tendance à exprimer des comportements inadaptés (Braver, 2012).

Cent soixante-seize participants ont été évalués par une batterie de tests informatisés, dont trois sont utilisés pour répondre aux hypothèses de cette étude :

Tâche de Simon (Simon, 1990). Dans cette tâche, les participants doivent répondre le plus rapidement et le plus précisément possible à la forme d'un stimulus présenté à l'écran (un carré ou un rond blanc), tout en inhibant la localisation de celui-ci (à droite ou à gauche de la croix de fixation). Le ralentissement post-erreur (i.e., différence des temps de réaction moyens après une erreur et après un essai correct) a été extrait des performances dans cette tâche. L'allongement des temps de réaction après une erreur est interprété comme une réallocation des ressources attentionnelles vers l'information pertinente pour la tâche en cours (i.e., la forme) afin d'éviter de commettre une nouvelle erreur dans les essais suivants. Par conséquent, cet effet est utilisé ici comme un indice d'ajustement proactif (Danielmeier & Ullsperger, 2011). Plus le ralentissement post-erreur est important, plus important est l'ajustement proactif mis en place.

Tâche de Signal Stop (Logan et al., 1984). Dans cette tâche, les participants doivent répondre le plus rapidement et le plus précisément possible en fonction de la direction d'une flèche blanche présentée à l'écran. Dans 25% des cas, la flèche devient rouge après son apparition et le participant doit alors inhiber la réponse automatique en cours d'exécution. Le temps de réaction nécessaire pour stopper l'action, appelé *Stop Signal Reaction Time* (SSRT), est utilisé comme un indice de l'efficacité des capacités d'inhibition comportementale. Plus le SSRT est long, plus le participant a besoin de temps pour inhiber avec succès l'action en cours d'exécution et donc, moins l'inhibition comportementale est efficace.

Balloon Analog Risk Task (Lejuez et al., 2002). Dans cette tâche, on demande aux participants de gonfler virtuellement 30 ballons en appuyant sur un bouton. Plus le ballon gonfle, plus le participant cumule des points. Néanmoins, à tout moment, le ballon peut exploser, faisant ainsi perdre tous les points jusqu'ici accumulés. Le participant a donc le choix entre arrêter de gonfler pour conserver les points ou prendre le risque de continuer de gonfler pour cumuler davantage de points. Le temps d'appui moyen pour gonfler les ballons est ainsi considéré comme un indice objectif de la propension à prendre des risques (RTI – *Risk-taking index*). Plus long est le temps d'appui moyen, plus forte est la propension à prendre des risques. Cet indice est ici utilisé comme un indice objectif d'impulsivité (par exemple, Reynolds et al., 2006).

Les résultats montrent que le ralentissement post-erreur est significativement prédit par le SSRT, β = 1.36, t(77.94) = 2.16, SE = 0.63, p = .034. Plus le temps de réaction nécessaire à l'inhibition d'une réponse inappropriée est long (i.e., longs SSRT), plus le ralentissement post-erreur est long. Néanmoins, cette balance entre capacités d'inhibition et engagement de processus proactifs semble réduite avec l'augmentation de la propension à prendre des risques, β = -0.17, t(82.17) = -2.08, SE = 0.08, p = .040 (cf. Figure C).

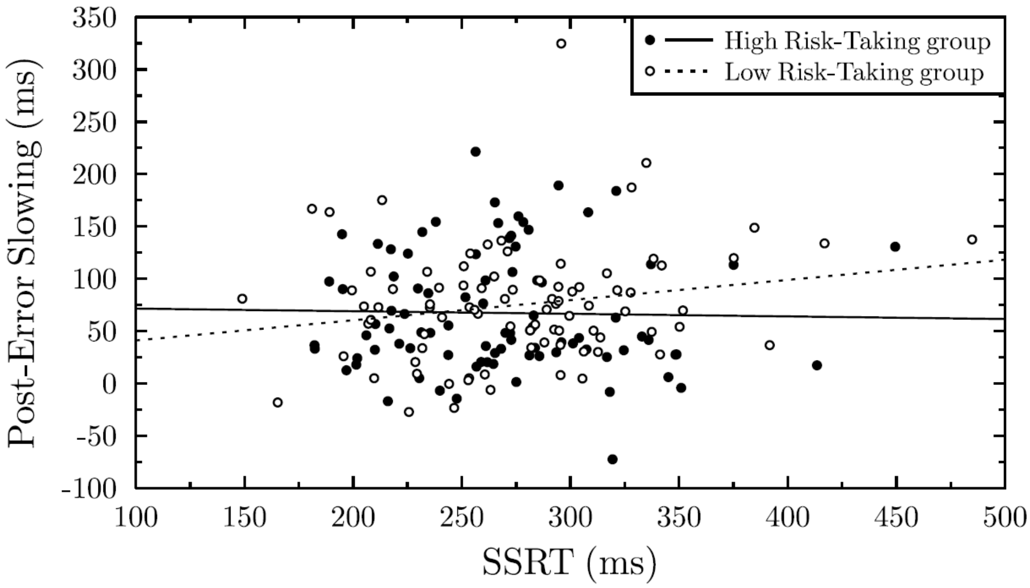

Figure C : Ralentissement post-erreur (ms) en fonction du SSRT (ms) et de la propension à prendre des risques. La ligne en pointillée représente la prédiction du ralentissement post-erreur par le SSRT du groupe de participants prenant le moins de risque. La ligne continue représente la prédiction du ralentissement post-erreur par le SSRT du groupe de participants prenant le plus de risque.

L'objectif de cette seconde étude était d'explorer la relation entre impulsivité et adaptation des mécanismes de contrôle à une contrainte interne, ici opérationnalisée par les capacités d'inhibition comportementale. À l'instar de l'efficacité des capacités de mémoire de travail qui favorise l'utilisation des mécanismes de contrôle proactif, l'hypothèse de l'étude était de considérer que de faibles capacités d'inhibition comportementale, potentiellement réduisant l'efficacité des processus réactifs, pourraient favoriser l'utilisation des mécanismes de contrôle proactif. De plus, nous faisions l'hypothèse de l'absence d'un tel effet chez des individus impulsifs. Les résultats de cette seconde étude sont en faveur de nos hypothèses. Une plus forte propension à prendre des risques chez des adultes sains semble associée à une moindre balance des faibles capacités d'inhibition comportementale (i.e., des longs SSRT) par de plus grands ajustements proactifs (i.e., plus longs ralentissements post-erreur).

Dans l'ensemble, les résultats des deux premiers axes de ma thèse suggèrent que l'impulsivité dans la population générale est associée à une plus faible augmentation du poids du contrôle proactif en réponse aux demandes externes (i.e., la tâche d'AX-CPT) et aux contraintes internes (i.e., les capacités d'inhibition comportementale). Ce défaut d'adaptation du poids accordé aux mécanismes de contrôle proactif pourrait expliquer l'émergence de comportements inadaptés chez des individus prédisposés à l'impulsivité. On retrouve ici la perspective de Dickman (1990) : l'impulsivité serait associée à un style de contrôle moins proactif, qui ne deviendrait "dysfonctionnel" que lorsqu'il ne serait plus assez adapté au contexte.

AXE 3 : Activités cérébrales de monitoring dans la population générale

Etude publiée : Grisetto, F., Delevoye-Turrell, Y. N., & Roger, C. (2019). Efficient but less active monitoring system in individuals with high aggressive predispositions. *International Journal of Psychophysiology, 146*, 125-132.

Dans les études précédentes, seule l'adaptation du poids des mécanismes de contrôle proactif et réactif en fonction des demandes externes et des contraintes internes a été explorée. Un dernier composant du système de contrôle cognitif reste donc à investiguer pour compléter ce projet de thèse : le *monitoring*. En effet, l'activité de monitoring est centrale dans les modèles théoriques du contrôle cognitif, puisqu'on considère que le monitoring d'une erreur et/ou d'un conflit provoque les ajustements proactifs et réactifs nécessaires à l'adaptation des comportements (Botvinick et al., 2001; De Pisapia & Braver, 2006). Pour avoir une vision plus complète du système de contrôle cognitif en relation avec l'impulsivité dans la population générale, j'ai donc conduit une troisième étude, en enregistrant les activités électroencéphalographiques (EEG) et électromyographiques (EMG) des participants, pour explorer l'activité du système de monitoring à travers l'étude de l'amplitude de l'onde ERN/Ne (i.e., *error(-related) negativity,* Falkenstein et al., 1991 ; Gehring et al., 1993, cf. Figure D). Originellement interprétée comme un indicateur de la détection des erreurs, cette activité fronto-centrale a néanmoins été observée dans des essais sans erreur. Des études ont en effet montré que l'amplitude de cette onde ERN/Ne est sensible à la nature de la performance du participant (i.e., distinction des réponses correctes et des erreurs, par exemple, Vidal et al., 2000), ainsi qu'à la motivation portée à la tâche (Hajcak et al., 2005). Les interprétations de l'onde ERN/Ne ont évoluées au fil de ces découvertes empiriques (cf. Chapitre 3.1.1). Aujourd'hui, l'ERN/Ne peut être considérée comme un indicateur de l'activité globale de monitoring, un "signal d'alarme" prenant en compte de nombreux facteurs (par exemple, motivation, anxiété, performance) pour indiquer au système les besoins en processus de contrôle pour réaliser la tâche en cours (Burle et al., 2008).

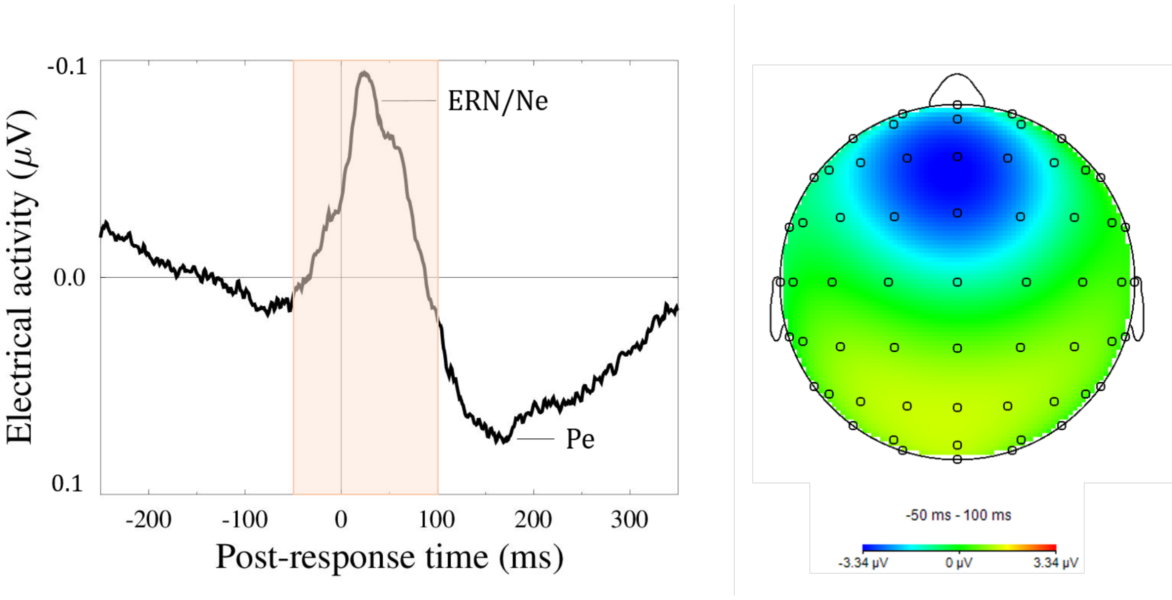

Figure D : Activité cérébrale correspondant à l'*error(-related) negativity* (ERN/Ne, Falkenstein et al., 1991; Gehring et al., 1993) localisée au niveau fronto-central.

