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THÈSE

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

THE NATURE OF REPRESENTATIONS IN AGREEMENT PROCESSING AND THE NEUROCOGNITIVE PROCESSING THAT UNDERLIES IT

LA NATURE DES REPRESENTATIONS ET DES PROCESSUS NEUROCOGNITIFS IMPLIQUES DANS LE TRAITEMENT DE L'ACCORD GRAMMATICAL

Présentée et soutenue publiquement
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This thesis is the final version which has been revised following the commentaries of the *rapporteurs*. Hence, revision has been made by adding some sentence for the purpose of the following points:

1. To clarify why the event related potential (ERP) data was time-locked to the onset of the verb (Chapter 6 and 7).
2. To clarify that the role of abstract and associative representations are not in opposition (Chapter 7 and 10).
3. To clarify that through the current results, abstract representations are observed through the double violation effect (Chapter 2, 3, 6, 7 and 10).

Apart from that, revision was also done for the figures in the following point:

1. To correct the figures' title and adjust the title in the list of figures.
2. To correct the image of Figure 18.
3. To add another figure, that is Figure 25.

Finally, as a result of this revision, the page numbering in the table of contents, list of figures, and list of tables is adjusted.

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Abstract – français

Cette thèse a pour objectif d'apporter une meilleure compréhension du traitement de l’accord sujet-verbe en langage parlé. L'accord entre un sujet et un verbe contient des informations sur les rôles thématiques qui permettent à l'auditeur de savoir qui est la personne qui fait l'action et le nombre de personnes impliquées dans cette action. Par conséquent, pour comprendre le sens d'une phrase, il est essentiel de reconnaître les mots qui partagent des relations sujet-verbe. À ce jour, en enregistrant l'activité cérébrale avec la technique de l’électroencéphalographie (EEG), il a été montré que les traits abstraits (nombre, personne et genre) sont utilisés lors du traitement de l'accord en lecture par l’introduction de violations morphosyntaxiques et les traits abstraits impliqués. Malgré cela, nous savons peu de choses sur la nature des représentations et des processus impliqués dans le traitement de l’accord. En utilisant des mesures cérébrales, cette thèse étudie la nature des représentations opérant dans le traitement de l'accord sujet-verbe en examinant deux niveaux de représentations possibles (abstrait et associatif) et leur flexibilité d'accès ainsi que le rôle de la prédiction dans l’accord sujet-verbe. Dans ce but, nous examinerons l’accord sujet-verbe en langage parlé dans la langue française.

Pour atteindre ces trois objectifs, nous avons mené trois études dans lesquelles nous avons manipulé à la fois la nature des violations d'accord en terme de traits abstraits (violation simple du trait de la personne, violation simple du trait du nombre, et double violation avec les traits de la personne et du nombre) et des représentations associatives en opposant des pronoms qui avaient soit une fréquence de cooccurrence élevée avec une flexion verbale en langue française (fréquence associative élevée) soit une fréquence de cooccurrence faible (fréquence associative faible). Nos résultats après l’écoute du verbe ont confirmé l'accès à des traits abstraits en langue parlée. De plus, il a été montré un accès aux représentations associatives dès l’écoute d’un pronom, ce qui amenait le système cognitif à prédire activement la flexion verbale fortement associée avec le pronom, tel que le traitement du verbe à bas niveau était affecté dès le traitement du phonème initial. Pour le second objectif, nous avons en plus manipulé les demandes de tâche dans deux expériences EEG avec les tâches de décision lexicale et de catégorisation grammaticale. Nos résultats après l’écoute du verbe ont montré qu'il y a une

certaine flexibilité dans l'accès aux représentations abstraites, de sorte que leur accès était renforcé en tâche de décision lexicale. Au contraire, la sensibilité aux représentations associatives entre le sujet pronominal et la flexion verbale était observée indépendamment de la tâche expérimentale employée. En ce qui concerne le troisième objectif, nous avons mené une étude en magnétoencéphalographie (MEG) avec les mêmes stimuli que dans nos précédentes expériences. Conformément à nos résultats en EEG, les données MEG suite à l'écoute du verbe ont montré une influence de la fréquence associative lors du traitement initial du verbe à un niveau phonologique au sein du cortex auditif primaire. Cela suggère que des représentations de haut niveau, telles que des représentations associatives, sont utilisées pour préactiver des flexions verbales, immédiatement après la reconnaissance du pronom, affectant le traitement de bas niveau de nouvelles informations. Cette prédiction en accord sujet-verbe était également associée à l'activation du cortex frontal inférieur et de l'aire motrice. Dans l'ensemble, cette thèse apporte une contribution importante à la compréhension de l'accord sujet-verbe en montrant un accès flexible à différents niveaux de représentations et le rôle de la prédiction à partir de régularités statistiques.

Abstract – English

This thesis is an attempt to contribute more information about subject-verb agreement in spoken language processing. The subject-verb agreement contains thematic role information that informs the listener who does the action and how many people are involved. To understand the meaning of a sentence, it is therefore essential to recognize words sharing subject-verb relationships. By recording the brain activity with the electroencephalography (EEG) method, it has been found that abstract morphosyntactic features (number, person, and gender) were accessed and separately used during agreement processing in reading when morphosyntactic violations were introduced and abstract morphosyntactic features were manipulated. Despite this, we know little about the nature of representations and processes involved in agreement processing. By using brain measures, this thesis investigates the nature of the representations operating in subject-verb agreement processing by examining two levels of representations (abstract and associative), the flexibility in accessing these two levels of representations and the role of prediction in the computation of subject-verb dependencies. To this end, we will examine the subject-verb agreement in spoken language processing with the French language.

To achieve these three aims, we conducted three studies in which we manipulated both the nature of agreement violations in terms of abstract features (single violation of person feature, single violation of number feature, and double violation of person and number features) and associative representations by contrasting pronouns which had either a high co-occurrence frequency with one verbal inflection in French language use (high associative frequency) or a low co-occurrence frequency (low associative frequency). Our ERP results elicited by spoken verbs when they were preceded by pronouns confirmed the access to abstract features representations in spoken language as soon as the verbal inflection is recognized. Moreover, it was found that associative representations were also used in the processing of subject-verb agreement. By using the associative representations after hearing the pronoun, the cognitive system actively makes a prediction about the upcoming verbal inflection, leading up to affect the verbal processing at low levels from its initial phoneme.

For the second aim, we also manipulated the task demands in two EEG experiments by using the lexical decision task (LDT) or the noun categorization task. Our ERP results time-

locked to verbs preceded by pronouns showed that there is flexibility in accessing the abstract representations such that their access was enhanced by the lexical decision task. On the contrary, the sensitivity to associative representations between pronominal subject and verbal inflection was observed, regardless the task demands, in lexical decision and noun categorization tasks.

Regarding the third aim, we conducted a magnetoencephalographical (MEG) study with the same stimuli as in our previous EEG experiments. In line with our previous findings, MEG data time-locked to the verb onset showed an influence of associative frequency in the early stage of verbal processing at phonological level in the primary auditory cortex. This suggests that higher-level representations such as associative representations were used to preactivate information related to the upcoming verbal inflection immediately after the recognition of pronouns, causing low-level processing of new information to be affected. This prediction in subject-verb agreement was also associated with the activation of inferior frontal cortex and motor area. Overall, this thesis makes a strong contribution in the understanding of subject-verb agreement by showing a flexible access to different representational levels and the role of prediction from statistical information in language use.

Résumé long

Le langage est une capacité humaine unique qui permet d'exprimer nos idées et de comprendre les idées d'autres individus, afin que nous puissions communiquer sans effort sur nos expériences passées ou nos projets. Cependant, pour qu'un message puisse être correctement transmis et reçu, il est nécessaire de suivre certaines règles. Par exemple, si les règles syntaxiques ne sont pas correctement appliquées, la personne ne peut pas comprendre le message véhiculé. L'une des règles qui régit la langue est l'accord grammatical. Par l'accord grammatical, il est possible de déterminer les mots qui ont des relations grammaticales communes, comme dans l'accord sujet-verbe, où la forme du verbe dépend des propriétés grammaticales du sujet. En particulier, en détectant les liens grammaticaux entre un sujet et un verbe, l'auditeur peut attribuer les rôles thématiques, c'est-à-dire qui réalise une action et combien de personnes participent à cette action, ce qui est essentiel pour comprendre le sens d'une phrase.

Actuellement, les études qui se sont intéressées au traitement de l'accord grammatical ont été menées lors de la lecture de phrases, comme les marques morphologiques signalant les relations grammaticales, sont plus présentes dans le langage écrit que dans le langage parlé. Cependant, dans des langues morphologiquement riches, les marques morphologiques s'expriment clairement en langage parlé. Dans cette thèse, nous étudions l'accord sujet-verbe à l'oral avec une langue morphologiquement riche qui est le français. Nous espérons étendre les résultats trouvés antérieurement dans l'accord sujet-verbe en situation de lecture à la langue parlée, mais aussi nous souhaitons mieux comprendre la nature des représentations qui sont utilisées lors du traitement de l'accord sujet-verbe. En nous basant sur la littérature antérieure, nous soutenons l'idée qu'il existe deux niveaux de représentations : les représentations abstraites et les représentations associatives qui sont supposées dans le traitement du langage. Dans le traitement de l'accord grammatical, les représentations abstraites codent les propriétés grammaticales des langues (Chomsky, 1995 ; Harley & Ritter, 2002 ; Pearlmutter, 2000), tandis que les représentations lexicales associatives codent les probabilités entre les mots (Corbett, 1991 ; Truswell & Tanenhaus, 1994 ; Seidenberg & MacDonald, 1999). Dans l'accord sujet-verbe, les représentations abstraites correspondent à l'utilisation des traits morphosyntaxiques comme la personne, le nombre et le genre, tandis que des représentations lexicales associatives sont liées à la fréquence de co-occurrence entre un sujet et la flexion verbale associée dans le

langage courant. Dans ce contexte, certaines études électrophysiologiques ont montré l’utilisation de représentations abstraites lors du traitement de l'accord sujet-verbe lors de la lecture de phrases. Il est intéressant de noter que le rôle des régularités statistiques a été bien étudié dans l'acquisition du langage, mais nous savons peu de choses sur la façon dont les régularités linguistiques affectent le traitement de l’accord grammatical dans la compréhension du langage. Par conséquent, nous allons tester dans cette thèse la possibilité d’un accès à des représentations lexicales associatives dans l'accord sujet-verbe et nous allons examiner l’implication à la fois de représentations abstraites et associatives dans l'accord sujet-verbe.

De plus, si deux représentations sont accessibles au cours du traitement de l'accord sujet-verbe, on peut se demander si une certaine flexibilité dans l'accès à ces représentations peut être présente ? La flexibilité cognitive est liée à la capacité d'adaptation quand l'environnement change. En ce qui concerne les représentations abstraites et associatives, notre objectif est d'examiner si elles sont accessibles de manière flexible, c'est-à-dire si l'accès à ces représentations dépend de la tâche demandée, ou si elles sont utilisées de manière automatique, c'est-à-dire si ces représentations sont toujours accessibles, quelle que soit la tâche demandée, pendant le traitement de l'accord. Il est intéressant de remarquer que dans la vie de tous les jours, les personnes sont souvent confrontées à un environnement changeant comme elles peuvent devoir comprendre une phrase dans un endroit sonore calme ou dans un endroit bruyant. Outre la capacité de filtrer l'information, une question encore non résolue est de savoir si la capacité à comprendre un message, en particulier de traiter l'accord sujet-verbe, est liée à cette capacité de flexibilité.

En outre, au-delà de la question de la nature des représentations, cette thèse se concentre sur la présence de mécanismes prédictifs dans le cadre du traitement de l'accord sujet-verbe. De plus en plus, de neuroscientifiques affirment que notre cerveau n'est pas passif en attente de nouvelles informations. Au contraire, il génère activement des prédictions sur les nouvelles informations à venir (Bar, 2009 ; Clark, 2011 ; Friston, 2012). Le fait d'avoir un fonctionnement cérébral pro-actif et de générer des prédictions sur les nouvelles informations à venir signifie que notre cerveau pré-active une information avant qu'elle ne soit reçue physiquement. Dans le cas où il y a une divergence entre la prédiction effectuée et l'information reçue physiquement, le système cognitif peut faire une mise à jour de sa prédiction afin d’optimiser ses prochaines prédictions. La capacité de prédiction dans le traitement du langage a été largement explorée dans le domaine de la compréhension du langage depuis une vingtaine d’année. Mais, on sait peu de choses sur le fonctionnement de la capacité de prédiction pendant le traitement de l’accord grammatical. La plupart des études antérieures en neuroimagerie sur les mécanismes prédictifs dans la compréhension du langage se sont particulièrement concentrées sur le langage écrit (par exemple, DeLong, Urbach et Kutas, 2005 ; Lau, Holcomb et Kuperberg, 2013), tandis que celles qui ont abordé dans le langage parlé (par exemple, Ettinger et al., 2014 ; Gagnepain et al., 2012 ; Gaston et Marantz, 2017 ; Gwilliams et al., 2018) étaient plus axées sur la reconnaissance des mots parlés.

En résumé, cette thèse a trois objectifs :

1. Etudier la nature des représentations impliquées dans le traitement de l’accord sujet-verbe en examinant deux niveaux de représentations (abstraites et associatives).
2. Examiner s'il existe une flexibilité dans l'accès à ces deux niveaux de représentations.
3. Examiner les mécanismes prédictifs dans le traitement de l’accord sujet-verbe

Pour ce faire, nous avons mené trois expériences. Dans ces expériences, nous avons utilisé les mêmes stimuli pour manipuler un accès aux représentations abstraites et associatives (plus de détails dans la section sur les stimuli du chapitre 7). En ce qui concerne les techniques de mesure utilisées, nous avons employé l'électroencéphalographie (EEG) dans les deux premières expériences et la magnétoencéphalographie (MEG) dans la troisième expérience. L'EEG est souvent utilisée dans les études sur le traitement de l’accord grammatical car elle permet d’avoir une précision de l’ordre de la milliseconde près sur l’activité du cerveau, ce qui en fait une bonne méthode pour saisir un processus qui se produit rapidement. Les deux premières expériences EEG ont été réalisées pour répondre aux deux premiers objectifs de cette thèse. La MEG a quant à elle une meilleure résolution spatiale pour identifier l’activation des zones du cerveau et nous l’avons utilisée pour atteindre notre troisième objectif. Par ailleurs, pour atteindre notre deuxième objectif, nous avons mis en œuvre deux tâches différentes : l'une était une tâche de décision lexicale et l'autre une tâche de catégorisation grammaticale.

Plus précisément, les chapitres de cette thèse présentent la structure suivante. Le chapitre 1 a pour objectif de présenter comment le langage est traité par le cerveau et comment est étudié le traitement du langage par l’utilisation de techniques de neuroimagerie. Dans ce chapitre, il est abordé les différentes méthodes d’investigation cérébrale qui ont été utilisées dans l'étude des bases neurales du langage. Après avoir rappelé l’approche historique de la neuropsychologie, nous décrivons l’ensemble des techniques de neuroimagerie non invasives mesurant l'activité cérébrale des participants qui effectuent une tâche particulière. Ces techniques peuvent être divisées en deux groupes : celles qui se concentrent sur les activités neuronales et ont une haute résolution temporelle, et celles qui se concentrent sur l'activation structurale et fonctionnelle du cerveau et ont une haute résolution spatiale. Après cette présentation, mais nous mettons l'accent sur les techniques qui sont directement liées à notre étude (c'est-à-dire l'électroencéphalographie - EEG et la magnétoencéphalographie - MEG), afin de familiariser le lecteur à ces techniques.