Trente-deux participants volontaires recrutés au sein de l'Université de Lille ont réalisé une tâche de Simon, composée de 1290 essais divisés en 10 blocs. Il était demandé au participant de répondre le plus vite et le plus précisément possible en fonction de la forme présentée à l'écran (i.e., un carré ou un cercle). Les stimulus pouvaient apparaitre à droite ou à gauche de la croix de fixation présentée au centre de l'écran. Dans 50% des essais, le stimulus apparaissait du côté ipsilatéral de la réponse à donner (i.e., essais congruents). Dans le reste des essais, le stimulus apparaissait du côté controlatéral de la réponse (i.e., essais incongruents). À la fin de la tâche, le participant répondait à deux questionnaires de personnalité : le BPAQ (Buss & Perry, 1992) et l'UPPS (Whiteside & Lynam, 2001) pour évaluer les tendances à réagir agressivement et les traits de personnalité impulsive, respectivement.

Durant l'ensemble de la tâche de Simon, les activités électriques musculaires et cérébrales des participants ont été enregistrées à l'aide de 2 électrodes externes placées sur chaque main au niveau des muscles impliqués dans les réponses (i.e., *flexor pollicis brevis*) et de 64 électrodes placées au niveau de la tête à l'aide d'un bonnet. L'enregistrement simultané de ces activités a permis l'étude des amplitudes ERN/Ne dans trois différents types d'essai (i.e., essais purs corrects, essais avec erreur et essais avec ébauches d'erreur). Ces amplitudes ont été comparées entre les participants en fonction de leurs scores de personnalité. Les participants dont le score était strictement supérieur à la médiane de la distribution des scores BPAQ/UPPS étaient considérés comme Hauts agressifs/impulsifs. Les participants dont le score était strictement inférieur à la médiane de la distribution des scores BPAQ/UPPS étaient considérés comme Faibles agressifs/impulsifs.

Les amplitudes ERN/Ne, quelque soit le type d'essai analysé (i.e., essais purs corrects, essais avec erreur et essais avec ébauches d'erreur) étaient plus petites dans le groupe Hauts Agressifs (-0.56 μV/cm^2) comparées au groupe Faibles Agressifs (-0.77 μV/cm^2), $F(1, 81) = 10.53$, $p = .002$, $\eta p^2 = 0.12$ (cf. Figure E). Néanmoins, ces différences d'amplitudes ERN/Ne n'étaient pas observées entre les groupes basés sur les scores de personnalité impulsive, évalués par le questionnaire UPPS, $F(1, 81) = 0.06$, $p = .815$, $\eta p^2 < 0.01$. Des analyses supplémentaires et préliminaires, considérant la variabilité du rythme cardiaque (i.e., un indice physiologique d'adaptation), ont montré que la réduction des activités de monitoring chez les participants les plus agressifs n'était visible que chez les sujets ayant une faible variabilité du rythme cardiaque (cf. Chapitre 9.2).

Les résultats de cet axe expérimental montrent que les amplitudes de l'onde ERN/Ne dans les différents types de performance (i.e., erreur, ébauches d'erreur et réponses correctes) sont réduites chez les individus ayant tendance à réagir de manière agressive. L'agressivité, dans la population générale, semble donc associée à une diminution globale des activités de monitoring. Cependant, dans la présente étude, nous n'avons pas observé ce même pattern de résultat pour des individus rapportant des traits impulsifs marqués. Ce résultat semble inconsistent avec de nombreuses études rapportant une réduction d'amplitude de l'onde ERN/Ne dans plusieurs populations pathologiques, caractérisées par une impulsivité marquée, telles que la schizophrénie (Mathalon et al., 2002) et la personnalité borderline (de Bruijn et al., 2006). Néanmoins, nos résultats distincts sur l'agressivité et l'impulsivité, en lien avec les résultats en population pathologique, semblent suggérer que seuls les comportements inadaptés, et non pas les traits de personnalité associés, pourraient être associés à une réduction globale de l'activité de monitoring. La personnalité impulsive ne s'exprimerait en comportements inadaptés que si le signal d'alarme, indiquant le besoin en processus de contrôle (Burle et al., 2008), serait diminué. En postulant un lien entre comportements impulsifs et inadaptation des mécanismes de contrôle, à partir des résultats comportementaux de la présente thèse (Axes 1 et 2), on pourrait faire l'hypothèse d'une relation entre les amplitudes de l'onde ERN/Ne et la capacité de moduler de manière flexible les poids des mécanismes de contrôle proactif et réactif aux demandes externes et aux contraintes internes. Des résultats préliminaires et exploratoires pour la tester ont été rapportés dans la présente thèse (cf. Chapitre 8.3), mais de futures études sont nécessaires pour explorer plus précisément cette hypothèse.

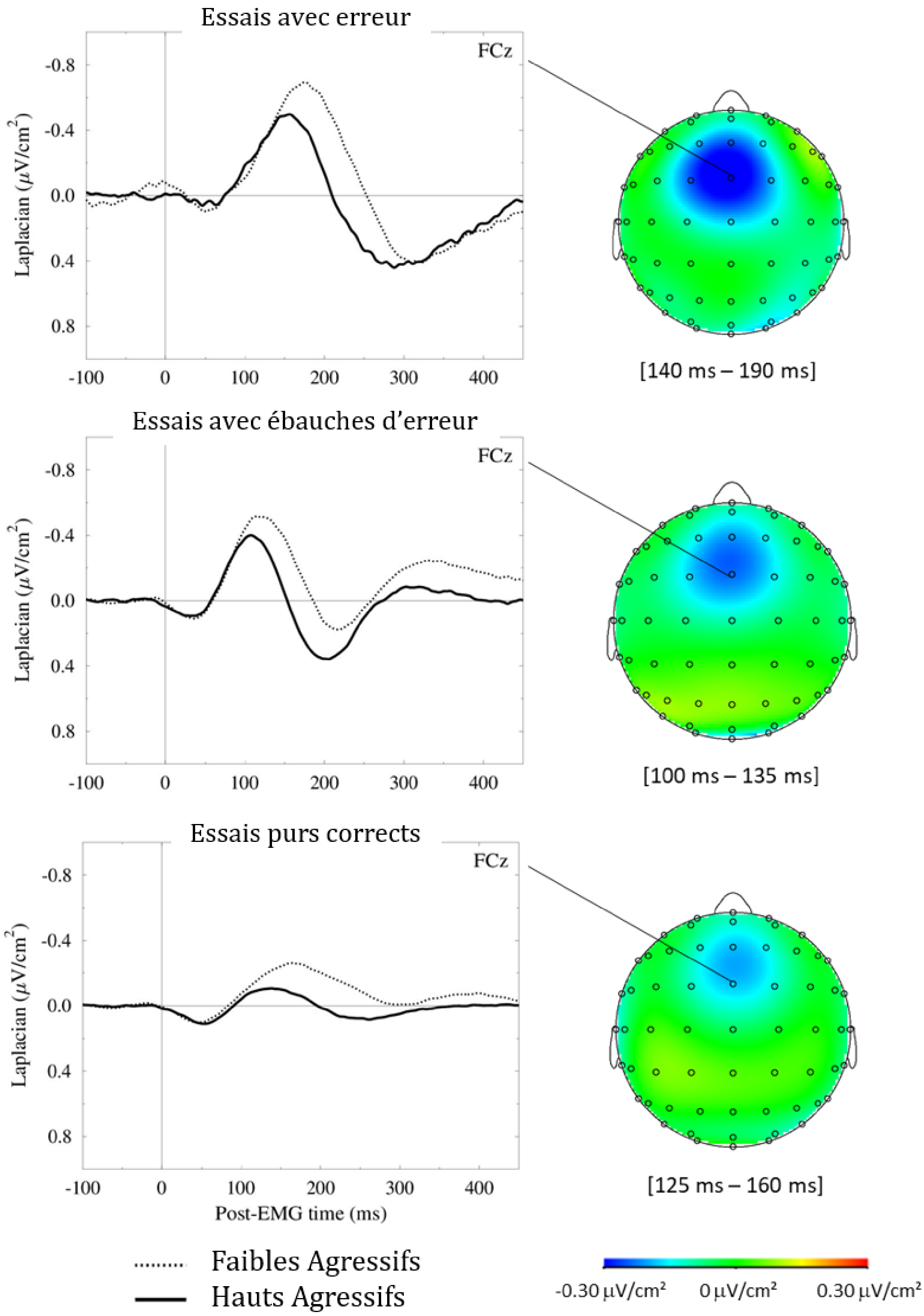

Figure E : Amplitudes de l'onde ERN/Ne dans les différents types d'essai en fonction du groupe d'Agressivité et topographies correspondantes.

Discussion générale

L'adjectif « impulsif » définit de nombreux traits de personnalité et englobe plusieurs patterns de comportements, pouvant être observés aussi bien dans la population générale que dans les populations pathologiques. Caractérisant un certain nombre de troubles psychiatriques (par exemple, abus de substance, troubles de la personnalité), l'impulsivité semble d'ailleurs augmenter les risques d'en développer (par exemple, Granö et al., 2004; Stautz et al., 2016; Rømer Thomsen et al., 2018; Granö et al., 2007; Fossati et al., 2004). Mon projet de thèse s'inscrit dans ce champ de recherche afin d'apporter des éléments empiriques pour mieux comprendre la relation entre impulsivité et émergence de comportements inadaptés. Plus précisément, mes recherches se sont focalisées sur le fonctionnement du système de contrôle cognitif chez des individus impulsifs dans la population générale. La relation entre les traits de personnalité impulsive et les comportements impulsifs semble en effet modérée par des capacités de contrôle cognitif efficaces (par exemple, Youssef et al., 2016; Robinson et al., 2009). Les capacités de contrôle cognitif semblent prévenir l'émergence de comportements impulsifs chez des individus prédisposés à en manifester. Néanmoins, dans ces études, le contrôle cognitif est évalué à travers des indices comportementaux indiquant son efficacité générale (par exemple, effet de congruence, taux d'erreurs), mais qui n'informent pas sur son fonctionnement (ou potentiels dysfonctionnements). Ainsi, mon travail de thèse s'est plus particulièrement focalisé sur l'étude des mécanismes de contrôle cognitif, en s'ancrant dans la théorie du double mécanisme de contrôle postulé par Braver et al. (2007); Braver (2012).

Selon Braver et al. (2007), deux mécanismes de contrôle indépendants sont nécessaires pour ajuster les comportements : le contrôle proactif et le contrôle réactif. Pour rappel, le contrôle proactif est défini comme un biais attentionnel sur et une sélection précoce des informations pertinentes pour la tâche en cours afin de faciliter la résolution de conflits futurs. Le contrôle réactif réfère à une correction tardive et en ligne d'un conflit suite à sa détection. Les deux mécanismes co-existent dans le système de contrôle cognitif mais un de ces mécanismes domine toujours sur l'autre en fonction des demandes de l'environnement et des contraintes internes, afin de réduire le coût cognitif du contrôle tout en préservant son efficacité. La pondération adaptée de ces deux mécanismes de contrôle au contexte donné est d'ailleurs cruciale pour l'adaptation des comportements (Braver, 2012). Cependant, au meilleur de ma connaissance, la capacité d'adapter le poids des mécanismes de contrôle est peu explorée en relation avec l'impulsivité, en faveur de l'étude des capacités réactives et proactives de manière indépendante. Au cours de ma thèse, j'ai donc exploré la capacité d'adapter le poids des mécanismes de contrôle aux demandes externes et aux contraintes internes chez des individus impulsifs de la population générale.

Un plus faible poids des mécanismes de contrôle proactif dans l'impulsivité

Dans l'ensemble, les résultats de ma thèse suggèrent que l'impulsivité serait associée à un plus faible poids accordé aux mécanismes de contrôle proactif, même quand ceux-ci sont favorisés par les demandes externes ou les contraintes internes. Dans un premier temps, l'analyse de l'indice de proactivité comportementale calculé à partir des performances à la tâche d'AX-CPT a montré que les individus impulsifs sont globalement moins proactifs sur l'ensemble de la tâche. De forts traits de personnalité impulsive seraient ainsi caractérisés par un style de contrôle cognitif moins proactif, pouvant en partie expliquer les tendances à agir sous le coup d'une impulsion. En effet, selon la théorie de Braver (2012), une plus faible dominance du contrôle proactif rendrait le système cognitif plus sensible aux informations non-pertinentes et aux distractions. Aussi, les individus impulsifs seraient plus susceptibles de réagir à ces informations, ce qui favoriserait l'émergence de comportements définis comme impulsifs. Cette conception de l'impulsivité est par ailleurs consistante avec Strack and Deutsch (2003) qui définissent le comportement impulsif comme une association entre un stimulus et un schéma comportemental, émergeant de manière automatique et qui requiert peu de ressources cognitives. Dans un second temps, l'analyse temporelle de l'indice de proactivité comportementale a permis de montrer que cette moindre dominance du contrôle proactif est en partie due à la lente adaptation des poids relatifs des mécanismes de contrôle pour s'adapter aux demandes de la tâche (Axe 1). De plus, une seconde étude a montré que de faibles capacités d'inhibition comportementale étaient moins contrebalancées par de plus grands ajustements proactifs avec l'augmentation de la propension à prendre des risques (Axe 2). Ces comportements impulsifs seraient associées à un plus faible engagement des ressources proactives, même si leur implémentation est contrainte par de faibles capacités réactives. Dans l'ensemble, les résultats suggèrent que l'impulsivité est caractérisée par un système de contrôle cognitif préférentiellement moins proactif, mais également moins flexible aux demandes externes (par exemple, la tâche d'AX-CPT, Axe 1) et aux contraintes internes (par exemple, les capacités d'inhibition, Axe 2). Quand cette configuration préférentielle du système n'est pas suffisamment adaptée aux demandes et aux contraintes des contextes dans lesquels évolue l'individu, des comportements inadaptés pourraient émerger.

Interprétations du défaut d'adaptation du poids du contrôle proactif

Dans cette thèse, les résultats comportementaux sont interprétés en faveur d'un déficit de la capacité d'adapter le poids des mécanismes de contrôle proactif en fonction de demandes externes et de contraintes internes chez les individus impulsifs. Néanmoins, il est important de souligner que d'autres interprétations sont possibles. Premièrement, nous pourrions argumenter que les différences observées entre les individus les plus impulsifs et les moins impulsifs sont dues à des différences motivationnelles. En effet, les individus les plus impulsifs pourraient être simplement moins susceptibles à engager des processus proactifs coûteux dans des situations peu motivantes, telles que les situations expérimentales utilisées dans les études de cette présente thèse. Étudier les performances d'individus impulsifs dans des contextes motivants (par exemple, compétition, objectif à atteindre pour obtenir une récompense) pourrait trancher sur cette question. Deuxièmement, il serait intéressant d'étudier l'effet de la consigne sur l'adaptation des mécanismes de contrôle durant la tâche d'AX-CPT. En effet, il a été montré que des consignes explicites induisent une augmentation de l'utilisation du contrôle proactif chez des jeunes adultes (Gonthier et al., 2016) et chez des patients schizophréniques normalisant ainsi leurs performances (Edwards et al., 2010). Des performances différentes avec des consignes implicites et explicites pourraient permettre de distinguer entre adaptation des mécanismes de contrôle spontanée ou forcée, respectivement, chez des individus impulsifs pour mieux définir le déficit, si déficit il y a.

Capacités d'adaptation des mécanismes de contrôle : un intérêt clinique ?

Les résultats de cette thèse, mettant en lumière l'importance de l'étude des capacités d'adaptation flexible du poids des mécanismes de contrôle, permettent également de réfléchir à de nouvelles pistes de recherche clinique. L'impulsivité est un facteur majeur de nombreux troubles psychiatriques regroupés pour la plupart sous le spectre externalisant (Beauchaine et al., 2017), caractérisé par des comportementaux inadaptés dirigés vers l'extérieur. Ce spectre est classiquement opposé au spectre internalisant, caractérisé par des affects négatifs et qui comprend des pathologies telles que les troubles dépressifs et anxieux ainsi que les troubles obsessionnels-compulsifs. Ainsi, si l'on considère que l'impulsivité est caractérisée par un système de contrôle cognitif moins proactif, on peut émettre l'hypothèse que les troubles du spectre internalisant seraient caractérisés, à l'inverse, par un système de contrôle cognitif trop proactif. La moindre dominance du contrôle proactif dans les troubles externalisants engendre une diminution du coût du contrôle, au détriment de son efficacité (i.e., émergence de comportements inadaptés). À l'inverse, un contrôle proactif exacerbé dans les troubles internalisants engendrerait une forte résistance aux informations non-pertinentes, au détriment du coût cognitif (Del Giudice & Crespi, 2018), pouvant également en partie expliquer les comportements rigides et surcontrôlés des individus. Récemment, Hogeveen et al. (2018) ont d'ailleurs rapporté qu'un plus grand poids accordé aux processus proactifs était associé à davantage de comportements compulsifs chez des enfants autistiques. Hallion et al. (2019) ont, par ailleurs, observé une augmentation du contrôle proactif chez des patients souffrant d'anxiété généralisée (*Generalized Anxiety Disorder* – GAD). L'indice de proactivité comportementale était ainsi supérieur chez les patients GAD (PBI = 0.23) que chez les sujets non-GAD (PBI = 0.17). La capacité de moduler de manière flexible les poids des mécanismes de contrôle cognitif pour s'adapter aux demandes externes et aux contraintes internes semblerait être une piste intéressante pour comprendre certaines manifestations cliniques, et donc une cible thérapeutique à envisager. Il serait donc important d'en comprendre les origines pour orienter les prises en charge. En se basant sur la littérature actuelle ainsi que sur certains résultats de la présente thèse, trois hypothèses sont proposées dans ce manuscrit pour expliquer le défaut d'adaptation du poids des mécanismes de contrôle proactif chez les individus impulsifs (cf. Chapter 12). Deux d'entre elles mettent en cause des dysfonctionnements exécutifs pour expliquer le défaut de modulation des poids des mécanismes de contrôle cognitif : (1) la flexibilité mentale réduisant la possibilité de shifter d'un mécanisme de contrôle à l'autre et (2) la mémoire de travail limitant les ressources proactives. La troisième hypothèse cible la diminution de l'activité du système de monitoring, en postulant une relation entre la force du signal d'alarme et l'adaptation des poids relatifs des mécanismes de contrôle. Ces hypothèses ne s'excluent pas entre elles, mais proposent plusieurs pistes de recherche, pouvant définir différents profils d'impulsivité et soulignant l'importance de la personnalisation des prises en charge.

Conclusion

Mon projet de thèse visait à apporter de nouveaux résultats empiriques pour aider à la compréhension des mécanismes cognitifs en lien avec l'impulsivité. Pour ce faire, j'ai exploré les relations entre l'impulsivité et les mécanismes de contrôle cognitif dans la population générale, à travers des indices aussi bien comportementaux qu'électrophysiologiques. Ancré plus particulièrement dans la théorie du double mécanisme de contrôle postulé par (Braver, 2012), l'objectif de ce travail était de participer à l'identification des processus spécifiques du système de contrôle cognitif pouvant modérer la relation entre personnalité impulsive et comportements impulsifs.

Les principaux résultats rapportés dans ce manuscrit suggèrent que l'impulsivité dans la population générale est associée à un système de contrôle cognitif moins proactif et à un défaut d'adaptation du poids des mécanismes de contrôle en fonction des demandes externes et des contraintes internes. Plus précisément, ma thèse démontre que les individus impulsifs accordent moins de poids aux processus proactifs, même si ceux-ci sont favorisés par les demandes de l'environnement ou certaines contraintes internes. Cette faible flexibilité à engager davantage les mécanismes de contrôle proactif quand nécessaires pourrait expliquer l'émergence de comportements impulsifs, quand la configuration du système de contrôle n'est plus adaptée au contexte. La capacité d'adaptation des poids des deux mécanismes de contrôle aux demandes externes et aux contraintes internes pourrait donc, en partie, modérer la relation entre personnalité et comportements impulsifs.