Puis, le chapitre 2 aborde les composantes de l'accord grammatical d'un point de vue linguistique, en particulier dans l'accord sujet-verbe. Après avoir décrit les trois traits morphosyntaxiques, qui sont les plus présents dans l'accord grammatical au sein de la plupart des langues (personne, nombre et genre), il est défini que l'accord grammatical est reconnu par le partage de mêmes propriétés grammaticales entre un élément dit « cible » et un élément appelé « contrôleur ». L'élément « contrôleur » est celui qui impose ses propriétés grammaticales à celles portées par l'élément « cible ». Au sein de ce chapitre, il est aussi présenté le traitement de l'accord grammatical selon une perspective neurocognitive. Dans cette partie, nous nous concentrons sur la présentation des trois principaux potentiels évoqués obtenus en EEG qui sont liés au traitement de l'accord sujet-verbe : N400, LAN et P600 (voir Molinaro, Barber, & Carreiras, 2011, pour une revue). Les deux derniers sont spécifiquement liés à l'accord sujet-verbe. Tandis que l'onde LAN (*Left Anterior Negativity*) est une négativité observée sur les électrodes antérieures gauches après à la détection d'une violation morphosyntaxique entre 300 et 500 ms, l'onde P600 arrive plus tardivement après une violation morphosyntaxique entre 500 et 800 ms, comme reflet d'un processus de réanalyse après la détection précoce d'une violation morphosyntaxique.

Ensuite, le chapitre 3 présente la notion de représentations mentales et décrit la distinction entre des représentations mentales abstraites et associatives ainsi que leur relation avec l'accord grammatical. Dans le traitement de l'accord grammatical, il y a deux types de représentations mentales proposées. Les représentations abstraites codent les propriétés grammaticales des langues, tels que les traits morphosyntaxiques comme la personne, le nombre et le genre (Chomsky, 1995 ; Harley & Ritter, 2002 ; Pearlmutter, 2000), tandis que les représentations lexicales associatives codent les probabilités entre les mots (Corbett, 1991 ; Truswell & Tanenhaus, 1994 ; Seidenberg & MacDonald, 1999). L'étude des traits morphosyntaxiques comme la personne, le nombre et le genre a amené certains chercheurs à proposer une organisation hiérarchique entre ces traits abstraits. Actuellement, il n'est pas mis en évidence par des études en EEG l'existence d'une organisation hiérarchique entre ces traits abstraits. Par contre, il a été montré par des études en EEG l'accès à des traits morphosyntaxiques abstraits en situation de lecture. Il reste donc à montrer leur accès dans le langage parlé et l'accès aux représentations lexicales associatives dans le traitement de l'accord sujet-verbe.

Par la suite, le chapitre 4 se concentre sur la flexibilité cognitive et la façon dont la flexibilité cognitive peut affecter l'accès des représentations mentales pendant le traitement de l'accord grammatical. L'automaticité est également considérée comme une option alternative. Plus précisément, après avoir défini la notion de flexibilité cognitive, il est présenté des études explorant la flexibilité cognitive dans le traitement du langage comme les travaux de Balota & Yap (2006) s'intéressant à la flexibilité d'accès des différentes représentations linguistiques selon les demandes de trois tâches, qui sont la tâche de décision lexicale, la dénomination et la lecture. Puis, il est décrit des études en EEG plaidant en faveur à la fois d'une certaine automaticité et de la flexibilité dans le traitement de l'accord sujet-verbe en regardant les réponses cérébrales évoquées après des violations morphosyntaxiques. Cependant, ces études n'ont pas étudié la flexibilité cognitive dans l'accès à différents types de représentations, abstraites ou associatives, qui sont impliquées dans le traitement de l'accord sujet-verbe.

Après avoir discuté la notion de flexibilité cognitive, le chapitre 5 traite des mécanismes de prédiction dans le traitement du langage et des facteurs permettant de l'étudier. Avant de présenter des études en EEG mettant en évidence des mécanismes prédictifs dans la compréhension du langage, nous avons abordé d'où vient la notion de prédiction. Cette notion a été préalablement définie dans le domaine de la perception, comme étant la capacité à pré-activer une information avant qu'elle soit reçue physiquement à travers une organisation hiérarchique amenant des informations de haut niveau à pré-activer des informations de bas niveau pour que les informations prédites soient les plus proches possibles des informations à recevoir physiquement. Par conséquent, vouloir mettre en évidence des mécanismes prédictifs dans la compréhension du langage oblige soit à trouver un effet des mécanismes avant l'arrivée de l'information prédite et soit à trouver un effet des mécanismes prédictifs à partir d'informations de haut niveau affectant l'activation des informations de bas niveau au niveau cérébral. Par ailleurs, il est proposé que des mécanismes prédictifs dans le domaine de la perception et dans le domaine du traitement du langage dépendent des régularités statistiques de l'environnement et de la langue apprise.

Ensuite, le chapitre 6 présente les objectifs de notre thèse et les hypothèses sur la base d'études antérieures. La relation sujet-verbe étudiée dans cette thèse est la relation entre un sujet pronominal et un verbe.

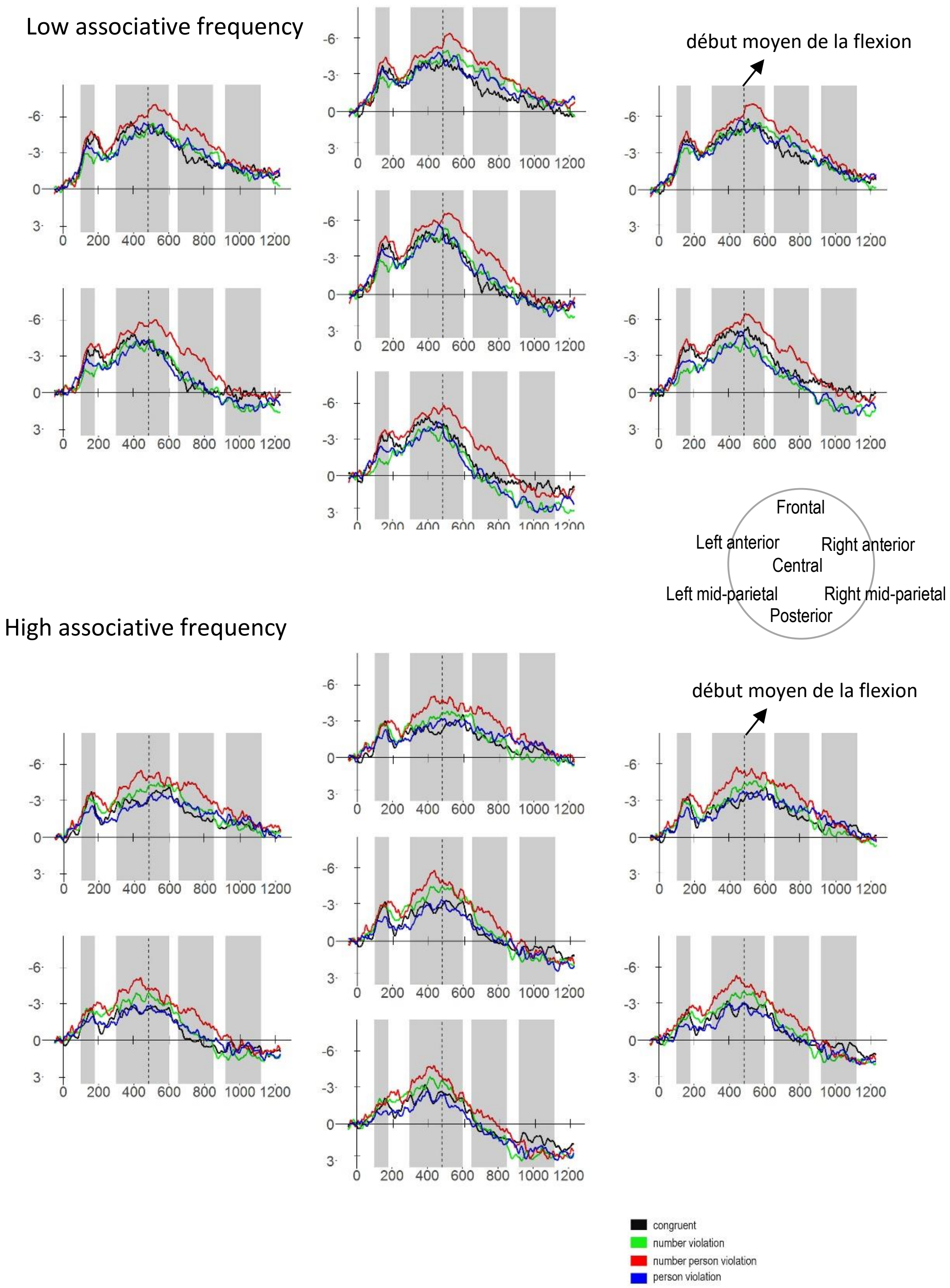
Pour atteindre le premier objectif de cette thèse, comme dans les études précédentes sur le traitement de l'accord grammatical, nous avons utilisé la technique EEG et manipulé les traits morphosyntaxiques abstraits pour créer des violations morphosyntaxiques (c'est-à-dire des violations de nombre, des violations de personne et des violations de nombre et de personne). Ces violations ont été construites pour observer des différences possibles entre le nombre de traits impliqués dans les violations (c'est-à-dire, une violation simple contre une violation double impliquant le trait de la personne et le trait du nombre) pour démontrer l'accès à des représentations abstraites dans l'accord sujet-verbe en langage parlé. Pour étudier l'accès à des représentations associatives, nous avons pris en compte la fréquence associative entre un sujet et ses flexions verbales en mesurant leur fréquence de co-occurrence dans l'utilisation de la langue. Plus de détails sont présentés dans la section méthode du chapitre suivant sur l'expérience 1 (chapitre 7). S'il y a un accès aux représentations associatives pendant le traitement de l'accord sujet-verbe, on peut s'attendre à ce que l'amplitude des potentiels évoqués soit affectée à partir du verbe par la fréquence associative entre un sujet et sa flexion verbale. Par ailleurs, comme des mécanismes prédictifs sont décrits comme associés à des régularités statistiques, nous avons émis l'hypothèse que le système active les représentations associatives à partir du sujet et l'utilise pour prédire la flexion verbale à un bas niveau de traitement, comme pendant le traitement phonologique. Comme l'onde N100 est connue comme étant le reflet du traitement phonologique (Cason & Schön, 2012; Getz & Toscano, 2019; Noe & Fischer-Baum, 2020; Obleser et al., 2006), nous nous attendons que l'amplitude de l'onde N100 soit modulée par la fréquence associative entre un sujet et ses flexions verbales à partir de l'écoute du verbe.

Suivant notre second objectif, s'il y a un accès à des représentations abstraites et associatives lors du traitement de l'accord sujet-verbe dans le langage parlé, nous souhaitons examiner s'il existe une flexibilité dans leur accès. Pour ce faire, nous avons manipulé les instructions de deux tâches tout en utilisant la même technique EEG et les mêmes stimuli que dans notre première expérience EEG. Pour chaque essai, dans les deux expériences, nous avons présenté un mot premier suivi d'une cible. Dans l'une des expériences (Expérience 1), nous avons demandé aux participants d'effectuer une tâche de décision lexicale sur la cible, où ils devaient répondre s'ils entendaient un pseudomot. Dans une autre expérience (Expérience 2), nous leur avons demandé d'effectuer une tâche de catégorisation grammatical sur la cible, où ils devaient répondre s'ils entendaient un nom. Nous avons ensuite comparé les potentiels évoqués après l'écoute du verbe dans les deux expériences. Nous nous attendions à un accès plus fort aux représentations abstraites dans le cas de la tâche de catégorisation grammaticale, tandis qu'il y aurait un accès plus fort aux représentations associatives dans le cas de la tâche de la décision lexicale.

Notre troisième objectif était d'isoler les zones du cerveau liées à la prédiction dans le traitement de l'accord sujet-verbe. À cette fin, nous avons utilisé la technique MEG, qui a une meilleure résolution spatiale par rapport à l'EEG (chapitre 9). Nous avons utilisé les mêmes stimuli que dans nos expériences EEG, avec la tâche de décision lexicale classique où les participants devaient répondre à la fois sur la cible pour les mots et les non mots. En lien avec la définition de la prédiction, nous nous attendions à ce que l'activation des structures cérébrales impliquées dans le traitement phonologique, comme le cortex auditif primaire et de manière générale dans le gyrus temporal supérieur, soit influencée par la fréquence associative entre le sujet et sa flexion verbale, comme reflet de la pré-activation d'informations de bas niveau par des informations de haut niveau. Nous faisons aussi l'hypothèse que l'activation du gyrus frontal inférieur devrait varier selon la fréquence associative, ce qui suggère une prédiction à un haut niveau des représentations associatives entre le sujet et sa flexion verbale. Nous nous attendions également à un accès aux représentations abstraites dans le gyrus frontal inférieur.

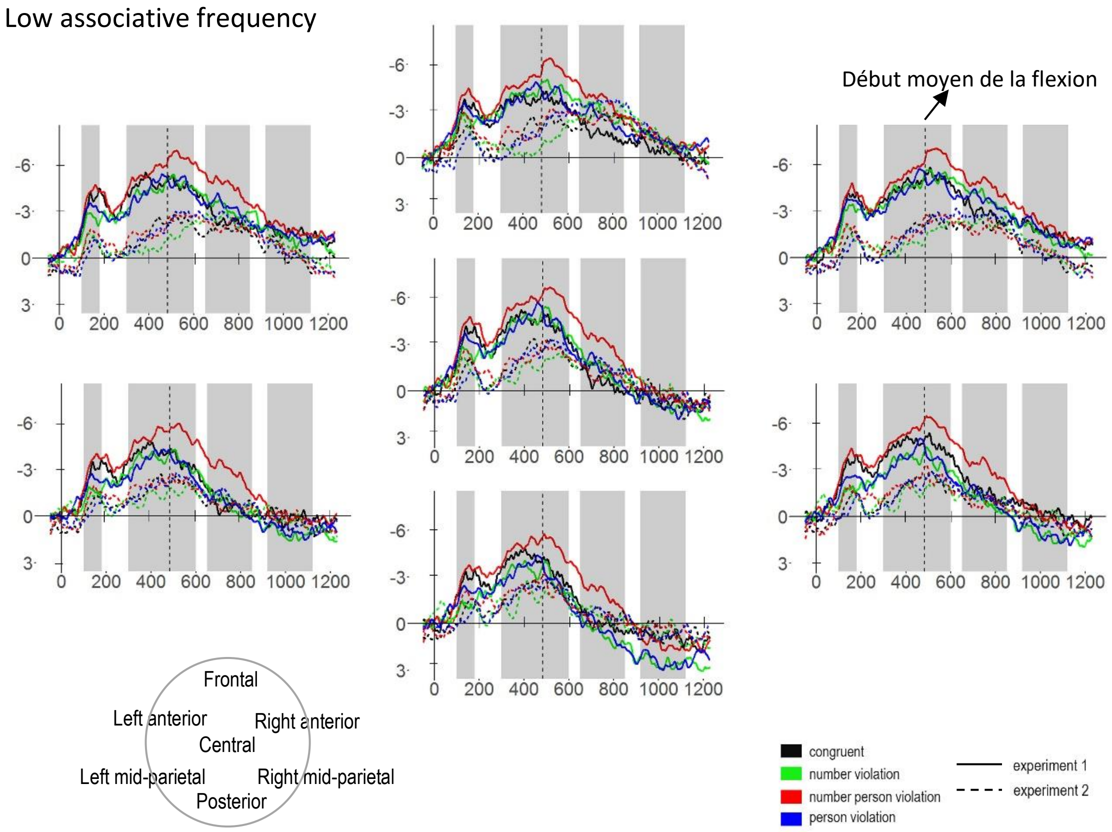
Dans les chapitres 7 à 9, nous présentons les expériences 1 à 3 consécutivement. Des détails sur les participants, les méthodes, les résultats et la discussion sont présentés. Les résultats de l'Expérience 1 reproduisent la plupart des résultats classiques des études en EEG sur le traitement de l'accord grammatical avec l'obtention d'une négativité antérieure suivie de l'onde P600, comme visible sur la figure 1. Nos résultats après l'écoute du verbe ont confirmé l'accès à des traits abstraits en langue parlée. De plus, il a été montré un accès aux représentations associatives dès l'écoute d'un pronom, ce qui amenait le système cognitif à prédire activement la flexion verbale fortement associée avec le pronom. La pré-activation de la flexion verbale affectait à un bas niveau le traitement du phonème initial. Dans l'ensemble, nous avons découvert qu'après avoir entendu un sujet, les informations statistiques sur l'accord sujet-verbe contenues dans les représentations associatives étaient utilisées pour fournir des informations sur la flexion possible du verbe à venir.