À long terme, la détermination de l'origine du défaut d'adaptation du poids des mécanismes de contrôle, si son rôle dans l'émergence des comportements impulsifs est confirmé, pourrait permettre de personnaliser les prises en charge thérapeutiques de différents profils impulsifs. Les interventions ciblant l'augmentation de la variabilité du rythme cardiaque sont prometteuses. Plusieurs études ont déjà montré que certaines de ces interventions (par exemple, activité physique, pleine conscience ou biofeedback) réduisent l'impulsivité et ses manifestations. Les résultats exploratoires présentés dans ce manuscrit semblent d'ailleurs indiquer que cette réduction serait médiée par la relation entre variabilité du rythme cardiaque et la capacité à moduler de manière flexible le poids des mécanismes de contrôle proactif et réactif en fonction de différents facteurs.

Part VI

Appendices

Appendix

Glossary

Cognitive control: Set of basic cognitive functions that are orchestrated to adjust behaviors to a constantly changing environment. It is composed of three main components: *monitoring*, *proactive control* and *reactive control* mechanisms.

Conflict monitoring: Capacity of the system to detect conflicts between multiple responses. The detection of a conflict is thought to trigger behavioral adjustments.

Congruency effect: Mean difference in the reaction times between congruent and incongruent trials. As reaction times are longer in incongruent trials than in congruent trials, the congruency effect is generally positive.

Gratton effect: Sequential effect that corresponds to a reduction in the *congruency effect* after incongruent trials compared to the *congruency effect* after congruent trials.

Impulsive motor action: Inappropriate execution of prematurely expressed motor action.

Impulsive behaviors: Behavioral components of the *impulsivity* construct, assessed through several experimental paradigms. In the literature, they are mostly divided into two categories: *impulsive motor action* and *impulsive decision-making.*

Impulsive decision-making: Choice of the most disadvantageous alternative when presented with multiple choices.

Impulsiveness: Personality component of the *impulsivity* construct, assessed through self-reported questionnaires. Impulsiveness gathers several personality traits such as sensation seeking, distractibility, risk-taking, lack of forethought, etc.

Impulsivity: Predisposition towards rapid, unplanned reactions to internal or external stimuli with a lack of regard for the negative consequences of these reactions to the impulsive individual or to the others. It is a broad construct that may refer to behaviors (see *Impulsive behaviors*) and to personality traits (see *Impulsiveness*).

Partial-errors: Small incorrect muscular activity that was detected, inhibited and corrected in time to execute the correct response.

Post-error slowing: *Sequential effect* that corresponds to an increase in the reaction times in correct trials following an error.

Proactive control: Preparatory attentional bias, anticipatory selection and active maintenance of the goal-relevant information to facilitate the future *conflict* resolution. It can be assessed through the observation of *sequential effects.*

Reactive control: Late correction of an engaged action through the retrieval of goal-relevant information when the interference occurs. It can be assessed through the observation of *partial-errors* or the SSRT.

Sequential effect: Behavioral adjustments that occur after an error and/or a *conflict*, observable in reaction times. The *post-error slowing* and the *Gratton effect* are two sequential effects.

Appendix

Ethical approval

Study I

Université de Lille

Comité d’éthique en sciences comportementales

<u>Président :</u>
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Villeneuve d’Ascq le, 03/05/2019

Références comité d’éthique :	2019-341-S70
Sigle :	**MECEEG**
Numéro de version et date :	**Version 2 du 26/04/2019**
Promoteur :	**ULille SHS – CHRU Lille**
Responsable Scientifique du projet :	**Clémence ROGER**

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 (CIL) ou du service juridique de votre université ou de votre organisme de recherche.

Pr Yvonne DELEVOYE-TURRELL
Présidente du comité d’éthique

Y. Delevoye

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Study II

Université de Lille

Comité d'éthique en sciences comportementales

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Villeneuve d'Ascq le 11/09/2019

Références comité d'éthique :	**2019-359-S74**
Sigle :	**COCA**
Numéro de version et date :	**Version 3 du 04/09/2019**
Promoteur :	**ULille SHS**
Responsable Scientifique du projet :	**Clémence ROGER**

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.

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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 (CIL) ou du service juridique de votre université ou de votre organisme de recherche.

Pr Yvonne DELEVOYE-TURRELL
Présidente du comité d'éthique

Y. Delevoye

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Study III

Université de Lille

Comité d'éthique en sciences comportementales

Président :
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Président adjoint :
Céline DOUILLIEZ

Personne ressource (dossier administratif) :
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Villeneuve d'Ascq le 20/12/2017

Références comité d'éthique :	**2017-9-S55**
Sigle :	**ECCA Conduite**
Numéro de version et date :	**Version 2 du 17/11/2017**
Promoteur :	**Lille 3**
Porteur projet :	**Yvonne Delevoye**

Date de la soumission : **02/10/2017**

Date de la réunion du comité d'éthique : **10/10/2017**

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

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Comité d'éthique en sciences comportementales

Président :
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Villeneuve d'Ascq le 29 mars 2016

Références comité d'éthique :	2015-9-S35
Sigle :	**INHIBITION-MOTIVATION**
Numéro de version et date :	**Version 2 DU 08/02/2015**
Promoteur :	**LILLE 3**
Porteur projet :	**Clémence Roger & Yvonne Delevoye**

Date de la soumission :	**08/10/2015**
Date de la réunion du comité d'éthique :	**22/10/2015 revu le 21/03/2016**
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.

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Pr Yvonne DELEVOYE-TURRELL
Présidente du comité d'éthique

Y. Delevoye

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Experimental appendices

.1 Calculation of the index of PBI adaptation

Here is presented the method used to calculate the index of adaptation of the proactive behavioral index (PBI) across blocks used in the Chapters 5.1, 5.2, 6.1, 8.3 and 9.1. The adaptation of PBI across blocks during the AX-CPT task was indexed by the slope coefficient β of the regression model: PBI = $\alpha + \beta$ Blocks.

R code

```
for (i in 1:length(unique(data$Subject)))
indDT <- subset(data, data$Subject == unique(data$Subject)[i])
model <- lm(PBI ~Block, indDT)
matrice[i,2] <- model$coefficients[2]
```

The above R code calculates and extracts the slope coefficient β of the regression model for each individual (i.e., "Subject"), allowing the investigation of inter-individual differences in the adaptation of control mechanisms (see Figure 2).

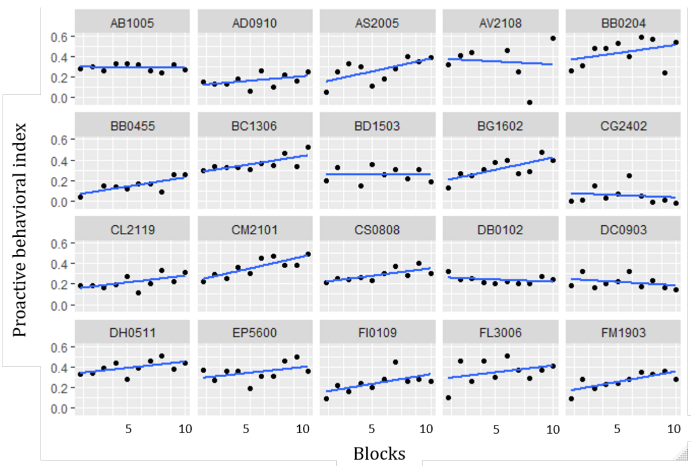

Figure 2 – **Representation of the inter-individual differences in the PBI adaptation across blocks.** Each subgraph represents one individual. Data collected in the Study I.

.2 Extraction of ECG signals from EMG data

To investigate the role of heart rate variability (HRV) in the adaptation of control mechanisms (see Chapter 9), we extracted the ECG information from the signal initially collected for the EMG data (i.e., investigation of the partial-errors). The EMG is the difference between the electrical activities of the two electrodes placed above the same muscle. This difference is used to suppress the cardiac activity, which is present and perfectly observable in each individual electrodes (especially above the muscle of the left hand).

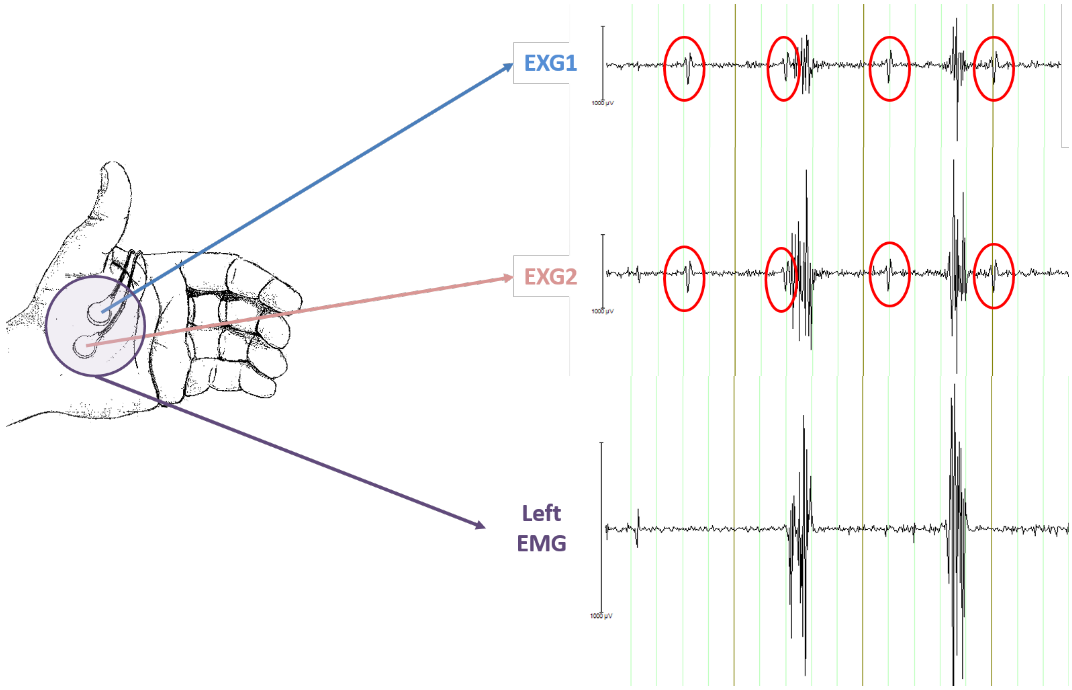

Figure 3 – **Representation of the ECG signal extracted from the EMG data.** To uncover partial-errors in the muscular activities, two electrodes on each hand are placed above the *flexor pollicis brevis*. Here, only the left hand is represented. The EMG data (i.e., left EMG) refers to the difference between the electrical activities of the two electrodes placed above the same muscle (i.e., EXG1 and EXG2). In the electrical signal recorded by the two electrodes, the heartbeats are visible (i.e., circled activities). The data used for this graph were collected in the Study IV. Drawing of the hand : Śmigasiewicz et al. (2020).

The ECG signal was therefore extracted from the EXG1 electrode placed above the *flexor pollicis brevis* of the left hand. Then, an algorithm was used to automatically detect the cardiac peaks (i.e., R peaks of the QRS complexes, see Figure 9.1). A visual inspection of the signal was performed to ensure the quality of the detection and to remove potential artifacts due to muscular activities. The algorithm calculated the RR intervals (i.e., the time difference between two subsequent R peaks). The standard deviations of the RR intervals (i.e., SDNN) were used as index of HRV.

.3 The Simon task adjusting algorithm

In the second study (cf. Chapter 5.2), the Simon task, used to assess cognitive control capacities, was modified by the implementation of an adjusting algorithm based on Rinkenauer et al. (2004). The purpose of this algorithm was to reduce the variability in error rates among the sample by decreasing (or increasing) the maximum response time (i.e., the deadline that is the time difference between the onset of the stimulus and the end of the trial) to favor error commission (i.e., 8% of errors). To adjust the deadline, the algorithm computed the error and omission rates of the previous block. According to these performance indices, the algorithm choose to decrease, increase or maintain the previous deadline.

In the first adjusting block, the deadline was initially set at 1000 ms, and participants were instructed not to make any errors. The first block enabled to have a good estimation of the distribution of reaction times in correct trials which is used to compute individually the deadline that will be imposed to the participant in the next block.The 84th percentile of the RTs distribution (i.e., P84) was to set the deadline for the second adjusting block. The instructions in the second and in the third block were similar to the classical instructions in the Simon task (i.e., respond as quickly and accurately as possible to the stimulus without making too many errors). In the second and third blocks, the error and omission rates were calculated to possibly adjust the previous delay in the next block as follows:

- If the omission rates was superior to 20%, the deadline increased of $P84/10$.
- If the error rate was superior to 10%, the deadline increased of $P84/10$.
- If the error rate was between 6% and 10%, the deadline was maintained.
- If the error rate was inferior to 6%, the deadline decreased of $P84/10$.

To notify participants of deadline changes, feedback was provided for three seconds at the end of each block: if error rate $< 6\%$: "*End of the block. Try to go faster.*", if error rate $> 10\%$: "*End of the block. Too much errors. Slow down.*" and if error rate in the adequate interval [6-10%]: "*End of the block. Your performance is good. Go on.*" Five experimental blocks followed these three adjusting blocks. During the experimental blocks, the error and omission rates were still computed within the algorithm to potentially adjust the deadline following the same aforementioned rules.

.4 UPPS questionnaire (Van Der Linden et al., 2006)

UPPS **Code : ______________________**

Vous trouverez ci-dessous un certain nombre d'énoncés décrivant des manières de se comporter ou de penser. Pour chaque affirmation, veuillez indiquer à quel degré vous êtes d'accord ou non avec l'énoncé. Si vous êtes **Tout à fait d'accord** avec l'affirmation encerclez le chiffre **1**, si vous êtes **Plutôt d'accord** encerclez le chiffre **2**, si vous êtes **Plutôt en désaccord** encerclez le chiffre **3,** et si vous êtes **Tout à fait en désaccord** encerclez le chiffre **4**. Assurez-vous que vous avez indiqué votre accord ou désaccord pour chaque énoncé ci-dessous. Il y a encore d'autres énoncés sur la page suivante.

	Tout à fait d'accord	**Plutôt d'accord**	**Plutôt en désaccord**	**Tout à fait en désaccord**
1. J'ai une attitude réservée et prudente dans la vie.	1	2	3	4
2. J'ai des difficultés à contrôler mes impulsions.	1	2	3	4
3. Je recherche généralement des expériences et sensations nouvelles et excitantes.	1	2	3	4
4. Je préfère généralement mener les choses jusqu'au bout.	1	2	3	4
5. Ma manière de penser est d'habitude réfléchie et méticuleuse.	1	2	3	4
6. J'ai des difficultés à résister à mes envies (pour la nourriture, les cigarettes, etc.).	1	2	3	4
7. J'essayerais tout.	1	2	3	4
8. J'ai tendance à abandonner facilement.	1	2	3	4
9. Je ne suis pas de ces gens qui parlent sans réfléchir.	1	2	3	4
10. Je m'implique souvent dans des situations dont j'aimerais pouvoir me sortir par la suite.	1	2	3	4
11. J'aime les sports et les jeux dans lesquels on doit choisir son prochain mouvement très rapidement.	1	2	3	4
12. Je n'aime vraiment pas les tâches inachevées.	1	2	3	4
13. Je préfère m'interrompre et réfléchir avant d'agir.	1	2	3	4
14. Quand je ne me sens pas bien, je fais souvent des choses que je regrette ensuite, afin de me sentir mieux tout de suite.	1	2	3	4
15. Ça me plairait de faire du ski nautique.	1	2	3	4
16. Une fois que je commence quelque chose je déteste m'interrompre.	1	2	3	4
17. Je n'aime pas commencer un projet avant de savoir exactement comment procéder.	1	2	3	4
18. Parfois quand je ne me sens pas bien, je ne parviens pas à arrêter ce que je suis en train de faire même si cela me fait me sentir plus mal.	1	2	3	4
19. J'éprouve du plaisir à prendre des risques.	1	2	3	4
20. Je me concentre facilement.	1	2	3	4
21. J'aimerais faire du saut en parachute.	1	2	3	4
22. J'achève ce que je commence.	1	2	3	4

	Tout à fait d'accord	Plutôt d'accord	Plutôt en désaccord	Tout à fait en désaccord
23. J'ai tendance à valoriser et à suivre une approche rationnelle et « sensée » des choses.	1	2	3	4
24. Quand je suis contrarié(e), j'agis souvent sans réfléchir.	1	2	3	4
25. Je me réjouis des expériences et sensations nouvelles même si elles sont un peu effrayantes et non-conformistes.	1	2	3	4
26. Je m'organise de façon à ce que les choses soient faites à temps.	1	2	3	4
27. D'habitude je me décide après un raisonnement bien mûri.	1	2	3	4
28. Quand je me sens rejeté(e), je dis souvent des choses que je regrette ensuite.	1	2	3	4
29. J'aimerais apprendre à conduire un avion.	1	2	3	4
30. Je suis une personne productive qui termine toujours son travail.	1	2	3	4
31. Je suis une personne prudente.	1	2	3	4
32. C'est difficile pour moi de me retenir d'agir selon mes sentiments.	1	2	3	4
33. J'aime parfois faire des choses qui sont un petit peu effrayantes.	1	2	3	4
34. Une fois que je commence un projet, je le termine presque toujours.	1	2	3	4
35. Avant de m'impliquer dans une nouvelle situation, je préfère savoir ce que je dois en attendre.	1	2	3	4
36. J'aggrave souvent les choses parce que j'agis sans réfléchir quand je suis contrarié(e).	1	2	3	4
37. J'aimerais la sensation de skier très vite sur des pentes raides.	1	2	3	4
38. Il y a tant de petites tâches qui doivent être faites que parfois je les ignore simplement toutes.	1	2	3	4
39. D'habitude je réfléchis soigneusement avant de faire quoi que ce soit.	1	2	3	4
40. Avant de me décider, je considère tous les avantages et inconvénients.	1	2	3	4
41. Quand la discussion s'échauffe, je dis souvent des choses que je regrette ensuite.	1	2	3	4
42. J'aimerais aller faire de la plongée sous-marine.	1	2	3	4
43. Je suis toujours capable de maîtriser mes émotions.	1	2	3	4
44. J'aimerais conduire vite.	1	2	3	4
45. Parfois je fais des choses sur un coup de tête que je regrette par la suite.	1	2	3	4

.5 AUDIT questionnaire (Gache et al., 2005)

Questionnaire AUDIT (acronyme de Alcohol use disorders test)

Questions :	**Score :**

1. Quelle est la fréquence de votre consommation d'alcool ?

Jamais	0
Une fois par mois ou moins	1
2 à 4 fois par mois	2
2 à 3 fois par semaine	3
Au moins 4 fois par semaine	4

2. Combien de verres contenant de l'alcool consommez-vous un jour typique où vous buvez ?

3 ou 4	1
5 ou 6	2
7 ou 8	3
10 ou plus	4

3. Avec quelle fréquence buvez-vous six verres ou davantage lors d'une occasion particulière ?

Jamais	0
Moins d'une fois par mois	1
Une fois par mois	2
Une fois par semaine	3
Tous les jours ou presque	4

4. Au cours de l'année écoulée, combien de fois avez-vous constaté que vous n'étiez plus capable de vous arrêter de boire une fois que vous aviez commencé ?

Jamais	0
Moins d'une fois par mois	1
Une fois par mois	2
Une fois par semaine	3
Tous les jours ou presque	4

5. Au cours de l'année écoulée, combien de fois votre consommation d'alcool vous a-t-elle empêché de faire ce qui était normalement attendu de vous ?

Jamais	0
Moins d'une fois par mois	1
Une fois par mois	2
Une fois par semaine	3
Tous les jours ou presque	4

6. Au cours de l'année écoulée, combien de fois avez-vous eu besoin d'un premier verre pour pouvoir démarrer après avoir beaucoup bu la veille ?

Jamais	0
Moins d'une fois par mois	1
Une fois par mois	2
Une fois par semaine	3
Tous les jours ou presque	4

7. Au cours de l'année écoulée, combien de fois avez-vous eu un sentiment de culpabilité ou des remords après avoir bu ?

Jamais	0
Moins d'une fois par mois	1
Une fois par mois	2
Une fois par semaine	3
Tous les jours ou presque	4

8. Au cours de l'année écoulée, combien de fois avez-vous été incapable de vous rappeler ce qui s'était passé la soirée précédente parce que vous aviez bu ?

Jamais	0
Moins d'une fois par mois	1
Une fois par mois	2
Une fois par semaine	3
Tous les jours ou presque	4

9. Avez-vous été blessé ou quelqu'un d'autre a-t-il été blessé parce que vous aviez bu ?

Non	0
Oui, mais pas au cours de l'année écoulée	2
Oui, au cours de l'année	4

10. Un parent, un ami, un médecin ou un autre soignant s'est-il inquiété de votre consommation d'alcool ou a-t-il suggéré que vous la réduisiez ?