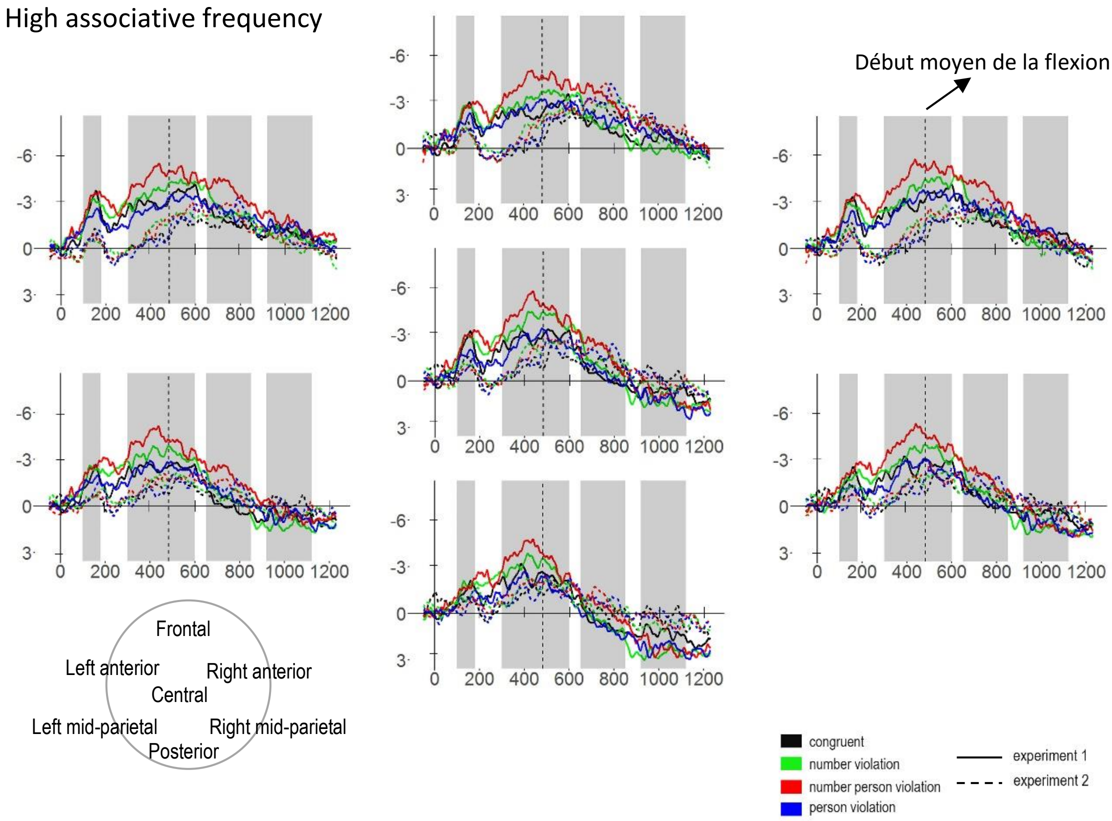
Figure 1. Potentiels évoqués après l'écoute du verbe (en haut, *low associative frequency*, fréquence associative faible, en bas, *high associative frequency*, fréquence associative forte)



Dans le chapitre 8, nous avons en plus manipulé les demandes de tâche dans deux expériences EEG avec les tâches de décision lexicale et de catégorisation grammaticale. Nos résultats après l'écoute du verbe ont montré qu'il y a une certaine flexibilité dans l'accès aux représentations abstraites, de sorte que leur accès était renforcé en tâche de décision lexicale comme visible dans la figure 2. Au contraire, la sensibilité aux représentations associatives entre le sujet pronominal et la flexion verbale était observée indépendamment de la tâche expérimentale employée. Par exemple, l'onde N100 était modulée par la fréquence associative entre un sujet pronominal et sa flexion verbale dans les deux tâches, les tâches de décision lexicale et de catégorisation grammaticale.

Figure 2. Potentiels évoqués après l'écoute du verbe (en haut, *low associative frequency*, fréquence associative faible, en bas, *high associative frequency*, fréquence associative forte)





En ce qui concerne les résultats liés au troisième objectif (chapitre 9), les données MEG suite à l'écoute du verbe ont montré une influence de la fréquence associative lors du traitement initial du verbe à un niveau phonologique au sein du cortex auditif primaire. Cela suggère que des représentations de haut niveau, telles que des représentations associatives, sont utilisées pour pré-activer des flexions verbales, immédiatement après la reconnaissance du pronom, affectant le traitement de bas niveau de nouvelles informations. Cette prédiction en accord sujet-verbe était également associée à l'activation du cortex frontal inférieur et de l'aire motrice. Dans l'ensemble comme discuté dans le chapitre 10, cette thèse apporte une contribution importante à la compréhension de l'accord sujet-verbe en montrant un accès flexible à différents niveaux de représentations et le rôle de la prédiction à partir de régularités statistiques.

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Preface

Language is a unique human ability that is used to express our mind and to understand others, so that we can communicate about our past experience or future plans effortlessly. However, it actually needs to follow certain rules so that a message can be properly transmitted and received. If the syntactic rules are not followed, a comprehender can naturally get confused. One of the rules that regulate language is agreement, a grammatical phenomenon that relates to the correspondence between words in a sentence and signals that words share common grammatical relations, such as subject-verb agreement whereby the form of the verb depends on the subject. From this subject-verb agreement, a comprehender will extract thematic role information, such as who is involved and how many people participate in the action. The ability to establish relationships between words and identify thematic roles is an essential element for the comprehender in understanding the meaning of a sentence. Researchers are therefore eager to understand how it occurs in the brain.

To understand this agreement phenomenon, researchers have mostly conducted studies in the visual domain (i.e., reading), because the marks signaling the grammatical relations, called morphological marks are more evident in written language than in spoken language. In fact, spoken language is generally less explored than written language. Unlike in reading, boundaries between words in spoken language are not that transparent and more properties need to be controlled, such as prosodic information, pitch and word duration (Ferreira & Anes, 1994). In this thesis, we therefore investigate the subject-verb agreement in spoken language with a morphologically rich language that is in French. By doing so, we expect not only to extend the findings from written language to spoken language, but also to discover the representations that are used during the computation of the subject-verb agreement. Based on prior literature, we argue that there are two levels of representations: abstract representations and associative representations that are assumed in language processing. In agreement processing, abstract representations encode the grammatical features of language (Chomsky, 1995; Harley & Ritter, 2002; Pearlmutter, 2000), while associative lexical representations code the probabilities between words (Seidenberg & Macdonald, 1999; Trueswell & Tanenhaus, 1994). In the subject-verb agreement, the former are related to grammatical features while the latter are related to the co-occurrence frequency between the subject and its inflection. Some electrophysiological studies have shown us that abstract feature representations are used during subject-verb agreement processing in the context of reading. Interestingly, the role of statistical regularities has been well studied in language acquisition but little do we know about how language regularities affect the agreement processing in language comprehension. Therefore, here we try to investigate this possibility and to explore access to abstract and associative representations in subject-verb agreement.

Moreover, if there are two representations that are accessed during the processing of the subject-verb agreement, could there be any flexibility in accessing them? Flexibility relates to the ability to adapt when the environment changes. Regarding abstract and associative representations, our aim is to investigate whether they are accessed flexibly, i.e. where representations are accessed depending on the demanded task, or they are used in an automatic manner, i.e., automatically, where certain representations are always accessed no matter what the demanded task is, during agreement processing. In natural settings, comprehenders are faced with a changing environment: they may need to comprehend a sentence in a quiet place or in a noisy place, yet they will still be able to understand and catch the message. Apart from the ability to filter information, a still unresolved issue is whether their ability to comprehend a message, particularly the subject-verb agreement, is related to flexibility.

Furthermore, beyond the issue of representational levels, this thesis focuses on the predictive mechanism of the subject-verb agreement. More and more cognitive neuroscientists argue that our brain is not just passive and waiting for input. Instead, it actively generates prediction (Bar, 2009; Clark, 2013; Friston, 2012). Being active and generating prediction indicates that our brain preactivates the information before it is received from the input; if there is a discrepancy between prediction and input, then the system needs to be updated. Language prediction is widely explored in the language comprehension domain, but little is known about how prediction operates during agreement processing. Most previous neuroimaging studies in language prediction focused on written language (DeLong et al., 2005; Lau et al., 2013) while those that tackled spoken language (Ettinger et al., 2014; Gagnepain et al., 2012; Gaston & Marantz, 2017; Gwilliams et al., 2018) were more focused on spoken word recognition rather than on agreement processing. Therefore, a lot still needs to be learnt about how prediction operates during the computation of the subject-verb agreement in spoken language.

To sum up, this thesis has three objectives:

1. To investigate the nature of the representations operating in agreement processing by examining two levels of representations (abstract and associative).
2. To investigate whether there is flexibility in accessing these two levels of representations.
3. To investigate the role of prediction in agreement processing.

To do so, we conducted three experiments. In all three of them, we used the same stimuli to manipulate the abstract and associative representations (more details in stimuli section of Chapter 7). Concerning the methodological techniques, we used electroencephalography (EEG) in the first two experiments and magnetoencephalography (MEG) in the third experiment. EEG is often used in agreement studies because it is precise to the millisecond, making it a good method to capture a process that occurs rapidly. The first two EEG experiments were carried out to provide answers to the first two objectives. MEG has better spatial resolution to identify brain areas and achieve our third aim. For our second objective, we implemented two different tasks: one was a lexical decision task and the other was a grammatical categorization task.

In terms of the structure of this thesis, the following chapters are structured as follows. Chapter 1 attempts to understand how language works in the brain and how it is studied thanks to the neuroimaging techniques. Chapter 2 discusses the components of language agreement, especially in the subject-verb agreement. Previous studies along with their methods and results are also explained here. Chapter 3 deals with the mental abstract and associative representations and their relation with language agreement. Chapter 4 focuses on cognitive flexibility and how it may affect the access for the mental representations during agreement processing. Automaticity is also considered as an alternative option. Chapter 5 deals with the role of prediction in language processing and the factors to study it. Chapter 6 is where our thesis aims are laid out based on previous studies. In chapters 7 to 9, we present experiments 1 to 3 consecutively. Details about the participants, methods, results and the discussion are presented. Chapter 10 summarizes the findings, discusses them, and indicates possible future directions.

Chapter 1
Comprehending language in the brain

We start this thesis by discussing neurocognitive approaches that have been used in studying the neural basis of language. We talk briefly and generally about these approaches but put more emphasis on techniques that are directly related to our study (i.e., electroencephalography – EEG and magnetoencephalography – MEG), to familiarize the readers with them and with the terms that are related to previous studies of subject-verb agreement in the following chapter.

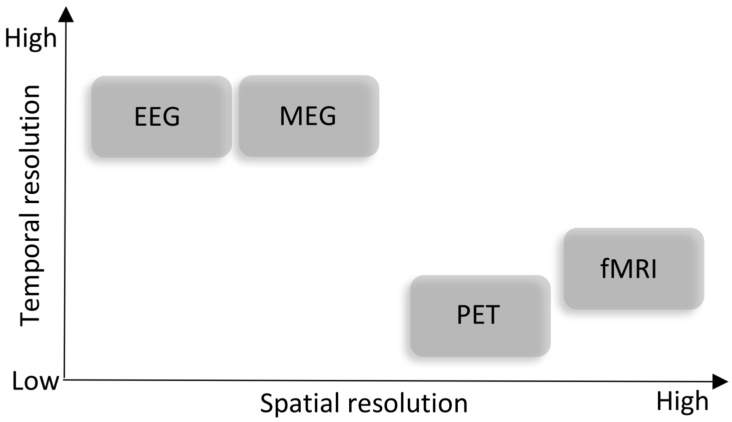
1.1 Neurocognitive techniques used to track language processing

Endeavors to understand how our brain processes language started in the nineteenth century. Initially, studies related to the language function in the brain were carried out in patients who had suffered brain damage or neurological disorders such as strokes or aphasia. Brain analysis was thus performed post-mortem. For instance, Paul Broca (1861) discovered the Broca area by studying patients who had suffered aphasia (i.e., a disability that cause difficulty in language comprehension). Studying damaged brains has shown which areas of the brain are involved during language processing. These studies have helped in understanding the impact of brain lesions on language. In other words, this method is fine to isolate brain areas related to a certain function. However, its major drawback is that after suffering brain lesions, patients may present a different cerebral reorganization from one patient to another. Furthermore, this technique does not provide any information about the online processing of language. For instance, as for clinical studies in patients with aphasia, the results could not explain how complex grammatical structures, such as embedded sentences, are processed on-line (Caramazza et al., 1978; Caramazza & Zurif, 1976; Friederici, 1982). Additionally, the results seemed to depend on the population (Sherman & Schweickert, 1989), since the type of aphasia may differ from one patient to another. For example, Sherman & Schweikert (1989) found that their aphasic participants performed well above chance in interpreting passive sentences, while other studies (Caplan & Futter, 1986; Schwartz et al., 1980) suggested that the accuracy of aphasic participants on a similar task was due to chance. Moreover, aphasic participants in Sherman & Schweikert (1989) were still able to perform syntactic processing despite their syntactic deficit. Nowadays, owing to the development of new technologies, we can compensate these limitations thanks to non-invasive neuroimaging techniques that help in collecting data from healthy participants.

These non-invasive neuroimaging techniques measure brain activity while participants perform certain tasks. Online processing can therefore be investigated. These techniques may be divided into two groups: those that focus on neural activities and have high temporal resolution, and those that focus on the structural system of the brain and have high spatial resolution. The former measure brain activity directly, such as electroencephalography (EEG) and magnetoencephalography (MEG). The latter measure it indirectly, such as functional magnetic resonance imaging (fMRI) and positron emission tomography (PET). Each of these techniques has advantages and disadvantages related to spatial and temporal resolution (Bunge & Kahn, 2009) associated with the measurement approach (see Figure 1. for illustration). As already mentioned, techniques that measure brain activity directly have high temporal resolution but poor spatial resolution, and vice versa for indirect measurement techniques. Each technique is discussed in more detail in the following sub-section: it starts with techniques that have high spatial resolution (fMRI and PET) and then switches to techniques that have high temporal resolution (EEG and MEG). We then describe the results obtained from these techniques, such as brain areas and event-related potential components that are related to language processing.

Figure 1

The comparison of neuroimaging techniques based on the temporal and spatial resolution



1.1.1 Functional magnetic resonance imaging

Functional MRI (fMRI) is an advanced technique that makes it possible to record brain activity and map it to high spatial and temporal resolution (Kim & Bandettini, 2010). It can be used to take brain images in high resolution while investigating the brain without dissecting it, as it measures the blood oxygen level-dependent (BOLD) signal (Bandettini, 2020; Heim & Specht, 2019). fMRI measures the metabolic brain response that comes from changes in the hemodynamic response through the BOLD signal: the oxygen is transmitted to neurons by hemoglobin because it has magnetic properties. The BOLD signal consists of hydrogen atoms that are present in water molecules in the brain. These hydrogen atoms then take up the energy provided by the magnetic field that comes from hemoglobin: this magnetic field can either be diamagnetic when the hemoglobin is oxygenated or paramagnetic when the hemoglobin is deoxygenated. This oxygenating process causes differences in the magnetic properties that affect the discharge of hydrogen atoms, it discharges energy at the same radio frequency until they are in a state of balance. The total sum of the discharged radiofrequency energy is then calculated by the MRI scanner. The energy calculated will decay over time due to several factors, one of them being homogeneities in the magnetic field. The latter also affects image intensity. Moreover, the BOLD signal not only depends on blood flow that has radiofrequency excitation but also on the inflow of fresh blood, which has not undergone excitation. Since the metabolic signal depends on the oxygen consumed in related brain areas, the temporal resolution is slower in comparison with EEG and MEG. Normally, the peak of the BOLD signal is recorded around five to six seconds after the stimulus input. Therefore, this technique is good for localization studies but might be not a good choice if one wants to study a process that concerns precise moments in time.