Non	0
Oui, mais pas au cours de l'année écoulée	2
Oui, au cours de l'année	4

.6 BPAQ questionnaire (Pham et al., 2011)

	Pas du tout			Tout à fait	
1. Il m'arrive de ne pas pouvoir contrôler l'envie de frapper quelqu'un.	1	2	3	4	5
2. Je peux en venir à frapper si on me provoque suffisamment.	1	2	3	4	5
3. Si on me frappe, je riposte.	1	2	3	4	5
4. J'en viens plus vite à la bagarre que la plupart des gens.	1	2	3	4	5
5. Si je dois être violent pour défendre mes droits, je le ferais.	1	2	3	4	5
6. Des gens m'ont tellement mis à bout que j'ai été amené à me bagarrer.	1	2	3	4	5
7. Il y a parfois des bonnes raisons qui poussent à frapper.	1	2	3	4	5
8. J'ai déjà menacé des gens que je connais.	1	2	3	4	5
9. J'ai parfois tant "perdu la boule ", que j'ai cassé des objets.	1	2	3	4	5
10. Quand je ne suis pas d'accord avec mes amis, je le dis ouvertement.	1	2	3	4	5
11. Je réalise souvent que je suis en désaccord avec les gens.	1	2	3	4	5
12. Quand les gens m'embêtent, je peux leur dire ce que je pense d'eux.	1	2	3	4	5
13. Je ne peux pas m'empêcher de polémiquer quand les gens ne sont pas d'accord avec moi.	1	2	3	4	5
14. Mes amis disent que je suis de nature polémique.	1	2	3	4	5
15. Je me calme aussi vite que je m'énerve.	1	2	3	4	5
16. Quand je suis frustré, mon irritation transparaît.	1	2	3	4	5
17. Parfois, je me sens comme un baril de poudre prêt à exploser.	1	2	3	4	5
18. Je suis souvent d'humeur inégale.	1	2	3	4	5
19. Selon certains amis, je m'emporte facilement.	1	2	3	4	5
20. Je "pète les plombs " parfois sans raison valable.	1	2	3	4	5
21. J'ai du mal à me dominer.	1	2	3	4	5
22. Je suis parfois rongé de jalousie.	1	2	3	4	5
23. La vie ne m'a pas bien traité, je n'ai pas de vaine.	1	2	3	4	5
24. Les autres ont été plus chanceux que moi dans la vie.	1	2	3	4	5
25. Je me demande pourquoi je suis si amer.	1	2	3	4	5
26. Des "amis" parlent sur mon dos.	1	2	3	4	5
27. Je me méfie des gens que je ne connais pas et qui se montre trop amicaux.	1	2	3	4	5
28. Je sens qu'on rit parfois derrière mon dos.	1	2	3	4	5
29. Je me demande ce que les gens veulent quand ils sont trop gentils.	1	2	3	4	5
30. Si ma colère envers quelqu'un rejoint un tel niveau, je suis capable de ruiner son travail.	1	2	3	4	5
31. Il m'est déjà arrivé d'être à tel point en colère contre quelqu'un que je lui ai tourné le dos et je suis parti en claquant la porte derrière moi.	1	2	3	4	5
32. Lorsque les gens sont autoritaires, je prends mon temps à faire ce qu'ils veulent, juste pour les narguer.	1	2	3	4	5
33. Parfois je fais courir des bruits à l'égard des gens que je n'aime pas.	1	2	3	4	5
34. Lorsque quelqu'un m'énerve vraiment, je suis capable de ne plus lui parler par représailles.	1	2	3	4	5
35. J'aime faire des farces aux gens, leur jouer de mauvais tours.	1	2	3	4	5

Appendix

Scientific popularization

.7 L'erreur comme signal d'alarme

Article de vulgarisation publié sur le site ***The Conversation***

Dans l'histoire du règne du vivant, la capacité d'adaptation a toujours été au cœur de la survie. Les espèces, animales et végétales, que nous connaissons aujourd'hui sont celles qui possèdent les caractéristiques physiques et/ou cognitives dont la valeur adaptative leur a permis de se reproduire à travers les millions d'années et les environnements changeants. A l'heure actuelle, à plus petite échelle, nos capacités d'adaptation sont toujours essentielles à notre survie.

Le contrôle cognitif

En effet, nous vivons dans un environnement qui change constamment. Dans la rue, de nombreux éléments, par exemple la foule, les voitures ou les obstacles, sont constamment en mouvement. À chaque instant, sans nécessairement nous en rendre compte, nous ajustons nos comportements aux modifications de l'environnement dans lequel nous évoluons. Cette capacité appelée contrôle cognitif regroupe un ensemble de fonctions cognitives qui nous permettent d'adapter nos comportements par rapport à nos intentions et notre environnement.

Pour illustrer cette capacité cognitive complexe, prenons l'exemple d'une situation quotidienne comme la conduite automobile. Lorsque nous conduisons, notre intention est d'atteindre notre destination tout en évitant de créer un accident pour préserver notre intégrité corporelle et celle d'autrui. Pour se faire, notre cerveau, en surveillant l'environnement (ici, la route) ainsi que nos propres actions, est capable d'évaluer si celles-ci sont toujours cohérentes avec la situation.

Dans le cas où une incohérence est détectée (un pied trop lourd sur l'accélérateur ou un ballon au travers de la route), notre cerveau modifie ou planifie une nouvelle séquence d'actions afin de réajuster le comportement (lever le pied pour ralentir ou dévier sa trajectoire pour contourner l'obstacle pour éviter l'accident). Ce contrôle se met en place en quelques millisecondes sans que nous nous en rendions nécessairement compte. Il survient en effet plus fréquemment que l'on ne l'imagine : notre cerveau est capable de détecter certaines toutes petites erreurs dont nous n'avons pas conscience.

La détection de l'erreur

Au sein de toutes les capacités cognitives qui nous permettent, dans notre exemple de la conduite, d'arriver à destination sain et sauf, l'une des plus essentielles est effectivement la détection de l'erreur. L'erreur, comprise ici comme une action inadaptée à l'environnement, peut donc être une action correcte (rouler à 50km/h en ville) qui devient inappropriée lorsque la situation dans laquelle on se trouve change (le ballon au milieu de la route).

Cependant, si nous pouvons apprendre de nos erreurs, encore faut-il se rendre compte lorsque nous en commettons ! Les erreurs, souvent perçues négatives, sont comme un signal d'alarme informant qu'un comportement est à changer ou même à ne pas reproduire. La capacité de détecter l'erreur (ou le changement dans l'environnement) permet de prendre en compte le comportement inadapté afin soit de ne plus le reproduire, soit de le corriger tant qu'il est encore temps.

Notre cerveau est donc capable de détecter ces comportements inappropriés avant même que l'on puisse en prendre pleinement conscience. Au niveau du cortex préfrontal (à l'avant du cerveau), la recherche en neurosciences et en particulier les techniques d'électroencéphalographie (EEG) ont montré la présence d'une activité électrique dont l'amplitude est modulée en fonction de la performance correcte ou incorrecte dans une tâche informatisée.

L'activité cérébrale y est beaucoup plus importante lorsqu'une erreur est commise que lorsqu'il s'agit d'une bonne réponse. Par ailleurs, son amplitude est encore plus grande quand l'erreur est sanctionnée, c'est-à-dire dans les situations où l'erreur a des conséquences négatives. La motivation à ne pas faire d'erreurs renforce le signal d'alarme du cerveau. Ce signal d'alarme est ensuite communiqué à d'autres structures du cortex préfrontal qui mettront en place des stratégies visant à prévenir les erreurs (guetter la présence potentielle d'un animal sur la chaussée après en avoir évité un).

Ce mécanisme de contrôle cognitif est de type proactif puisqu'il anticipe les difficultés qui pourraient être rencontrées, et adapte nos comportements en fonction.

La correction de l'erreur

Néanmoins une action inadaptée doit pouvoir être contrôlée au moment même où elle est commise puisqu'elle peut, dans certaines situations, avoir des conséquences graves pour les individus. Notre cerveau doit donc être capable non seulement de détecter l'erreur mais de la corriger à temps. Ce type de contrôle cognitif est dit réactif. Lorsque cet animal sort subitement de la forêt et traverse la route, notre environnement a changé et notre comportement actuel n'y est plus adapté : il faut le corriger en planifiant, le plus rapidement possible, une nouvelle action (bouger son pied vers la pédale de frein).

Cette fois, pour étudier ces capacités de contrôle réactif, c'est à nos muscles qu'il faut s'intéresser ! L'électromyographie (EMG) permet en effet d'enregistrer l'activité électrique des muscles et de révéler des mouvements imperceptibles à l'œil nu. Cette technique a permis, entre autres, la découverte des ébauches d'erreur, des faibles activités musculaires incorrectes qui précèdent les réponses correctes.

L'ébauche d'erreur (ou erreur partielle) est une mauvaise action qui a été détectée et corrigée par notre cerveau avant qu'elle ne devienne une réelle erreur ! Avant même que l'on puisse percevoir que nous sommes en train de nous tromper, l'erreur engagée est corrigée par le cerveau, et plus particulièrement par plusieurs fonctions cognitives, regroupées sous le nom de fonctions exécutives.

Imaginez votre trajet habituel pour vous rendre au travail. Le samedi, vous vous engagez sur la même route mais au lieu de tourner à gauche pour aller au bureau, aujourd'hui vous devez aller à droite. Par automatisme, ou par manque d'attention, vous engagez l'action de mettre le clignotant à gauche. Avant même de vous rendre compte de votre erreur, cette action, détectée comme inadaptée à la situation par votre cerveau, est stoppée. Votre cerveau planifie en même temps un nouveau comportement, celui de mettre le clignotant à droite.

Grâce à de simples électrodes placées sur les muscles des mains impliquées dans les réponses à donner, nous pouvons donc inférer sur l'efficacité du contrôle cognitif réactif. En effet, la proportion d'ébauches d'erreur sur l'ensemble des erreurs engagées permet de calculer un ratio de correction : à quel point l'individu a été capable de rattraper ses erreurs à temps ? Aussi, le temps qui sépare l'ébauche d'erreur et l'action correctrice nous informe sur le temps nécessaire à la correction : à quelle vitesse l'individu se corrige-t-il ?

L'étude du contrôle cognitif, à travers des approches électrophysiologiques (EEG et EMG), montre que notre cerveau est capable d'adapter nos comportements, après la détection d'une action inappropriée commise ou en train d'être réalisée. La détection de cette « erreur » comportementale, dont nous n'avons pas forcément conscience, permet la mise en place de deux mécanismes de contrôle qui se complètent. L'un est réactif et corrige l'action au moment où elle devient inadaptée. L'autre est proactif et anticipe les difficultés en modifiant en prévention notre comportement.

.8 Les "impulsifs invisibles" : pourquoi et comment les démasquer ?

Article de vulgarisation publié sur le site ***Echosciences Hauts-de-France***

Au quotidien, de nombreux comportements sont qualifiés d'impulsifs. Par exemple, sentir l'odeur d'un pain au chocolat et, sans réfléchir, aller s'acheter une viennoiserie ; ou crier « chocolatine » sur quelqu'un qui dit « pain au chocolat » sont des comportements impulsifs. Ainsi, nous sommes tous plus ou moins impulsifs et nous sommes capables de mettre des mots sur ce type de comportement : « il agit toujours sur un coup de tête », « elle démarre au quart de tour… ». Et surtout, il nous parait facile de les expliquer : « je ne peux pas m'en empêcher », « je n'arrive pas à me contrôler ». Pourtant, l'impulsivité reste un sujet de recherche important en psychologie et certaines facettes de l'impulsivité sont encore mal connues.

Pourquoi étudier l'impulsivité ?

Au-delà de caractériser des comportements plus ou moins communs et problématiques (comme les achats compulsifs, les agressions…), l'impulsivité est également au cœur de nombreux troubles psychiatriques. En effet, plusieurs études ont montré que l'impulsivité augmentait les risques de développer un trouble psychiatrique et en aggravait la sévérité. Prenons l'exemple des addictions (à l'alcool, au tabac ou aux drogues dures) : l'impulsivité représente non seulement un facteur de vulnérabilité aux comportements addictifs, mais augmente aussi la sévérité de l'addiction (le nombre de substances par exemple), ainsi que le risque de rechute et d'abandons des traitements. L'impulsivité impacte donc différentes étapes de la maladie et en complique sa prise en charge. Cependant, il existe plusieurs concepts se rapportant à l'impulsivité, rendant sa définition et son étude compliquée. Aussi, si l'on connait aujourd'hui l'importance de l'impulsivité dans les prises en charge cliniques de certains troubles, il est important de répondre à la question : « Mais au fait, qu'est-ce que l'impulsivité ? ».

Plusieurs formes d'impulsivité

L'adjectif « impulsif » vient du mot latin impellere signifiant « heurter, pousser à, inciter à ». Être impulsif c'est donc agir, ou plutôt réagir de manière incontrôlée, suite à une impulsion qui nous pousse à l'action. Cette définition est très générale et permet d'englober deux aspects comportementaux distincts : l'action impulsive et la prise de décision impulsive (Figure 4).

- L'action impulsive correspond à un comportement rapide, qui se traduit par une

Figure 4 – Ces deux comportements sont caractérisés impulsifs. A gauche, l'action impulsive. A droite, la prise de décision impulsive. Source : *Pixabay*

action inappropriée par rapport à la situation (par exemple, hurler sur cette personne qui demande un « pain au chocolat »). Cet aspect de l'impulsivité serait lié à une analyse de la situation trop rapide et incomplète pour aboutir à une action appropriée. Au quotidien, ce comportement peut être observé au Jungle Speed. Dans ce jeu, le but est d'être le premier à saisir un totem au centre de la table dès que deux cartes identiques sont retournées. Pour compliquer la tâche, certaines cartes sont très similaires. Dans le feu de l'action, il est facile de se tromper et de saisir le totem alors que les cartes étaient en réalité légèrement différentes. Le plus souvent, nous parvenons à stopper notre action avant d'attraper le totem, mais quelqu'un de très impulsif aurait beaucoup plus de difficultés à ce jeu.

- La prise de décision impulsive représente un aspect comportemental de l'impulsivité plus lent. Elle correspond au fait d'avoir tendance à privilégier des solutions immédiates mais désavantageuses (voire contraires aux objectifs) plutôt que les solutions différées mais avantageuses qui ne donnent donc pas de satisfaction dans l'immédiat (par exemple, acheter un pain au chocolat malgré son régime). L'expérience du chamallow de l'équipe de Walter Mischel de l'Université de Standford [3] met en lumière les prises de décision impulsives chez des enfants. Dans une pièce isolée, des enfants sont laissés face à une assiette sur laquelle est posée un unique chamallow. Il leur est indiqué qu'ils peuvent à tout moment manger le chamallow, mais que s'ils attendent le retour de l'adulte, ils en auront deux ! On observe que les plus jeunes enfants ont des difficultés à résister à la

3. Mischel, W., Ebbesen, E. B., & Raskoff Zeiss, A. (1972). Cognitive and attentional mechanisms in delay of gratification. *Journal of personality and social psychology, 21*(2), 204.

tentation de manger immédiatement le chamallow. Certains d'entre eux ne peuvent en effet pas s'empêcher d'en prendre des petits morceaux... Cette forme d'impulsivité est davantage liée aux aspects émotionnels et motivationnels.

Pourquoi agissons-nous de manière impulsive ?

Les comportements impulsifs existent à différents degrés. La recherche en psychologie s'est particulièrement intéressée à l'étude des comportements impulsifs dans des populations pathologiques en identifiant les fonctions cognitives impliquées. Ces dernières sont un ensemble de capacités nous permettant de percevoir, de filtrer, de mémoriser, de traiter ou encore d'utiliser les informations présentes dans l'environnement afin d'interagir avec celui-ci.

L'inhibition, la fonction cognitive qui nous permet d'arrêter des processus afin de réguler nos comportements et nos pensées, a été largement mise en cause dans l'émergence des comportements impulsifs. Un manque d'inhibition amène en effet à faire des erreurs fréquentes et/ou à ne pas pouvoir s'empêcher de faire un choix alors que l'on en connaît les conséquences négatives. Les difficultés d'inhibition sont donc liées aux comportements impulsifs identifiés plus tôt : l'action et la prise de décision impulsives.

Cependant, tous les impulsifs n'ont pas forcément de difficultés d'inhibition... Il existe en effet des « impulsifs invisibles » qui, malgré des traits de personnalité impulsifs importants, ne manifestent pas toujours des comportements inadaptés, et cela grâce à des capacités d'inhibition efficaces (Figure 5). Leur impulsivité n'émerge que dans certaines situations particulières (par exemple, une situation stressante, un moment de fatigue...). Néanmoins, ces traits de personnalité impulsifs restent un facteur de vulnérabilité au développement de troubles psychiatriques. Il est donc important de pouvoir démasquer ces « impulsifs invisibles ».

Pourquoi sommes-nous impulsifs ?

Dans ma thèse, je m'intéresse donc aux « impulsifs invisibles », c'est-à-dire... tout le monde ! Dans cette population, certaines personnes sont plus prédisposées que d'autres à agir de manière impulsive dans certaines situations. Cette différence réside dans les traits de personnalité. Comment démasquer les individus les plus à risque d'agir de manière impulsive ? En repartant de la définition globale de l'impulsivité (une réaction incontrôlée à une impulsion), j'étudie le lien entre les degrés de personnalité impulsive et les fonctions cognitives spécifiques au contrôle de l'action.

Le contrôle de l'action est basé sur un ensemble de fonctions cognitives, dont l'inhibition, regroupées sous le terme de contrôle cognitif. Le contrôle cognitif nous permet d'adapter nos comportements en fonction des situations, particulièrement quand celles-ci sont im-

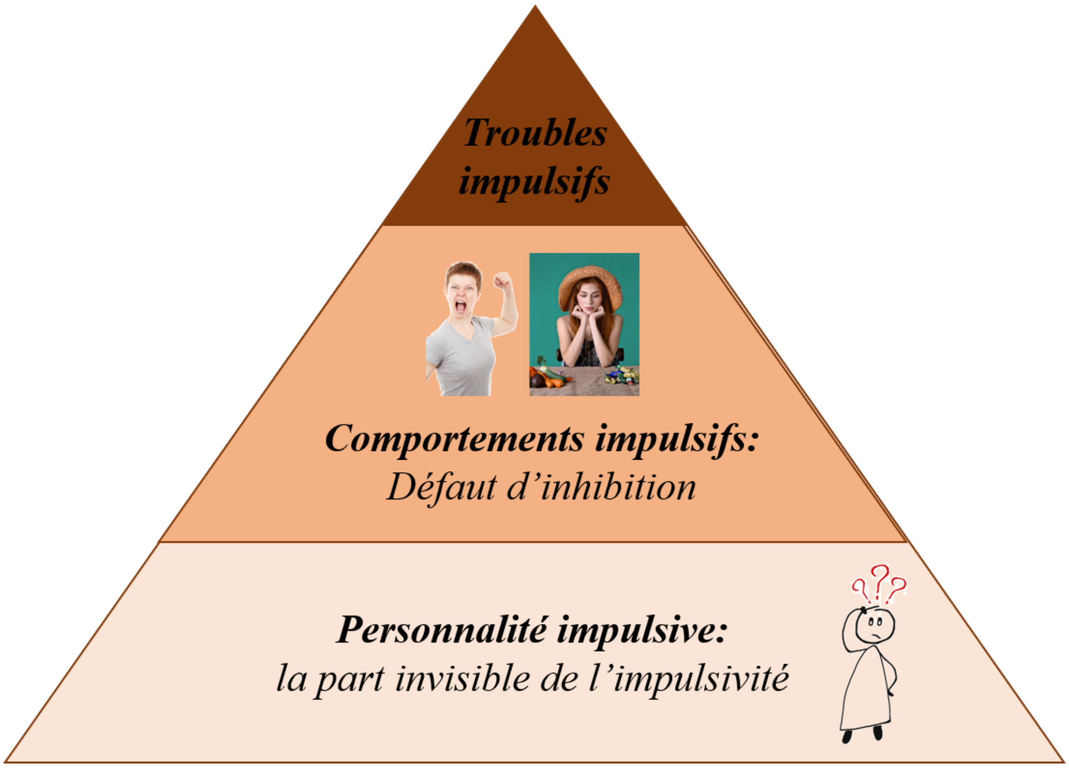

Figure 5 – Nous sommes tous, plus ou moins, des "impulsifs invisibles". Les plus impulsifs d'entre nous manifestent, dans certaines situations, des comportements impulsifs : leur capacité d'inhibition leur fait défaut. Lorsque les capacités d'inhibition sont complétement défaillantes, des troubles du comportement émergent. Source : *Pixabay*

prédictibles. Par exemple, conduire requiert fortement les capacités de contrôle cognitif afin d'ajuster constamment nos comportements aux changements qui s'opèrent lors du trajet (un obstacle, un embouteillage, un panneau routier. . .). Deux mécanismes de contrôle complémentaires, illustrés dans l'article de Todd Braver [4], chercheur à l'Université de Washington, nous permettent d'adapter nos comportements :

Le mécanisme de contrôle réactif nous permet de corriger l'action au moment où celle-ci devient inadaptée (par exemple, freiner brusquement en voyant un piéton traverser). Il est donc principalement supporté par les capacités d'inhibition définies plus haut. Néanmoins, ce mode de contrôle est facilement perturbé (par un état de fatigue ou de stress). Le second mécanisme de contrôle, dit proactif, est plus robuste puisqu'il correspond à une focalisation attentionnelle sur la tâche en cours (par exemple, baisser la musique en arrivant dans une rue piétonne particulièrement bondée). Ce maintien de l'attention permet de rester concentré et imperturbable pour atteindre son objectif.