1.1.2 PET scan

Unlike fMRI, PET uses radioactive isotopes (e.g., carbon, nitrogen and oxygen molecules) to measure the changes in brain blood flow. It measures brain function through regional cerebral blood flow (rCBF), metabolism, neurotransmitters and radiolabeled drugs (Berger, 2003). This method uses radioactivity by detecting the isotope that is injected into the vein. The isotope enters the brain after around 30 seconds and in the following 30 seconds, the radiation reaches a peak that can be detected by a PET scanner. For experimental purposes, the measurements can be done up to ten times or more, with ten to fifteen minutes' intervals. The strongest activation is normally found in an area that is constantly activated during an experiment. In terms of resolution, PET has a lower spatial and temporal resolution than fMRI, so the latter may also be performed for localization purposes. The temporal resolution is also very poor since there is a delay of several seconds. The acquired data is therefore an indirect measure of blood flow and, akin to fMRI, it does not measure neural activity. Nevertheless, PET also has advantages, as it is not as sensitive to movement as fMRI thus PET data can therefore not easily be affected by a movement artifact. Moreover, PET provides information about the neuronal metabolism and the neurotransmission

1.1.3 Electroencephalography

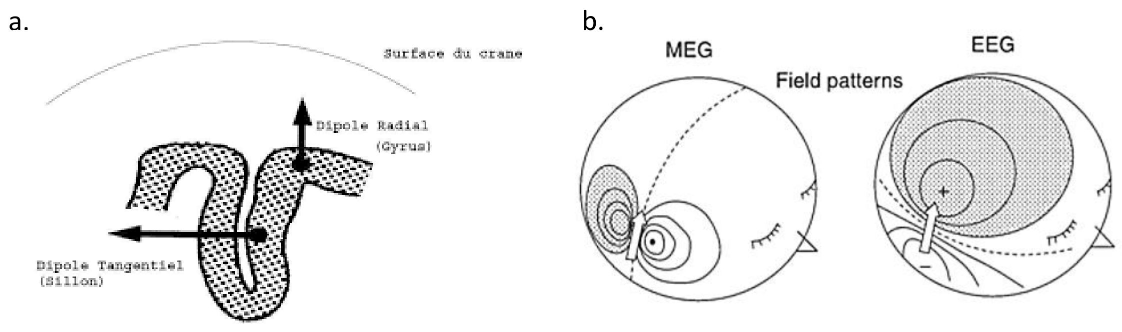
Electroencephalography (EEG) is the oldest non-invasive technique that measures brain activity. It was first developed by Hans Berger (Gloor, 1969) who was a physiologist. In the beginning, he worked with patients who had skull defects from the war. He then discovered that brain activity could also be recorded from a normal scalp. Importantly, at that time, he only used two electrodes to record brain activity over the frontal and occipital sites. Rather than locating the neuronal sources, he was more focused on the notion of integrated activity of the whole brain. He observed its repetitive electrical activity and its particular rhythmicity, and labeled them as alpha and beta activities. The frequency of alpha activities ranges between 8 and 12 Hz, and it is related to processes that require attention. The frequency of beta activities ranges between 15 and 30 Hz, and it is related to working memory and motor processes.

The waves identified from recorded electrical currents came from many synchronous pyramidal neurons. The current itself is produced by neurons that communicate with other neurons. When the information is received by the other neurons, it results in a postsynaptic potential (PSP). In PSP, there is a temporary change in the electric polarization of the membrane of neurons because excitatory or inhibitory neurotransmitters are released. These voltage differences generate radial electric polarization (i.e., electrical field that contains positive and negative current, see Figure 2a) that reaches the scalp surface and is then picked up by the EEG electrodes. To record this electrical activity, ground and reference electrodes are also needed (Luck, 2014). The ground electrode functions as a virtual ground that eliminates the surplus of static electricity in participants. The ground electrode is used only for the aforementioned purpose, so while it does not record any signal, it is required to allow the recording of other electrodes and reference channels. The reference electrode is required for noise reduction purposes. It is normally placed on the mastoid, i.e. the backbone of the ear. Exogenous electrodes are also used to detect artifacts that arise from biological signals, such as eye blinks and eye movements, which are usually unavoidable during experimental trials.

Although EEG can measure the electric activity to the millisecond, it lacks spatial resolution. This is due to the fact that EEG is more sensitive to the radial dipole, which is close to the scalp surface. The signal also degraded when it passes through the skull. It is therefore more difficult to localize the source, which is also known as the inverse problem. Moreover, the number of electrodes that cover the scalp area in EEG was limited. This is also considered as a disadvantage for source localization because with a small number of electrodes, it is hard to pinpoint the source of activity. However, EEG caps with up to 260 electrodes are now available. The more electrodes are used in the experiments, the better the possibility to achieve source localization, although 64-128 electrodes are adequate for this purpose. Several mathematical methods have also been developed to enhance the accuracy of source localization (e.g., LORETA and sLORETA).

Figure 2

The illustration of electrical flow in a current dipole



Note. a.) Difference between dipole directions: EEG is more sensitive to radial dipole while MEG is more sensitive to tangential dipole; b.) Current dipole in MEG vs. EEG. From *MEG: an Introduction to Methods* (p.8), by F.H.L. da Silva, 2010. Oxford. Copyright 2010.

1.1.4 Magnetoencephalography

As compared to EEG, magnetoencephalography (MEG) is quite a recent discovery, dating back to the 1960s. MEG measures the magnetic fields generated by brain activity (Da Silva, 2010). The origin of brain signals is the same as in EEG, in that it uses a magnetic field that joins the electrical current originating from PSP. However, unlike EEG, MEG uses the magnetic field that is generated by the tangential dipole (see Figure 2b for comparison). This dipole is generated by pyramidal neurons that are aligned perpendicularly with the cortex surface, near to the MEG sensors. Like EEG, MEG records brain signals that are near to the scalp, but the recorded magnetic field is not distorted by the skull like the electric current is in EEG. The magnetic field is picked up by planar gradiometer sensors and recorded by Superconducting Quantum Interference Devices (SQUIDS) technology. A pick-up coil is cooled down by liquid helium for conductivity purposes and then measures the magnetic flux. MEG uses around 102 (or more) planar gradiometer sensors, which makes it possible to record the magnetic signals over almost the entire surface area of the scalp. MEG therefore has better spatial resolution than EEG, although the temporal resolution is similar. To perform localization in MEG data, MEG sensors need to be aligned with scalp coordinates, which are obtained through a head scan using the standard electromagnetic digitization system. MRI data is also required for the alignment process and it can improve the quality of localization. However, if MRI is not available, a head template can be used as an alternative, for example FsAverage from FreeSurfer. This practice is quite common in MEG studies that perform source localization.

Sometimes, EEG and MEG are combined (Horwitz & Poeppel, 2002 for discussion) to obtain better insights into the neuroanatomical basis of cognitive function. By combining them, one may obtain better spatial and temporal resolution, since they are complementary: MEG is sensitive to the tangential dipole, which is not well captured by EEG, while EEG is sensitive to the radial dipole, which is not well captured by MEG

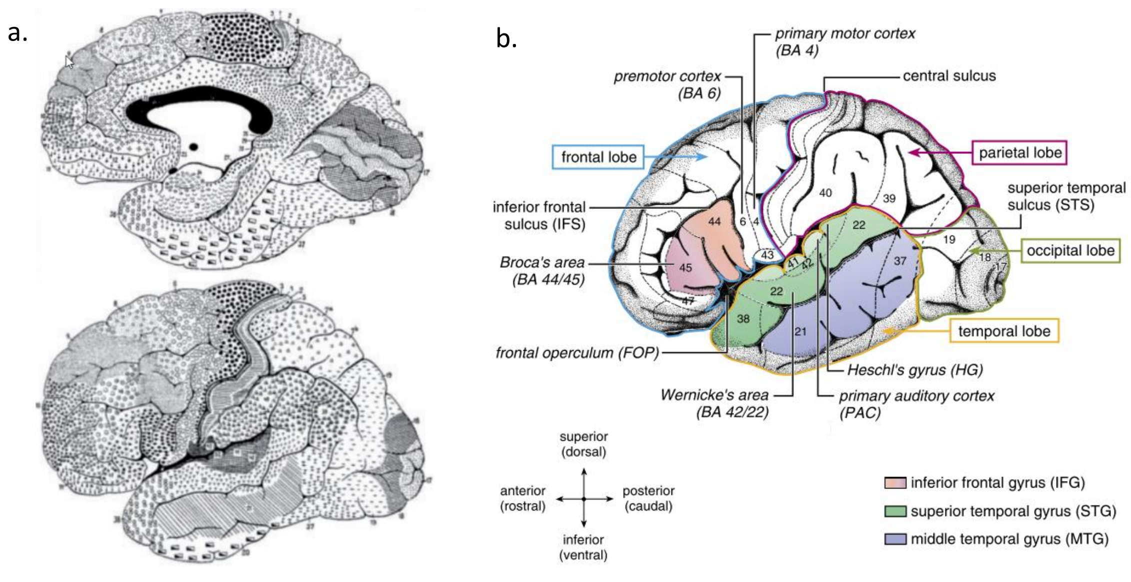
1.2 Results from brain studies

1.2.1 Brain regions related to language processing

In the beginning, before the progress on neuroimaging techniques, attempts to study the brain were essentially post-mortem studies and in patients who had suffered brain damage. A good example of studies in patients is the case of Phineas Gage, which provided information about the functioning of memory and language. It highlighted the notion of brain lateralization, showing that language processing was more dominant in the left hemisphere than in the right hemisphere. In terms of post-mortem studies, one renowned example is a study by Korbini Brodmann on the cytoarchitecture (i.e., cellular architecture) of the cerebral cortex, as shown in Figure 3a. His work was not directly language-related but more about brain mapping and he identified 47 brain areas. Importantly, his work is still used nowadays and his popularity has increased with localization studies.

Figure 3

Brodmann areas that are associated with language



Note. a.) Broca's map of human cerebral cortex. From *Brodmann: a pioneer of human brain mapping-his impact on concepts of cortical organization*, by K. Zilles (2018), Brain, 11, p. 3264; b.) Brain regions that are language-related. From *The Brain Basis of Language Processing: From Structure to Function*, by A. Friederici, 2011, *Physiological Reviews*, 91, p.1359

The brain areas that Brodmann identified are known as the Brodmann areas (BA). Here, we discuss areas that are mainly related to language processing (see Figure 3b), for instance Broca's area. According Brodmann's cytoarchitecture, Broca's area is located in

BA 44-45, which is known as the inferior frontal gyrus (IFG) (Figure 3b). Another classic area that is related to language is Wernicke's area. Like Broca, Wernicke worked with patients who suffered from speech and language disorders. Wernicke's area is located in BA 42/22 around the superior temporal gyrus (STG) area (Friederici, 2002, 2009, 2011; Friederici & Gierhan, 2013) (Figure 3b). Nowadays, thanks to the technological progress, we can confirm the findings from previous studies – such as the areas mentioned above – and investigate other areas that might be related to online language processing. Studies that used techniques such as fMRI have provided more information on the IFG, of which Broca's area is a part. The findings show that the IFG is related to speech comprehension (i.e., comprehending the meaning of linguistic input in the form of spoken language) (Adank et al., 2011; Obleser & Kotz, 2010; Raettig et al., 2010; Rodd et al., 2005; Zekveld et al., 2006) and lexical processing (i.e., recognizing word from the input) (Fiebach et al., 2002; Jessen et al., 2000; Kiehl et al., 1999; Rogers & Davis, 2017), including a sensitivity to lexical properties with word frequency and word concreteness. Fiebach et al. (2002) investigated lexical access using a lexical decision task (LDT, a task where participants need to differentiate words from non-words). By manipulating word frequency, they found that it affected the activation of the left IFG. Jessen et al. (2000) and Kiehl et al. (1999) looked into the concreteness of words (i.e., concrete word represents object in real world). They found activation by abstract words in the IFG, although they found it occurred in a different hemisphere. Jessen et al. (2000) suggested that abstract words and concrete words activated the left IFG, while Kiehl et al. (1999) observed activation by abstract words in the right IFG. In addition to that, IFG is also related to syntactic processing (Embick et al., 2000; Henderson et al., 2016; Matchin & Hickok, 2020).

Studies in grammatical agreement also showed activation over this IFG area both in production (Kielar et al., 2011) and in processing (Carreiras et al., 2015; Quiñones et al., 2014, 2018; Raettig et al., 2010). Quiñones et al. (2014) showed that grammatically correct sentences increased activation over left IFG compared to sentences that involved person violation. For sentences that involved morphosyntactic violation, their result suggested that strong activation was observed over middle frontal gyrus. Furthermore, in terms of number violation in subject-verb agreement, Carreiras et al. (2015) showed stronger activation in IFG for short sentences that involved number violation than congruent sentence.

Apart from the frontal area, temporal lobe also plays a crucial role in language processing. In the temporal lobe we have primary auditory cortex (PAC) which is a cortical area that is related to auditory processing and it is located in the transverse temporal gyrus (TTG). Therefore, it is natural that the TTG should be activated during spoken language recognition, as observed by Deschamps & Tremblay (2014). They asked participants to listen to syllable stimuli passively and found that the TTG was involved in syllabic processing; other studies also indicated the same thing (Hutchison et al., 2008; Tremblay et al., 2013). Tremblay et al. (2013), who also used syllables as speech stimuli and compared it to non-speech stimuli (i.e., bird sounds), added that the TTG was also sensitive to the statistical properties of speech input. Phonological processing is also related to superior temporal gyrus (STG) (Binder et al., 2000; Liebenthal et al., 2005; Moses et al., 2016; Pasley et al., 2012; Rimol et al., 2005). Furthermore, there is also middle temporal gyrus (MTG) that is related to semantic retrieval (Friederici et al., 2000; Kotz et al., 2002; Ruff et al., 2008). In subject-verb agreement studies, left MTG is related to the processing of number and person feature (Mancini et al., 2017). In Mancini et al. (2017), it was found that person violation elicited activation over the anterior and posterior site of MTG, while number violation induced activation over the posterior site of MTG.

Those brain regions were found because the current neuroimaging techniques have a good spatial resolution and allow us to study language online processing. Nevertheless, it is also a common to study language processing with neuroimaging technique that has low spatial resolution, such as EEG. Yet, nowadays with the technological progress, EEG has more electrodes that enables it to do a better localization. Nonetheless, one of the most common way to look at the EEG data is through the event-related potential (ERP) analysis which enables us to see the brain response towards a targeted cognitive function. In the following sub-section, we look at the ERP components that are particularly related to language processing.

1.2.2 Event-related potential components

In his first experiments, Berger identified the rhythmicity of brain waves. Nowadays, researchers measure the average of waveforms from repeated brain activities time-locked to the onset of the sensory, cognitive or motor responses. The result of the averaging measure is waveforms with a certain polarity (i.e., positive or negative) that is known as event-related potential (ERP). This ERP method was discovered around the 1930s and rapidly developed in the 1980s. Many studies use the ERP technique because of its benefits.

Luck (2014) summarized these advantages in six points. First, it provides online data regarding the neural processing of a certain cognitive activity, something that cannot be captured by behavioral techniques. However, ERP is not recommended for a cognitive process that requires long-term memory consolidation, because "*slow voltage drifts are present on the scalp due to non-neural factors (e.g., skin potentials), and these drifts add more and more variance to the waveform as time passes after the time-locking point*" (Luck, 2014; p.31). Second, we can determine whether or not manipulation affects the cognitive process, since the method provides online data. Third, it can identify multiple neurocognitive processes, which cannot be achieved with behavioral techniques because the latter collect data after the cognitive process has occurred. For instance, in neurolinguistic studies, left anterior negativity (LAN) reflects syntactic processing, and P600 reflects the reanalysis process. Fourth, ERP provides online measurement continuously during the task. Fifth, it provides information that links the cognitive process to the brain, although it does not give direct information regarding brain areas; however, source localization is possible with a mathematical algorithm and a specific hypothesis. Sixth, ERP can be used for medical purposes, in that it can measure brain function related to neurological disease and identify whether medical treatment has an effect or not.

To obtain an ERP measure, EEG signals are recorded and markers are placed to the signal correspond to the targeted cognitive processing. This EEG raw data is then being filtered to remove noise and artifacts from the data. Filtering is an important part of cleaning ERP data because there might be voltage drifts that could lead to a false effect. In other words, the observed effect might not be the sole result of the experimental manipulation. There are two types of filters: low- and high-pass filters. A low-pass filter attenuates high frequency and lets low frequencies pass. The high-pass filter does the contrary. A bandpass filter is when both filters are applied. Filtering needs to be done carefully because inappropriate use of filters may distort the data by introducing a new artifact. According to Tanner et al., (2015), an excessive use of high-pass filtering may cause new peaks in the waveforms. The amplitude of these peaks depends on the cutoff frequency. The polarity of the artificial peak that is created by a high-pass filter is the opposite of the excessive use of low-pass filter. To avoid this, using a high-pass filter is recommended between 0.01 and 0.1 Hz, a setting which has been widely used and recommended by other researchers (Duncan et al., 2009; Kappenman & Luck, 2010; Luck, 2014). For the low-pass filter, the recommended setting is 30 Hz (Duncan et al., 2009; Kappenman & Luck, 2010; Luck, 2014), which is also known as a half-amplitude cutoff. Another option to reduce noise in the data by using independent component analysis (ICA), which excludes components that are already known as artifacts (e.g., eye blinks/movements and heartbeats). It is usually performed on the raw data prior to the filtering process.

After cleaning the raw data, epoch can be obtained by extracting the targeted EEG signal in a certain time window. A baseline correction is also applied to reduce offset variance, since several factors (e.g., skin hydration or static electric) may influence the offset values of each participant. Baseline correction is done by subtracting the pre-stimulus voltage values from the epoch voltage values. Baseline correction is crucial (Luck, 2014; Urbach & Kutas, 2006) because it reduces sources of variance, such as random voltage drifts, which can make data lose statistical power and become less reliable. ERP is then obtained by taking the average of epoch data. To keep the quality of the ERP, we need to take into account the signal-to-noise ratio (SNR) value. The common perception to enhance the SNR, meaning increase the signal and reduce the noise, is by increasing the number of (epoch) trial during the averaging because the noise value decrease in the averaging when the trial increases. However, it needs to be noted that doubling the trials does not means increasing the signal because the relation between trials and SNR is not linear (Luck, 2014). Furthermore, after the ERP data is obtained, it can also be re-referenced: for instance, if the reference channel is on one side of the mastoid only, it can be re-referenced to both sides of the mastoid area during offline processing. Another referencing option is average reference (i.e., taking the average from all electrodes as reference); mind that the choice of the reference would affect the signal.

ERP fluctuations are both time-locked and phase-locked to the stimulus and vary in amplitude and duration. ERP components are negative or positive peaks appearing in the ERP data; examples are shown in Figure 4b. Furthermore, ERP components have particular scalp distributions where it is normally related with, as seen in Figure 4a. According to Luck (2014), there are three categories of ERP components: 1) exogenous sensory components reflecting bottom-up and top-down processing; 2) endogenous components showing that the neural response is affected by the task; 3) motor components indicating that the neural response is related to the motor action. These three types of components might relate to each other. Their names are based on the direction of the polarity, the onset latency of the peak component and the scalp distribution. For example, N100 is a component that is known to be related to the auditory processing of stimuli (e.g., Parasuraman & Beatty, 1980; Picton et al., 1999; Winkler, Tervaniemi, & Näätänen, 1997; Wolpaw & Penry, 1975; Woods, 1995). The N letter in N100 indicates the negative polarity of the peak, while the number 100 indicates that this component is usually observed in the first 100 ms after the onset of the target. However, there are no standardized rules for naming ERP components.

Figure 4

Event related potential components that are relevant to language

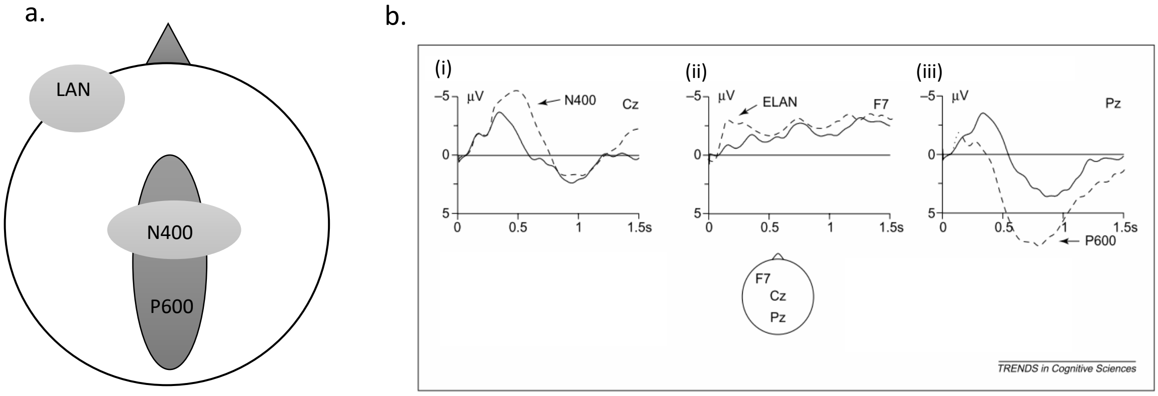


Figure 4. a.) Topographic illustration of ERP components; b.) Illustration of ERP component peaks, modified from Friederici (2002)

[1] "He took a sip from the transmitter" – semantic violation condition from Kutas & Hillyard (1980)

[2] Dutch sentence examples and their English literal translation are taken from Gunter, Stowe, & Mulder (1997)

a. "*De vuile matten warden door de hulp* ***geklopt***" – semantically correct, syntactically correct
The dirty doormats were beaten by the housekeeper.

b. "*De vuile matten warden door de hulp* ***kloppen***" – semantically correct, syntactically incorrect
The dirty doormats were beat by the housekeeper.

In neurolinguistic studies, ERP components are obtained after detecting an anomaly in sentence stimuli. The anomaly is an incongruity in either the syntactic or semantic aspect of the sentence. One of the first components to be found was N400 in the study by Kutas & Hillyard (1980), when participants were asked to read sentences with semantic violations such as example [1]. N400 is a negativity shift around 300-500 ms over the centroparietal sites after the onset of a target word (i.e., noun). Indeed, N400 has been identified with semantic processing during the processing of sentences (Astésano et al., 2004; Thornhill & Van Petten, 2012; Van Berkum et al., 1999) but it is also sensitive to a semantic priming effect (in which a prime and a target are semantically related) (Bentin et al., 1985; Brown &

Hagoort, 1993; Koivisto & Revonsuo, 2001), a repetition priming effect (Basirat et al., 2018; Besson et al., 1992; Okita & Jibu, 1998; Petten & Kutas, 1991; Swaab et al., 2004), a word frequency effect (Barber & Carreiras, 2003; Dambacher et al., 2006; Dufour et al., 2013; Van Petten, 2014), word concreteness manipulation (Barber et al., 2013; Lee & Federmeier, 2008; Palmer et al., 2013), and gender agreement processing (Guajardo & Wicha, 2014; Osterhout et al., 1997; Wicha et al., 2004; Wicha, Bates, et al., 2003; Wicha, Moreno, et al., 2003). Furthermore, recent studies have shown that N400 is related to prediction in language comprehension (Brunellière et al., 2019; Brunellière & Soto-faraco, 2015; DeLong et al., 2005; Szewczyk & Schriefers, 2018), which is discussed more lengthily in Chapter 4 about language prediction.

LAN is a negative-amplitude wave which lasts 300-500 ms after the onset of a word. As its name indicates, its polarity is centered over the left anterior sites. A syntactic violation sentence, as in example [2b.], originated from Gunter et al. (1997), can elicit LAN. Studies therefore use morphosyntactic anomalies that involve person and number violations (Mancini et al., 2011a; Nevins et al., 2007), gender violation (Barber & Carreiras, 2005; Gunter et al., 2000), case violation (Münte & Heinze, 1994; Roehm et al., 2005), or tense violation (Baggio, 2008).

At a later stage, LAN and N400 are often followed by P600, a positive wave occurring around 500-600 ms over the posterior sites that is known as an index of reanalysis after detecting syntactic violation (Barber & Carreiras, 2005; Frisch et al., 2002; Simona Mancini et al., 2011a; Münte et al., 1997; Silva-Pereyra & Carreiras, 2007). Interestingly, some studies have suggested that P600 reflects semantic violation but is not always preceded by N400 (Kim & Osterhout, 2005; Kolk et al., 2003; van Herten et al., 2005). P600 is also related to a language process that requires attention (Gouvea et al., 2010; Schmidt-Kassow & Kotz, 2009), because it was not observed in certain studies where attention was absent (Batterink et al., 2010).

To understand how language is processed in the brain, particularly the computation of the subject-verb agreement, we first need to understand what it is. Therefore, in the following chapter, we explain what grammatical agreement is, since the subject-verb agreement is part of it, and how agreement is processed in the brain according to previous EEG studies.

Chapter 2
Grammatical agreement

2.1 Forming verb agreement through morphosyntax

From linguistic studies, we know that a morpheme is a word fragment and that syntax is how words are arranged to form sentences. Morphology is the study of words and their various parts: the word stem (i.e., a word base that can be independent on its own) and its affixes, which can either be prefixes (i.e., one or more phonemes added at the beginning of the word stem) or suffixes (i.e., one or more phonemes added at the end of the word stem). While syntax is about the arrangement of words in a sentence, inflection is how a word is modified to convey meaning. For instance, in the case of subject-verb agreement, the verb provides thematic information about who does the action and how many people are involved in it. This verb inflection therefore provides syntactic information about the person, number, and sometimes when it is paired with adjective, gender of the persons involved in the action. Morphology and syntax are interlinked, because morphemes need syntax to form proper words.

2.1.1 Morphology

Through the study of morphology, we learn about the composition of words. Morphology also refers to the various phonological forms of morphemes, called allomorphs. For instance, the '-ed' morpheme in regular verbs in the past tense is pronounced /t/ after voiceless consonants (e.g., asked, baked, cooked, talked). There are views suggesting that words and phrases are distinct because words, as in the example of past tense verbs above, do not consist of sequences of morphemes. However, according to distributed morphological theories, there is no such distinction. Furthermore, morphemes can be combined to form nouns, verbs, and adjectives that are derived from the root morpheme (i.e., the root word) (Marantz, 2015). A root word that is part of the open-class vocabulary is also called word stem; it allows combination with syntactic information or lexical category if it is used in a sentence. Word stem or root morpheme, can be combined in a derivational way (in a noun) or in an inflectional way (as in verb agreement). A derivational morpheme forms a new word, such as a noun or an adjective, by combining a root word with a prefix or suffix. An inflectional morpheme is usually observed in verb agreement when the root morpheme is combined with a suffix that adds syntactic information. There have been attempts to differentiate derivational morphology from inflectional morphology, but Marantz (2015) considered that there were no striking differences between them. According to Bickel & Nichols (2007), inflectional morphology is a kind of derivational morphology that is sensitive to the grammatical environment. In morphologically rich languages, these inflections depend on person [4b], number[4a], gender [4c] and tense [4a&b], which indicates when the action takes place.

[4] a. *'je chante'* – I sing, present tense
'ils chantent' – they sing, present tense
b. *'je chantai'* – I sang, past tense
'nous chantions' – we sang, past tense
c. 'le chanteur est heureux' – the singer$_{\text{masculine}}$ is happy$_{\text{masculine}}$
'la chanteuse est heureuse' – the singer$_{\text{feminine}}$ is happy$_{\text{feminine}}$

Subject-verb agreement is a good example of inflectional morphology because one can observe a grammatical relation between a subject feature (person, number, gender) and a verb. According to distributed morphology (Halle & Marantz, 1994; Harley & Noyer, 1999; Marantz, 1997), a hierarchical structure can be observed in subject-verb agreement, which is subject to a recursive merge operation (i.e. the ability to combine two syntactic features to form a new one). There are three core properties in distributed morphology: late insertion, underspecification, and syntactic hierarchical structure all the way down. "Late insertion" refers to the idea that morphemes are organized according to the hierarchical structure of syntactic and semantic features mapped to phonological features. "Underspecification" means that phonological items do not need to be fully specified for the syntactic positions where they may be inserted. "Syntactic hierarchical structure all the way down" indicates that the inserted morpheme is structured hierarchically according to syntax. (Noyer, 1997) suggested that insertion in morphemes can be restricted by using a universal hierarchy of features (Carminati, 2005; Greenberg, 1963; Harley & Ritter, 2002; Silverstein, 1985). Phonological string that has the highest hierarchy in the feature is thus inserted.

2.1.2 Syntax

Syntax is the set of grammatical rules that governs the arrangement of words in a sentence. However, it can be independent of semantics: for instance, in *'la maison a soif'* - 'the house is thirsty', the syntax is correct but the sentence does not make sense. Yet, syntax and semantics are still intertwined as explained by distributed morphology (Marantz, 1997), which views syntax as a computational system that merges phonology and semantics. Syntax moves words around to build structured sentences. This structure is governed by grammatical rules and if they are violated, as in [5b], the sentence might be hard to understand.

[5] a. *J'ai*$_{1person.singular}$ *déja mangé ce matin* – congruent
I have already eaten this morning
b. *J'avons*$_{1person.plural}$ *déja mangé ce matin* – incongruent
I $_{\text{(they)}}$have already eaten this morning

Furthermore, according to distributed morphology, sentence structure has a meaning. This structure is guided by syntax and correct from incorrect sentences may be differentiated by using it [5]. For instance, when reading or hearing an incorrect sentence as in [5b], French native speakers would easily detect the error because it does not respect syntactic rules. Moreover, as can be noticed between [5a] and [5b], syntax provides regulation not only based on the syntactic features in subject-verb agreement, such as person and number but, in French, it also cares about the contraction that depends on the last phoneme of a pronoun and the first phoneme of the following word. For a pronoun that ends with a vowel, such as *'je'* and *'tu'*, if they are followed by a verb that begins with a vowel, then there will be a contraction between the subject and the verb, such as in [5]. In short, syntax interacts with morphology in such a way that a correct verb is generated.

2.2 Subject-verb agreement

We have seen that syntactic rules need to be followed so that a verb inflection can provide grammatical information. Regarding grammatical agreement, Steele says "*The term agreement commonly refers to some systematic covariance between a semantic or formal property of one element and a formal property of another*" (as cited in Corbett, 2003, p.1). Grammatical agreement involves several grammatical properties (e.g., number, person, gender). This thesis will focus only on subject-verb agreement including number and person properties. As mentioned earlier, subject-verb agreement is manifested between a subject (e.g., a pronoun with pronominal subject-verb agreement) and a verb inflection. For example, in English, there are –s inflections for the third person (e.g., 'He runs') or plural objects (e.g., 'two apples'). English can be categorized as a language that is morphologically poor in the sense that it does not have a lot of variance in subject-verb agreement compared to morphologically rich languages like French (see [6] for example). Owing to these differences between languages, there has been a debate about how inflections are processed in subject-verb agreement. Some argue that morphologically poor languages rely more on semantics, while morphologically rich ones rely more on syntax (Berg, 1998; Márquez-Caamaño, 2016; Outeiral & Acuña-Fariña, 2012). However, according to distributed morphology, subject-verb agreement will always be the result of processing morphological sequences that involve a syntactic merger and a phonological realization, regardless of the language.

[6] a. *Je$_{1person.singular}$ lis$_{1person.singular}$ un$_{masc}$ livre$_{masc}$* –I read a book
b. *Vous$_{2person.plural}$ lisez$_{2person.plural}$ un$_{masc}$ livre$_{masc}$* – you read a book
c. *Elle$_{3person.singular}$ lit$_{3person.singular}$ un$_{masc}$ livre$_{masc}$* – She reads a book

In short, subject-verb agreement requires a verb that agrees with its subject in all syntactic features, such as number and person. These features are explored in the following sub-section. We then discuss the mechanism behind it from a linguistic perspective and agreement processing in the brain, which is reflected through ERP components.