Une équipe de chercheurs français de l'Université de Lyon [5] a d'ailleurs montré qu'au quotidien nous utilisons davantage les mécanismes de contrôle proactif afin d'adapter

4. Braver, T. S. (2012). The variable nature of cognitive control: a dual mechanisms framework. *Trends in cognitive sciences, 16*(2), 106-113.

5. Criaud, M., Wardak, C., Ben Hamed, S., Ballanger, B., & Boulinguez, P. (2012). Proactive inhibitory control of response as the default state of executive control. *Frontiers in psychology, 3*, 59.

notre comportement à notre environnement. Le proactif serait notre « mode par défaut ». Néanmoins, le maintien de l'attention dans la stratégie proactive nous est coûteux en énergie. Dans des situations plus prédictibles, nous adaptons donc notre mode par défaut pour passer en mode « réactif » et économiser nos ressources cognitives.

L'hypothèse testée dans ma thèse est que les traits de personnalité impulsive font varier le mode de contrôle par défaut. L'impulsivité serait associée, d'une part, à une préférence pour les mécanismes réactifs et, d'autre part, à des difficultés d'adaptation de cette stratégie en fonction des situations. La préférence pour les mécanismes réactifs chez les impulsifs serait adaptée dans des contextes prédictibles. Néanmoins, dans des situations imprédictibles ou complexes (par exemple, une situation stressante), la préférence pour le mode réactif et la difficulté à adopter un mode de contrôle proactif engendreraient des comportements impulsifs inadaptés. Ces derniers ne seraient donc pas seulement liés à un défaut d'inhibition, mais également à des stratégies de contrôle inadaptées. Les individus les plus impulsifs auraient des difficultés à anticiper et à reconnaitre les situations qui nécessitent une adaptation du mode de contrôle, engendrant alors l'émergence de comportements inadaptés.

À terme, mon travail de thèse pourrait mener à précocement prévenir les manifestations comportementales impulsives et les difficultés sociales et psychiatriques qui en découlent. Une des applications directes serait de proposer des exercices travaillant les capacités d'adaptation des stratégies de contrôle, et plus seulement les capacités d'inhibition. L'apprentissage de l'utilisation de stratégies de contrôle plus proactives pourrait devenir une nouvelle cible d'action dans la gestion des troubles du comportement afin de potentiellement réduire l'impact négatif des tendances impulsives.

Appendix

Curriculum Vitae

Fanny GRISETTO

SCALab UMR CNRS 9193 — Doctorante en Psychologie
Université de Lille — Psychologue clinicienne
E-mail : fanny.grisetto@univ-lille.fr — 25 ans

Formation Universitaire

Depuis 2017 ***Doctorat en Psychologie*** **en cours de préparation à l'Université de Lille - UFR de Psychologie.**
Directrices de thèse : Dr. Clémence Roger et Pr. Yvonne Delevoye-Turrell -
Laboratoire de Sciences Cognitives & Sciences Affectives - SCALab UMR CNRS 9193 (CNRS, ULille).

2015-2017 ***Master en Psychologie*** *- Université de Lille, obtenu avec mention TB.*
Parcours : Psychologie des Processus Neurocognitifs et Sciences Affectives (PPNSA).
Obtention du titre de Psychologue.

2012-2015 ***Licence de Psychologie****, Université Sorbonne Paris Nord (Paris-XIII), obtenu avec mention TB.*

Expériences Professionnelles

2020 - 2021 **Attachée Temporaire d'Enseignement et de Recherche** - UFR de Psychologie, ULille.
50% recherche et 50% enseignement (96h eqTD).

2017 - 2020 **Contrat Doctoral et Activités complémentaires du contrat doctoral**:
Financement de thèse : Université de Lille (50%), Région Hauts-de-France (50%).
Activités complémentaires : enseignement et vulgarisation scientifique.
Partenariat industriel avec l'entreprise ECCA-Conduite:
Recherche appliquée, revue de littérature, formations de psychologues.

2016 - 2017 **Psychologue stagiaire, spécialisée en neuropsychologie (620 heures)**
Tuteur : Fabien Rulkin - Clinique psychiatrique Parc Monceau, Lille.
Gestion de groupe: conception et animation d'ateliers mémoire et de remédiation de la cognition sociale.
Bilans neuropsychologiques : entretien clinique, passation de tests neuropsychologiques, analyse et synthèse.
Remédiation cognitive : utilisation du programme RECOS, adaptation et création d'exercice.
Psycho-éducation : transmission de connaissances lors d'ateliers thématiques (mémoire, cognition sociale)

2014 - 2015 **Psychologue stagiaire, spécialisée en neuropsychologie (100 heures)**
Tutrice : Mercé Llach Forcada - Consultation mémoire en SSR, CHI de Poissy/St. Germain-en-Laye.
Capacité d'écoute et de conduction d'entretien & Réalisation de bilans neuropsychologiques

Compétences

Thématiques de recherches	Impulsivité, contrôle cognitif, traitement de l'erreur.
Méthodes d'études	Réponses comportementales : temps de réaction, erreurs.
	Électrophysiologie : électromyographie (EMG), électroencéphalographie (EEG).
Logiciels	BrainVision, Statistica, R, LaTeX, Word, Excel, PowerPoint.
Langues	Anglais (niveau B2, CLES, mai 2015).

Enseignements

2020 - 2021 **Contrat ATER** - UFR de Psychologie, ULille - 96h eqTD.

2017 - 2020 **Activités complémentaires du contrat doctoral**: UFR de Psychologie - ULille - 154h eqTD.

Licence de Psychologie :
- *Méthodologie disciplinaire*, 36h TD.
- *Statistiques descriptives*, 12h TD.
- *Psychologie cognitive*, 16h TD.

Licence MIASHS parcours Sciences Cognitives :
- *Neurosciences fonctionnelles*, 8h CM et 26h TD.
- *Perception & Motricité*, 12h CM et 28h TD.

Master 2 STAPS :
- *Contrôle Moteur*, 4h CM.

Vulgarisation scientifique

2020 *Les impulsifs invisibles : pourquoi et comment les démasquer ?*, sur le site **Echosciences Hauts-de-France.**

2018 *L'erreur comme signal d'alarme*, sur le site **The Conversation**.

2018 Participation à la Fête de la Science. Création et animation d'un atelier *"Est-il possible d'éviter l'erreur ?"* auprès de groupes scolaires et du grand public.

Publications scientifiques - ACL

Grisetto, F., Delevoye-Turrell, Y. N., & Roger, C. (2019). Efficient but less active monitoring system in individuals with high aggressive predispositions. *International Journal of Psychophysiology, 146*, 125-132.

Preprint

Le Denmat, P., **Grisetto, F.**, Delevoye-Turrell, Y.N., Dinca, A., Desenclos-El Ghoulti, I. & Roger, C. (in prep). The contrasted impact of risk-taking tendency and cognitive control on driving behaviour: a large-scale population study with on-road evaluation.

Grisetto, F., Delevoye-Turrell, Y.N., & Roger, C. (submitted). Slower adaptation of control strategies in individuals with high impulsive tendencies.

Grisetto, F., Le Denmat, P., Delevoye-Turrell, Y.N., Vantrepotte, Q., Davin, T., Dinca, A., Desenclos-El Ghoulti, I. & Roger, C. (submitted). The broken proactive-reactive control balance in high risk-takers.

Communications orales - C-COM

Grisetto, F., Delevoye-Turrell, Y., & Roger, C. (2019). *Understanding impulsiveness using the dual mechanisms of control (DMC) framework.* Presentation to Université Catholique de Louvain (UCL), Cross-Border Vision of the Links Between Action and Cognition in Psychology (VITACOG), November 14-15, Louvain-la-Neuve, Belgium.

Le Denmat, P., **Grisetto, F.** & Roger, C. (2019). *Prévenir plutôt que réagir : le contrôle proactif s'installe lorsque le contrôle réactif est moins performant.* Journée Scientifique des Jeunes Chercheurs, November 15, Lille, France.

Roger, C., **Grisetto, F.**, & Delevoye-Turrell, Y. (2019). *Revealing cognitive control processes in normal impulsivity using electrophysiological recordings.* Annual Meeting of the Belgian Association for Psychological Sciences (BAPS), May 14-15, Liège, Belgium.

Grisetto, F., Delevoye-Turrell, Y. & Roger, C. (2018). *Approche électrophysiologique des capacités de contrôle cognitif chez des individus impulsifs sains.* Communication au 59ème congrès annuel de la Société Française de Psychologie (SFP), September 5-7, Reims, France.

Grisetto, F., Delevoye-Turrell, Y. & Roger, C. (2018). *Revealing cognitive control processes in normal population by electrophysiological recordings.* Communication at the 4th international conference of the European Society of Cognitive and Affective Neuroscience (ESCAN), July 19-22, Leiden, The Netherlands.

Communications affichées - C-AFF

Grisetto, F., Delevoye-Turrell, Y., Bardou, M. & Roger, C. (2019). *Modulation of the effect of aggressiveness on performance monitoring by the heart rate variability.* European Society of Cognitive Psychology, September 25-28, Tenerife, Spain.

Grisetto, F., Delevoye-Turrell, Y., & Roger, C. (2018). *Revealing cognitive control processes in normal impulsivity by electromyographic recordings.* Annual Meeting - Society for Psychophysiological Research, October 3-7, Quebec City, Canada.

Grisetto, F., Vantrepotte, Q., Delevoye-Turrell, Y. & Roger, C. (2018). *Risk-taking behaviors have an impact on proactive control abilities.* 4th international conference of the European Society of Cognitive and Affective Neuroscience (ESCAN), July 19-22, Leiden, The Netherlands.

Grisetto, F., Delevoye-Turrell, Y., & Roger, C. (2016). *The influence of personality traits on inhibition capacities: individual differences in cognitive control.* Annual meeting of Cognitive Neurosciences and Psychophysiology Society, September 29-30, Lille, France.

Grisetto, F., Delevoye-Turrell, Y. & Roger C. (2016). *The influence of personality traits on inhibition capacities: individual differences in cognitive control.*. Annual meeting of Cognitive Neurosciences and Psychophysiology Society, September 29-30, Lille, France.

Roger, C., **Grisetto, F.**, & Delevoye-Turrell, Y. (2016). *The influence of personality traits on the ability to correct online erroneous actions.* 6th Motivation and Cognitive Control Symposium, August 24-26, St Andrews, United Kingdom.

Organisation de conférences

2f-NIRS 2017 Membre du comité d'organisation de la 4ème réunion annuelle du réseau français des utilisateurs du NIRS.

Prix et distinctions

2019 Prix Innovation Challenge Doc' : montage de projet de recherche auprès d'une entreprise (EvoluCare).

Formations professionnelles

2017, 2019 Sauveteur Secouriste du Travail (SST).
2018 - 2019 Formations à l'enseignement dans le supérieur.