2.2.1 Agreement features

There are three main features in language agreement: person, number and gender. Researchers (Carminati, 2005; Greenberg, 1963; Harley & Ritter, 2002; Silverstein, 1985) suggested that there is a hierarchy between these agreement features. In *Universals of Language*, Greenberg suggested that not all languages have the notion of gender, but when they do, they also have number and person. If they have number, they always have person but not necessarily gender. In this hierarchy, person thus occupies the highest place followed by number and gender.

2.2.1.1 Person

Person is a universal feature that can be found in many languages. It consists of a first, a second, and a third person. Thanks to this feature, we know who is involved in the narration, whether it is the speaker and/or other parties. For example, the *"-s"* inflection indicates the third-person singular *"he"* or "she" in English. In morphologically rich languages, each person has its own inflection.

2.2.1.2 Number

This feature indicates how many people are involved in the narration. To differentiate between singular and plural, Silverstein (1985) argued that a singular's position is higher than the plural form. The number feature is also indicated by a certain inflection that differentiates singular from plural; for instance, the "-s'" inflection for plural in English.

2.2.1.3 Gender

Gender is usually observed in inflections attached to nouns and adjectives. In nouns, gender is not necessarily related to biological gender; for instance, *"a chair"* is feminine *"une chaise"* in French, but this is only grammatical as a chair is an object without biological gender. In adjectives, gender is more semantically related; in French, the adjective depends on the subject's gender, for instance, *"he is happy" – " il est heureu**x**", "she is happy" – "elle est heureu**se***".

Among languages expressing the notion of gender, some languages have two genders, feminine and masculine (e.g., French, Spanish, Italian, Portuguese), while others have three, such as feminine, masculine, and neuter (e.g., German, Dutch, Serbian, Norwegian).

2.2.2 Agreement mechanism: a linguistic perspective

The idea that agreement is feature-sharing comes from Chomsky's (1957) *The Minimalist Program* (*The MP*), where he argued that agreement is context-sensitive and follows certain grammatical rules. Furthermore, in *The MP*, he introduced the idea of feature-checking in subject-verb agreement in which it relies on the asymmetry (i.e., agreement relations between two elements wherein they need to have the same agreement features) between subject-verb. The agreement features cannot be checked if there is a mismatch because this condition would cause derivation cancellation. Chomsky (2000) updated his proposal on feature-checking and proposed operation agree that allows feature valuation. Therefore, a feature is valued only if it is agreed upon. Below, we cited Mancini's (2018) summary about three basic assumptions on agreement based on *The MP*:

> (i) *Feature syncretism*: Features are expressed as a feature bundle on a single position in the syntactic tree (Tense), and are uniformly dealt with by the syntactic operation of Agree;
> (ii) *Asymmetry*: Agreement proceeds asymmetrically from the controller to the target. For instance, in subject-verb agreement, the person and number features expressed on the

subject determiner phrase are copied onto the verb by the formal operation Agree. Features are valued and interpretable on the nominal argument, hence they are visible to the interpretive system, while they are uninterpretable on the verb, as mere formal copies of the nominal specifications. Agree connects the two positions, checks and values the features on the verb.

(iii) *A narrowly syntactic operation*: Agree operates within the domain of Narrow Syntax, as uninterpretable features need to be erased from the derivation before these are transferred to the interpretive system. (Mancini, 2018, p. 14-15)

In contrast with Chomsky, Frampton & Gutmann (2000) proposed that "*agreement is feature-sharing, independent of value*" because unvalued and valued features combine. According to this idea, agreement is found in both controller (i.e., features that carry the semantic or syntactic value inherently) and target, as seen in [7]. The way we interpret a target thus depends on the controller.

[7] *une grande maison* – a big house
target controller

Agreement is recognized through the controller, and the agreement features that are present in both target and controller are known as feature-sharing. In terms of feature analysis, Haug & Nikitina (2016) suggested that there are two possibilities. First, as suggested by Frampton & Gutmann (2000), syntax is paired with semantics, which means agreement features are recognized based on the syntactic locus of the controller. The second view is syntax pairs with a morphology that allows the possibility for morphology and syntax to be intertwined in a sense that there is a syntactic projection of words when there is the morphological exponent (i.e., the implementation of phonology in morphosyntactic properties). Haug & Nikitina (2016) called the second view, syntactic feature-sharing, which is also similar to Chomsky's Minimalism. That being said, there could be a way to interpret agreement features: one that involves the semantic component and the other which uses the morphological exponent.

2.2.2.1 French verb agreement

Previous studies (Estivalet & Meunier, 2016; Meunier & Marslen-Wilson, 2004) have suggested that French verbs are processed through morphological decomposition. For instance, Meunier & Marslen-Wilson (2004) conducted two lexical decision task experiments to study how the inflection in regular and irregular verbs is processed. In their experiment, they had three types of prime stimuli and four types of targets. The prime stimuli were verbs in the regular form (e.g., *'aimerons'* – 'we will love'), allomorphic form (e.g., *'aimons'* – 'we love'), and control (e.g., *'porterons'* – 'we will carry'); they were presented auditorily. For the target verb conditions, the first two conditions were regular (e.g., *'aimer'* – 'to love') and morphophonological constraint (e.g., *'semer'* – 'to sow'). They were more regular compared to the last two conditions: subregular (e.g., *'peindre'* – 'to paint') and idiosyncratic (e.g., *'aller'* – 'to go'). These targets were presented visually. The results showed a strong effect of morphological priming and no differences between regular and irregular verbs. Since the stimuli were not only morphologically related but semantically related as well, a second experiment was conducted where the same experimental conditions were used, with an added semantic control condition. In the second experiment, prime and target were not semantically or morphologically related but overlapped orthographically. No semantic priming effect was found but only a morphological priming effect, which suggests that French verbs are processed through morphological decomposition. The fact that there was no difference between regular and irregular verbs suggests that verbs are not merely stored in word form in the lexicon. This result is in line with the notion of distributed morphology (Halle & Marantz, 1994; Marantz, 1997), in that there is a hierarchical structure in morphological forming through a syntactic merge operation (Marantz, 1984).

2.2.3 Agreement mechanism: a neurocognitive perspective

Subject-verb agreement is one of the most common forms of grammatical agreement. Naturally, it is of great interest for neurocognitive scientists, who have mostly explored the topic in the visual domain. Studies in the auditory domain remain rarer. In the previous chapter, we talked about the EEG technique and how we obtain ERP. In this section, we focus on the three main ERP components that are related to the processing of subject-verb agreement: N400, LAN and P600 (see Molinaro, Barber, & Carreiras, 2011, for review). The latter two are specifically related to subject-verb agreement.

2.2.3.1 Left anterior negativity

As mentioned in Chapter 1, Left Anterior Negativity (LAN) is negativity elicited over the left anterior sites, described as a result of morphosyntactic detection. It occurs between 300 and 500 ms after stimuli. In subject-verb agreement, the stronger amplitude of the LAN component can be observed after reading or hearing sentences with morphosyntactic violation (i.e., number violation, person violation or both), such as *'je restons chez moi'* (I stay$_{1person.singular}$ at home) in comparison to *'je reste chez moi'* ('I stay$_{1person.plural}$ at home'). One of the early findings in subject-verb agreement related to LAN was reported by Osterhout & Mobley (1995): they found the LAN effect for number violation in English. Regardless of the language, many studies have shown a LAN modulation in agreement computation related to both number and person (e.g., in English: Dube et al., 2016; Tanner, 2019; in Finnish: Palolahti et al., 2005; in French: Brunellière, 2011; in German: Rossi et al., 2005; in Hindi: Nevins, et al., 2007; in Italian: Vicenzi et al., 2003; Angrilli et al., 2002; in Spanish: Mancini et al., 2011a,b). It is common to observe a syntactic anomaly caused by bilateral anterior negativity (AN), which means preferential polarity is not observed over left anterior sites (in English: Shen et al., 2013; in French: Isel & Kail, 2018; in Spanish: Hinojosa et al., 2003; Silva-Pereyra & Carreiras, 2007; Slovak: Hanulíková & Carreiras, 2015). Despite this difference, the time-course of the AN component is still the same as that of the LAN.

2.2.3.2 P600

A centro-parietal posterior positivity normally lasts between 500 and 800 ms and is also known as a syntactic positive shift (SPS) (Hagoort et al., 1993). It demonstrates the reanalysis process after processing the syntactic agreement violation. In subject-verb agreement studies, P600 is often observed following the LAN effect after detecting syntactic violation (Angrilli et al., 2002; Barber & Carreiras, 2005; Brunellière, 2011; Dube et al., 2016; Mancini et al., 2011a; Palolahti et al., 2005; Rossi et al., 2005; Silva-Pereyra & Carreiras, 2007; Tanner, 2019; Vincenzi et al., 2003). As evidence of hierarchical features in agreement processing, Mancini et al. (2011a) found differences between number and person violation, where person violation elicited stronger amplitude and more fronto-central positivity than number violation, whose distribution was more posterior. However, Silva-Pereyra & Carreiras (2007), who used Spanish sentences as stimuli and did not find any differences between number and person violation. Mancini et al. argued that this might be due to the fact that Silva-Pereyra & Carreiras used both the first and second persons in their pronoun stimuli, as shown in [9], while Mancini et al. (2011a) used only a third person subject, as shown in [8]. Thus, this might have increased the sensitivity towards the syntactic violation; additionally, this might also occur because across languages, third person has stronger morphological marker compared to first and second person. For instance, in French, *'je'*-'I' and *'tu'*-'you' shared the same inflection in some conditions, but the third person, *'il'* and *'elle'* always have a distinct inflection compared to first and second person.

[8] a. Los cocineros$_{\text{3person.plural}}$ cocinaron$_{\text{3person.plural}}$ un pescado muy rico – congruent
The cooks$_{\text{3person.plural}}$ cooked$_{\text{3person.plural}}$ a very tasty fish
b. El cocinero$_{\text{3person.singular}}$ cocinaron$_{\text{3person.plural}}$ un pescado muy rico – number violation
The cook$_{\text{3person.singular}}$ cooked$_{\text{3person.plural}}$ a very tasty fish
c. El cocinero$_{\text{3person.singular}}$ cocinaste$_{\text{2person.singular}}$ un pescado muy rico – person violation
The cook$_{\text{3person.singular}}$ cooked$_{\text{2person.singular}}$ a very tasty fish
[9] a. Nosotros$_{\text{1person.plural}}$ entiendo$_{\text{1person.singular}}$ la idea – number violation
We$_{\text{1person.plural}}$ understand$_{\text{1person.singular}}$ the idea
b. Tú$_{\text{2person.singular}}$ entiendo$_{\text{1person.singular}}$ la idea – person violation
You$_{\text{2person.singular}}$ understand$_{\text{1person.singular}}$ the idea
c. Ustedes$_{\text{2person.plural}}$ entiendo$_{\text{1person.singular}}$ la idea – number person violation
You$_{\text{2person.plural}}$ understand$_{\text{1person.singular}}$ the idea

Even though Silva-Pereyra & Carreiras (2007) did not find differences between person and number features, they found differences between single and double violations, in which double violations elicited larger P600 amplitude. Another ERP study that found differences between number of feature violation (single vs. double) was by Zawiszewski (2016); apart from that similar pattern was also observed in behavioral studies (Lambert & Kail, 2001; Mancini et al., 2014). These kind of differences that we found within the type of features violation (number vs. person feature) and within the number of features violation (single vs. double) indicated that abstract representations are accessed during the processing of subject-verb agreement.

Furthermore, in terms of subject-verb agreement in spoken language, previous studies (Dube et al., 2016; Hasting & Kotz, 2008) showed that P600 can be elicited in an early time window. For instance, P600 was observed at around 350 and 590 ms in the study by Dube et al. (2016), where they manipulated number feature agreement in English sentences [10], and at around 300 and 800 ms in the study by Hasting & Kotz (2008), where they manipulated person feature agreement in German sentences [11]. Another reason why this effect was observed early might be because the ERP was time-locked to the offset of the verb stem.

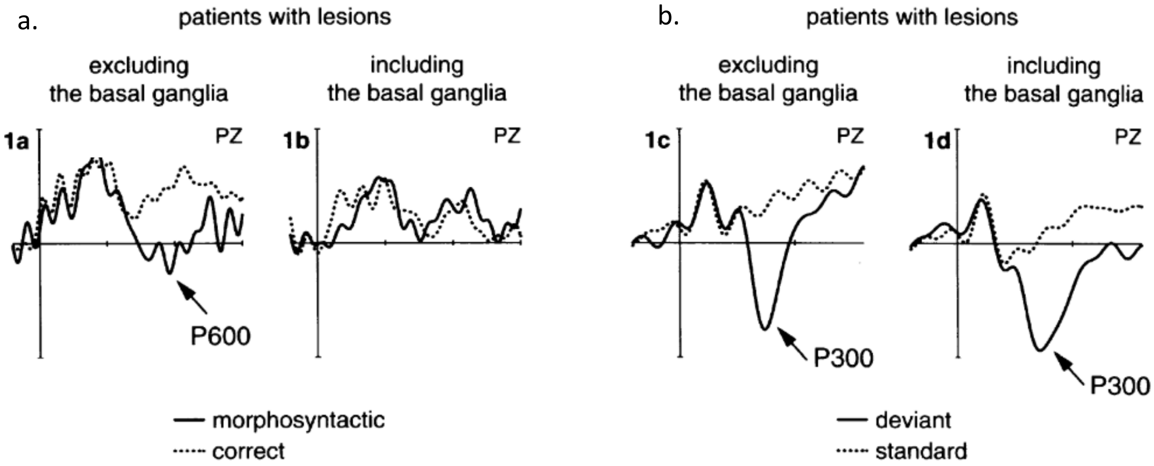
[10] a. The boys often cook on the stove - congruent
b. The boys often cooks on the stove – incongruent
[11] a. er$_{\text{3person.singular}}$ kagelt$_{\text{3person.singular}}$ – he bowls, congruent
b. er$_{\text{3person.singular}}$ kagelst$_{\text{2person.singular}}$ – he bowl, incongruent

The time window of P600 may be categorized either as early (500-750 ms) or late (750-1000ms). According to Molinaro et al. (2011), the former is more sensitive to person and gender violation while the latter seems to be more sensitive to gender and number violation. They also argued that late P600 allowed a more thorough reanalysis process since one can go back to the previous stage to verify the information before reanalyzing the violation.

Concerning the early time window, P600 shares similar characteristics with P300, which is commonly known as P3, or more specifically P3b. P3 is indeed differentiated into P3a and P3b based on their polarity: P3a is fronto-central (250-280 ms) while P3b (250-500 ms) is akin to P600, whose polarity is centro-parietal. Some researchers have thus argued that P600 is not a component that is specific to syntax processing and that it may in fact be a member of the P3 family (Coulson et al., 1998; Osterhout & Hagoort, 1999; Sassenhagen et al., 2014). In contrast, some studies have tried to differentiate these two components, such as the study by Frisch, Kotz, Von Cramon, & Friederici (2003). Among the 14 aphasic participants in their experiment, seven had lesions in the basal ganglia, while the other seven did not. In the first experiment, participants listened to passive German sentences with a morphosyntactic violation. In the second experiment, the same participants heard standard tones and performed an auditory oddball task. The results of the first experiment showed that P600 after the morphosyntactic violation was observed in patients who did not have lesions in the basal ganglia. In the second experiment, P300 was observed in both groups of patients, which indicated that it was not affected by the lesions in the basal ganglia (see Figure 5).

Figure 5

The difference between P300 and P600 in aphasic patients



Note. Figure adapted from Frisch et al. (2003) illustrating ERP responses at the Pz electrode where negativity is plotted upwards and each tick in the x-axis indicates 500 ms. Their study was an attempt to distinguish P600 from P300 by conducting two experiments in aphasic patients with or without basal ganglia lesions. a.) In the first experiment, results were time-locked to the verb onset when participants listened to correct passive sentences. Response is depicted by the dashed line. For passive sentences with a morphosyntactic violation, response is depicted by the solid line. b.) In the second experiment, participants performed an auditory oddball task and the data was time-locked to the onset of the tone. The solid line depicts the brain's response to a deviant tone while the dashed line depicts the response for a standard tone.

In the same vein, Yano et al. (2019) also tried to distinguish the two ERP components by a sample size analysis. They wanted to see whether P300 and P600 required the same number of samples. They did two experiments with a different group of participants: in the P300 experiment, in their stimuli they used a regular triangle as standard stimulus and an inverted triangle as the target. The order of the stimuli was randomized and participants were asked to respond when they spotted the target. In the P600 experiment, they used Japanese sentences in which they manipulated the grammatical congruency and asked participants to read and judge the acceptability of the sentence. According to the result of the sample size analysis, P300 needed five to seven participants to obtain a stable result, while P600 required a sample size of around 20-30 participants for a reliable result. The authors also argued that the difference between P300 and P600 might be due to the different tasks given to the participants. The P300 experiment used a no-go task, while the P600 experiment used a two-alternative forced choice (AFC) task for the sentence acceptability judgment task. They also argued that two AFC tasks increased the positive amplitude compared to other tasks, such as silent reading with no other task. Those studies have demonstrated that P300 and P600 are two different components, and that P600 seemed to be more language related component.

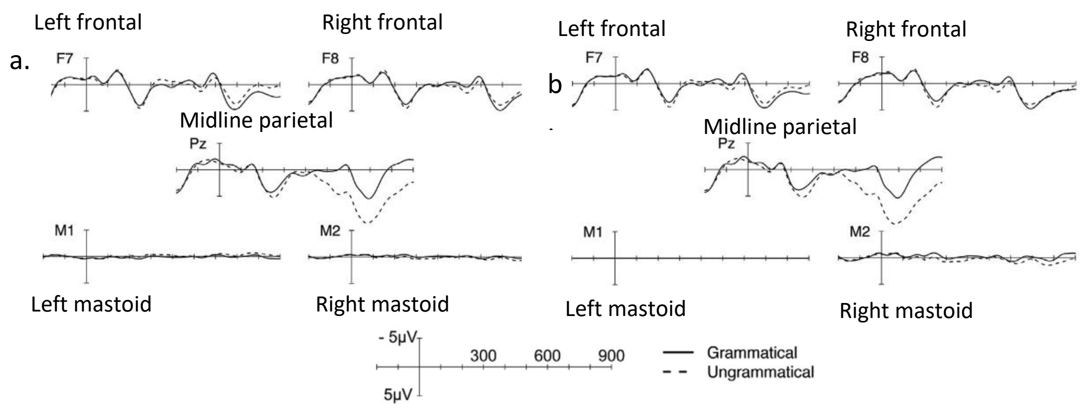
2.2.3.3 Biphasic LAN-P600

Since it is common to observe both LAN and P600 in agreement studies, the pair is known as the biphasic process LAN-P600 (Caffarra et al., 2019; Mancini et al., 2011a). However, not all previous studies found this biphasic effect (e.g., Tanner & van Hell, 2014). In his comment to Molinaro et al. (2011), Tanner (2015) gave a cautionary note on interpreting LAN as a biphasic effect. In line with Osterhout et al. (2004), he argued that this biphasic effect could be due to individual differences and distortion during the ERP grand averaging process (i.e., averaging ERP data for each condition across participants), because other authors (e.g., Tanner & Van Hell, 2014) did not find this effect. To support this view, his team reanalyzed the result of one of his subject-verb agreement studies (Tanner & Van Hell, 2014) in which he looked at individual differences. Among 40 participants, they found only N400 or P600, which means LAN was absent in individual data but was observed after averaging the data from all participants. To reanalyze that data, they took into account issues such as channel referencing, individual differences and sample size, which were suggested by Molinaro et al. (2011) to support the reliability of the LAN effect that Osterhout et al. (2004) had questioned.

Regarding the first issue about data referencing, Molinaro et al. (2011) argued that the way the data is referenced affects the ERP result. They also suggested that LAN would be more visible if the data were referenced to the average of mastoids. To tackle that first issue, Tanner (2015) thus compared his data when it was referenced to the left mastoid and when it was referenced to the average of both mastoids. Although the choice of a reference channel may affect the ERP waveforms, Tanner’s results suggested that there were no significant differences between using the left mastoid or the average of both mastoids as a reference (see Figure 6).

Figure 6

The comparison between using the left mastoid and the average of left and right mastoids in ERP data from the subject-verb agreement study



Note. ERP responses from subject-verb agreement data in the study by Tanner and Van Hell (2014), time-locked to the onset of the verb. The solid line depicts the grammatical response and the dashed line depicts the ungrammatical response. a.) The ERP here used the averaged mastoids reference; b.) The ERP here used the left mastoid reference. The figure is adapted from Tanner (2015).

Concerning the second issue about individual differences and sample size, which was also raised by Osterhout et al. (2004), Molinaro and colleagues argued that if a biphasic LAN-P600 effect was the result of individual differences, there should be other studies reporting a N400 effect only. Yet such a result is rarely observed in agreement, particularly in subject-verb agreement. In response to Molinaro et al. (2011), Tanner (2015) did a Monte Carlo simulation (i.e., a mathematical simulation that is used to model the different probability of results when confronted with uncertainties) on the data from his previous study (Tanner & Van Hell, 2014). The results supported the idea that individual differences could create a misconception of the LAN effect during ERP averaging. He noted that LAN itself exists as a component but that caution is required when interpreting biphasic LAN-P600.

In response to this, Caffarra and colleagues (2019) showed that among 80 participants, such that biphasic LAN-P600 effect is observable in each of them and not merely in the ERP grand average from all participants. Caffarra et al. (2019) suggested this may have been the case because their study was conducted in Spanish, which is a morphologically richer language than English, the language used in Tanner & Van Hell's study. The sensitivity in detecting syntactic violation was therefore higher in Caffarra et al.'s (2019) study, which somehow seemed to have refuted the previous argument against biphasic LAN-P600 effect. Molinaro et al. (2015) also argued that the N400 effect that Tanner observed in the ERP grand average across participants might be due to the stimuli that probe more the lexical-semantic processing than the computation of syntactic dependencies. In the study by Tanner & Van Hell (2014), subject-verb agreement was interrupted by an in-between phrase that is underlined in [12]. This phrase might lead to have more sensitivity to semantic processing and to reduce syntactical processing, which is usually reflected by LAN.

[12] a. The clerk <u>at the clothing boutique</u> was severely underpaid and unhappy - congruent
b. The clerk <u>at the clothing boutique</u> were severely underpaid and unhappy - incongruent

All in all, the caution required in interpreting biphasic LAN does not imply and should not be interpreted as meaning that LAN is an artifact component in agreement studies. Moreover, the fact that LAN is observed or not in a study seems to depend on the properties of language and stimuli that are used in the experiment. Overall, these LAN and P600 components reflect the fact that the system accesses higher-level representations to compute the syntactic dependencies. This linguistic information needs to be stored in language representations to be used effortlessly. The following chapter explores the issue of these representations among other mental representations.

Chapter 3
Mental representations

3.1 What are mental representations?

A representation could be defined as a meaningful way to symbolize something that is not directly present. For instance, during wartime, soldiers took a photo of their family with them because they could not be with them physically. That photo became a representation of their family. Likewise, in our cognitive system, we build representations of the external world we perceive because our brain cannot directly access the external world without the five sensory faculties. Therefore, mental representations contain information that we perceive through those faculties, which are then transformed into mental code and stored in our long-term memory.

How we encode the external world in our minds is quite abstract and has been a long-standing topic for philosophers, psychologists and cognitive scientists. It is important to understand what mental representations mean in cognitive terms before we seek to understand how they are used in neurolinguistic terms. Markman (1999) offered four dimensions of representation. First, a representation consists of a represented world (e.g., nature, transportation, etc), which is symbolized internally in our cognitive system. For instance, in some languages, gender is represented by an article, such as in [13]. We can see in [13a.] that the article represents the gender of the object in a grammatical system. In [13b.]; the article also represents the gender of the human being.

[13] a. *la*$_{\textit{feminine}}$ *grande*$_{\textit{singular/feminine}}$ *table* – French
The big table
b. *la directrice*$_{\textit{feminine}}$ / le directeur$_{\textit{masculin}}$ French
The director$_{\textit{feminine/masculin}}$

Second, it consists of a representing world, i.e. the representations and symbols that represent the external world. According to Markman, a representing world would blur the information about a represented world, as it is the consequence of a representational decision. For instance, a representing world can be observed in verb conjugation: if we look at the past participle of the verb *'lire' : 'lu' (*'read'), we have the information that the action has occurred but we do not know when. Third, a representation consists of a set of representing rules that connect information from the representing world to the external world. Markman divides the relationship between the representation and the external world into two categories: analog and symbolic. The former has a fixed representational system between the representation and the external world, as in [13b.]. The latter requires a convention to fix the relationship between the representation and the external word, as in [13a.]. Fourth, a representation involves a process that uses the representation information to achieve a goal. According to Markman, without a process that executes the action, the first three elements would be pointless because they would merely be a possibility of representation. Without the fourth element, the representation would not exist. To build a representation, it is necessary to know how to use it so that the information from the external world can be extracted and stored in the memory. If we put it in a linguistic context, the fourth element is the reason why we are able to notice a grammatical mistake in a sentence. In this line, Jackendoff (2017) argued that a mental representation is about how the brain encodes information and proceeds to respond. However, representation is not solely about storing information in the memory but also about highlighting the action to interpret it.

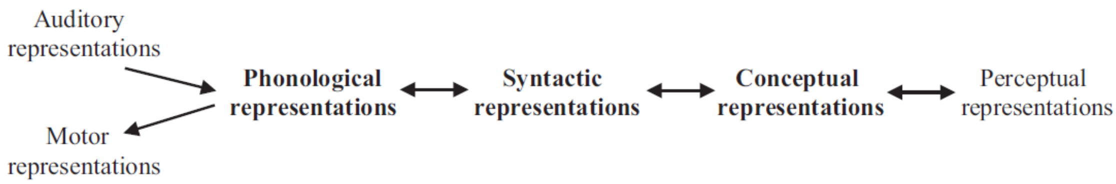
3.2 Language representations

Jackendoff (2019) pointed out that mental representations are not uniform. It is therefore necessary to distinguish language representations from the general term of mental representations. Language representations are built to produce and process language. In accordance with Markman about the importance of the know-how, we ought to look at language processing models because they can provide us with a better understanding of language representations by showing us how they are accessed. To explain language models, we used Marr's (1982) three-level cognitive analysis as a framework. These three levels are: 1) the computational level, which concerns the purpose and how the system processes things; 2) the algorithmic level, which builds a mathematical model aiming at mimicking the cognitive behavior; 3) the implementational level or the hardware level, which explains how the brain is wired. Each of these levels is independent of the others but they are meant to serve as a tool to explain what, why, and how a cognitive phenomenon occurs. Marr's levels of analysis are used so that we can see if similar representations are used at all levels.

An example of a computational model is the parallel architecture model (Figure 7) proposed by Jackendoff. This model involves linguistic representations such as phonological representations (i.e., the sound structure of words), syntactic representations (i.e., the grammatical structure of words), and conceptual (i.e., the semantic meaning of words) representations, as seen in Figure 7. Each linguistic representation is independent of the others but they are linked by a bidirectional interface, except for auditory to phonological, and phonological to motor representations, because auditory depicts the perceiving process while motor representations are related to the producing process. Jackendoff highlighted the importance of bidirectionality as it allows us to perceive and produce language. Without it, we cannot communicate things that we see or hear. For the single direction between auditory representations to phonology representations, he suggested that speech input is mapped into auditory representations (i.e., sound structure) before entering the phonological representations. Syntactic representations are the bridge between phonological representations and conceptual representations. Moreover, perceptual representations are connected to conceptual representations so that we may express ourselves directly about what we perceive visually.

Figure 7

Representations in parallel architecture



Note. Model with overall parallel architecture proposed by Jackendoff (2019). Arrows represent the interface between representations. Two arrows show bidirectionality.

In spoken language, there are spoken-word recognition models such as the cohort model (Marslen-Wilson & Welsh, 1978; Marslen-Wilson & Tyler, 1980), which tries to explain how spoken words are processed. This model has three stages of word recognition: access, selection and integration. Each stage emphasizes the importance of linguistic representations, such as phonological, syntactic and semantic representations. During the first stage, acoustic-phonetic inputs are matched to the lexicon, and words that are aligned with the input onset are activated. In the selection stage, words that do not meet the subsequent input are excluded. This process keeps repeating until it reaches the most probable candidate. It is then followed by integration, which is the last stage of the cohort model. Integration is a phase where syntactic and semantic information related to the words is activated; in a sentence, words are checked within the context, and if a word violates the contextual rule, it is excluded.

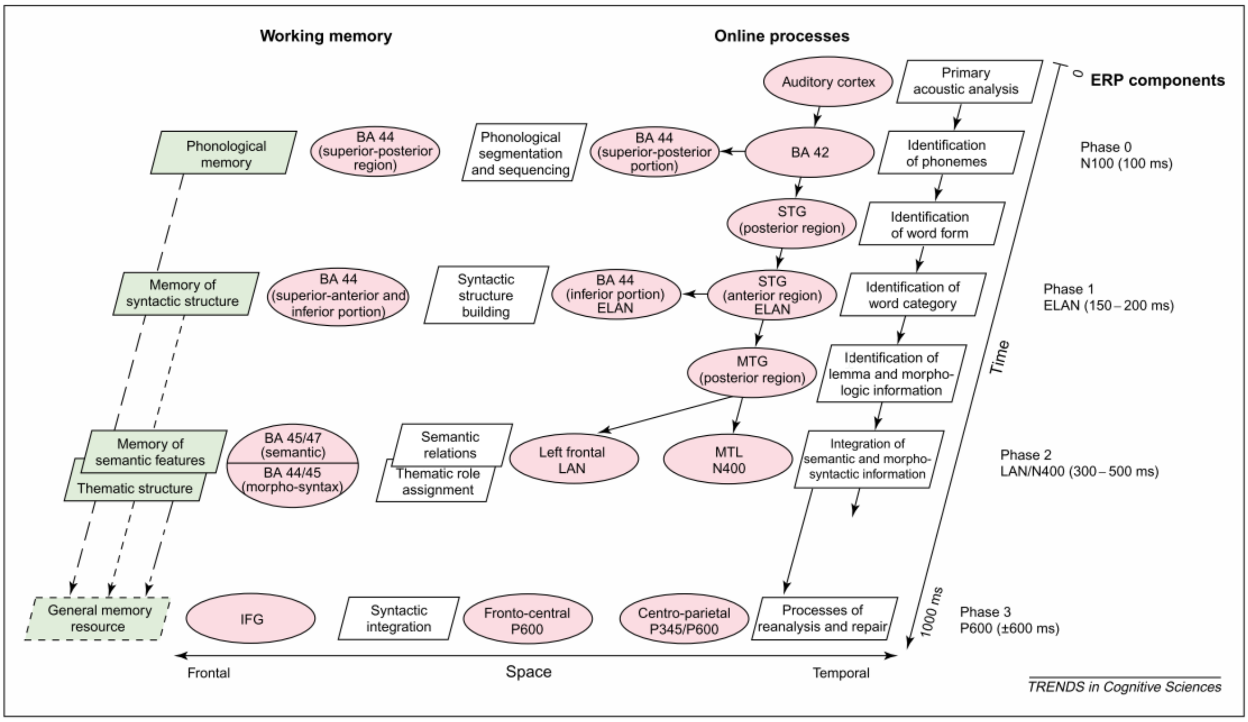
Following Marr's second level, the algorithmic level, some models mathematically aim at imitating spoken-word recognition, for example, TRACE (McClelland & Elman, 1986) and the Shortlist model (Norris, 1994). From these mathematical models, we learn the importance of accessing linguistic representations because they attempt to model representations to imitate the word recognition process. TRACE is a connectionist model that has three layers of nodes: feature, phoneme and word layer. Activation in the feature node spreads activation to the phoneme and word layers. The temporal aspect is important in spoken word recognition because spoken words are processed incrementally and the auditory input can decay over time. To accommodate the temporal factor (i.e., time dimensions as spoken language unfolds over time), TRACE allows reduplication of phoneme and word layers that activate overlapping words. The activation that involves phonological representations occurs parallelly in phoneme and word layers, so there is no inhibition between layers. However, there is inhibition within the same layer since nodes with higher activation inhibit nodes with lower activation. Moreover, TRACE is an interactive model which allows top-down access, which means a higher level of linguistic representations, such as word representations, could affect input processing at low levels (such as in phoneme layer). Due to this interactive activation, TRACE allows reduplication of features, phonemes, and words at every point of time; nevertheless, reduplication is criticized because it seemed to be improbable for the memory as the reduplication increased over time. Therefore, Shortlist, was developed after TRACE to answer the criticism about duplication. Shortlist has two levels of processing: input and word layer. Although it is simpler than TRACE, it still emphasizes the importance of linguistic representations, such as phoneme and lexical layers. It is similar to the cohort model in that its input is a string of phonemes, followed by a thorough lexical search resulting in a set of word candidates. An interactive activation network of word candidates is then generated based on information from linguistic representations, and the candidates are duplicated over time. The competition between them is akin to that in TRACE. Word candidates with stronger activation inhibit candidates with lower activation. To constrain word activation, Shortlist uses information from phonological representations. It relies on lexical stress since some languages use the rhythmic distinction between strong and weak syllables for segmentation. Activation of word candidates decreases when a neighboring input cannot form a possible word. The identified candidate has the strongest activation and is the most equivalent to the input.

These two models thus highlight the importance of phonology and lexicon. They do not take syntax into consideration because they focus on words rather than sentence processing.

Regarding the implementational level, there is the neurocognitive model developed from neuroimaging results by Friederici (2002), as seen in Figure 8. This model confirms the importance of linguistic representations (i.e. phonological, syntactic and semantic representations) and provides information about the stages of spoken-word processing in a sentence. According to this model, phonology is processed as early as 100 ms after input, as indicated by the negative amplitude that is known as N100. Around 150 and 250 ms after input, the negative amplitude, called ELAN, depicts the processing of word category information from the auditory input. This is then followed by the processing of morphosyntactic and semantic information around 400 ms, associated with LAN/N400. A positive amplitude shift occurring around 600 ms (known as P600) indicates a reanalysis process after detecting a violation. This model has shown that linguistic representations are accessed during online spoken language processing.

Figure 8

Neurocognitive model of auditory sentence processing derived from ERP components



Note. The illustration was adapted from Friederici (2002).

In a nutshell, all of the models mentioned above, following Marr's three levels of analysis, highlight the importance of linguistic representations, such as phonology, syntax and semantics, which are part of abstract representations. In the following section, we discuss abstract representations.

3.2.1. Abstract representations

3.2.1.1 The organization of abstract representations

Abstract representations are related to high-level cognitive functions such as inhibition, reasoning, problem-solving and language (Tranel et al., 2003). As far as language is concerned, abstract representations relate to how language is processed. As we have seen earlier, spoken language models emphasize abstract representations, such as lexical representations (e.g., the cohort model), while others also consider syntactic and semantic representations.

From previous chapter, we have seen that abstract representations, such as syntax, participate in forming verb inflections. In previous studies on agreement processing where verbal inflection was targeted, morphosyntactic features were accessed to process the agreement. If the system encounters an agreement violation, this would be reflected through an increase in the ERP amplitude component (Barber & Carreiras, 2005; Gunter et al., 2000; Mancini et al., 2011b, 2011a; Nevins et al., 2007; Silva-Pereyra & Carreiras, 2007). Previous studies in subject-verb agreement (Simona Mancini et al., 2011a; Silva-Pereyra & Carreiras, 2007; Zawiszewski et al., 2016) have showed that differences in the amplitude or topographical distributions were depended on the type or number of feature violation. Furthermore, these differences indicated that the abstract representations are accessed as the system has different pathway in addressing agreement violation.

It has been postulated that syntactic features in agreement, such as number, person and gender, are presented hierarchically (Carminati, 2005; Corbett, 1979; Greenberg, 1963; Harley & Ritter, 2002) In line with this notion, (Mancini et al., 2011a) claimed that the result of their EEG study during subject-verb agreement processing in written language supported this notion as they found differences in topography between number and person feature. In subject-verb agreement studies, there have been many studies focusing on this hierarchical feature topic; we know little about whether the brain supports this notion or not. Nonetheless, there have been attempts to investigate brain areas related to syntactic hierarchy (for review see Friederici et al., 2011; Matchin & Hickok, 2020). For instance, studies using artificial grammar suggested that syntactic hierarchy activated BA 44-45 (Bahlmann et al., 2006, 2008; Friederici, Bahlmann, et al., 2006). Another study by (Friederici et al., 2009) used natural grammar and fMRI method: the authors compared sentences that used hierarchical structure with sentences that used linear structure. They found that the processing of hierarchical sentences was related to the inferior frontal gyrus (IFG), posterior superior temporal gyrus (pSTG) and the superior temporal sulcus (STS).

Apart from hierarchical processing in abstract representations, sentence comprehension can be processed sequentially by using the statistical information of word properties, as suggested by Frank et al. (2012). They argued that syntactic hierarchical structure is not essential to explain how language is used because the sequential structure is simpler and that the system tend to process language linearly rather than hierarchically. In line with this, Conway et al., (2010)suggested that word predictability in auditory speech perception is affected by sequential structure. Moreover, evidence about the importance of statistical information also come from computational modelling studies, such as by Mccauley & Christiansen (2011) who simulate language comprehension and production in children. Their model matches findings in children's result in Saffran (2002), suggested that the sequential structure, which relies on the statistical properties of words, plays a role in language processing. As for subject-verb agreement, Gillespie & Pearlmutter (2011, 2013) showed that subject-verb production relies more on linear distance than hierarchical distance, other studies in agreement production also highlighting the importance of statistical properties of language (Haskell et al., 2010; Haskell & MacDonald, 2003, 2005; Thornton & MacDonald, 2003). Recognizing the importance of statistical information, in this thesis we would like to explore the statistical properties in subject-verb agreement, such as the association frequency between a subject and its inflection.

3.2.2 Associative representations

Associative representations are built by the co-occurrence of more than one stimulus at the same time, which is why they become associated. In other words, these representations are built through an associative learning strategy and implemented through habituation: a certain behavior or the targeted response is shaped by associating it to a certain stimulus. This learning strategy was pioneered by Pavlov (1927) and Skinner (1963). Initially, they used it to shape animal behavior; for example, Pavlov trained his dogs to associate the sound of bells with food. Consequently, whenever the dogs heard that sound, they would salivate. Since then, associative learning has become a staple in psychology to describe certain human behavior and language. However, in language, association does not seem as popular as it is in psychology. This might be because Chomsky placed great emphasis on the importance of grammar as an innate function in humans. Nevertheless, recent studies in language acquisition have shown that through habituation, children can quickly extract regularities from language (Aslin et al., 1998; Gómez & Gerken, 2000; Kidd, 2011; Saffran et al., 1996).

Importantly, association and statistical learning are not the same things, although they might be interlinked, and associative learning also makes use of statistical properties (Fiser & Aslin, 2002). The latter does not necessarily require association, while the former can extract statistical regularities based on association; for instance, in subject-verb agreement, the system extracts the frequency of a pronoun occurring with a certain inflection. A study by Smith & Yu (2008) could serve as evidence that associative and statistical learnings are linked. They conducted a study with a preferential looking task to see whether infants aged 12 to 14 months old could perform word-referent pairing between six new 'words' (e.g., *'bosa', 'gasser', 'manu', 'colat', 'kaki'*, and *'regli'*) and novel objects that they introduced during the training. During the training session, they presented target words which were the novel words or distractors; two words were presented with two object referents. The stimuli presentation was randomized and no information was provided regarding which object referred to which word. However, there was a consistency in the paired patterns (i.e., co-occurrence between a certain novel object with a novel word). For the experimental trials, infants were presented with a single word and two potential referents. The results showed that the duration of children's gazes was longer for the target object than for the distractors, which suggested that the participants were sensitive to the statistical regularities of the word-referent pairings. Moreover, Smith and Yu (2008) argued that the underlying mechanism of the statistical extraction in their study was not the same as in speech stream segmentation (Johnson & Tyler, 2010; Mattys et al., 1999; Mattys & Jusczyk, 2001; Pelucchi et al., 2009; Saffran & Wilson, 2003). In speech segmentation, the children would focus mainly on the occurrence frequency but in the study by Smith and Yu (2008), they focused on the regularity of the pairings between word and object. Smith and Yu also posited another possible learning strategy: associative learning, in which infants collect information about the associative strength of the co-occurrence and no co-occurrence between word and paired object; the associative strength then converted into statistical information. Nonetheless, their result could not strongly confirm this hypothesis. They suggested that further studies would be needed to confirm these findings.

In their review about statistical learning, Thiessen et al. (2013) suggested that statistical learning was related to task demands. They therefore created three different task categories: conditional relation tasks, such as word segmentation; distributional information tasks, such as category learning; and tasks involving the relation between perceptual characteristics of the input, such as cue learning. Based on these task categories, they ruled out three types of statistical learning: conditional statistics, cue-based statistics, and distributional statistics. The first concerns the strength of the relationship between two factors that usually occur together. The second is usually observed in studies with infants, where segmentation can be performed based on phonotactic cues, stressed syllables, and lexical stress. The last one concerns the frequency of exposure, since differentiating one from the other is affected by exposure duration. The association between a pronoun and its inflection in agreement processing could fall into the first category, conditional statistics, as conditional relation is usually observed in sequential word presentation. For instance, if we take the phrase 'happy birthday', it is more frequent to see the word 'happy' paired with 'birthday' rather than 'village'. In the processing of subject-verb agreement, we focus on the co-occurrence of pronouns and their inflections in this thesis.

Until now, we have seen that statistical learning and associative learning both make use of regularity in language. Therefore, associative learning could fall into the statistical learning category. We have seen the importance of statistical learning in language acquisition. In regards to grammatical agreement, Pulvermüller (2002) has suggested that subject-verb agreement is processed sequentially through detectors that link the representations of morphemes that co-occur together; nonetheless, to the extent of our knowledge this hypothesis has not been tested, thus little is known about the role of associative representations in the grammatical agreement computation. However, in production domain, as mentioned earlier, previous studies have showed that statistical information are used during agreement production (Haskell et al., 2010; Haskell & MacDonald, 2003, 2005; Thornton & MacDonald, 2003). For instance, Haskell et al. (2010) reported that statistical properties that is based on language exposure affect grammatical agreement production. In their study they used collective head nouns to investigate the effect of exposure in grammatical agreement; on top of that, the head nouns were used as story prime sentence, the number feature of the verb was manipulated as well. In their experiment, participants were asked to read the story sentences and complete a fragment of the story. They found that the used of plural verb after collective noun prompted the use of plural verbs erroneously during sentence completion. They argued that that this result showed the way the system select verb agreement was influenced by prior experience (Haskell & MacDonald, 2003, 2005; Thornton & MacDonald, 2003).

From those studies we learnt that agreement production also makes use of language statistical properties related to the exposure frequency of previous production. Yet, little is known about the role of associative representation (i.e., co-occurrence frequency between a subject and its inflection) in subject-verb agreement. This thesis is thus an attempt to investigate whether associative regularity is also used in subject-verb agreement processing. Considering that both abstract and associative representations might be involved in subject-verb processing, we would like to know how the cognitive system accesses them and if there is any flexibility in the process. Cognitive flexibility allows us to adjust our representations to the environment to reach our goal. This topic is explored in the following chapter.

Chapter 4
Language and cognitive flexibility

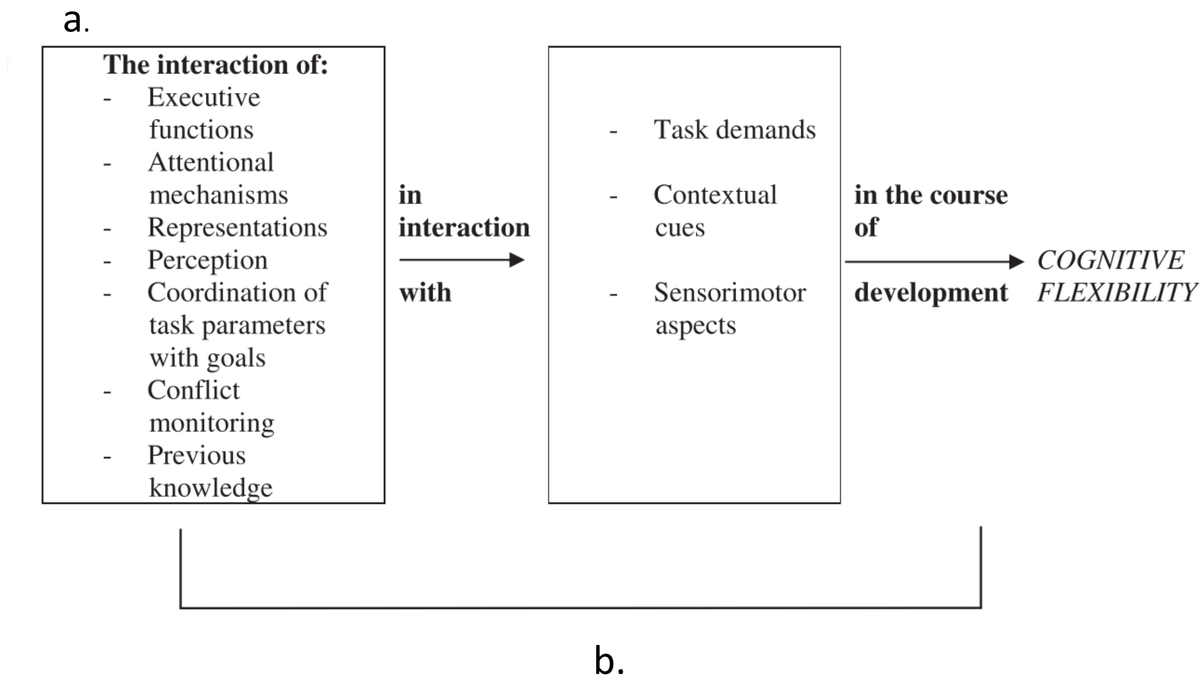
4.1 What is cognitive flexibility?

Cognitive flexibility is the ability to adapt to various situations in order to respond to task demands. It is a distinguishing feature of our cognitive ability that is part of our high executive function (Miyake et al., 2000). It is usually studied by using several switching tasks. For instance, object-sorting requires participants to categorize an object into two different but appropriate categories. The Wisconsin Card Sorting Test (Grant & Berg, 1948) is a classical cognitive reasoning task where participants are asked to classify cards based on the color, shape and number of their symbols. The Stroop task (Stroop, 1935) is another classical language-related task in which names of colors and the colors these names are printed in are mismatched; participants are then asked to name the ink color. All of these tasks have in common that participants need to be able to switch from one representation to another with all of the required attention. Deák (2003) underlined that flexibility involves the adaptation of the cognitive ability by shifting attention and selecting information that guides the system in achieving a goal response. Therefore, Deák defines cognitive flexibility as an active structure adjustment of representations and responses, based on information from both linguistic and non-linguistic input. Flexibility thus seems to be a goal-oriented cognitive ability, since it adjusts the system to achieve a target response.

In order to adjust the system, Ionescu (2012) argued that cognitive flexibility involves an interaction between cognitive mechanisms and perceptual information, as depicted in Figure 9. She suggested in her framework that cognitive flexibility is a result of interaction between cognitive mechanisms (e.g., attention and prior knowledge) with two other factors: task demand and context. This means that cognitive flexibility is an adjustment in the system in using the cognitive mechanisms due to the task demand.

Figure 9

A unified framework of cognitive flexibility



Note. A.) List of cognitive mechanisms; b.) This line shows the interaction between the cognitive mechanisms in the first box with the perceptual information that is obtained from the second box. This illustration is adapted from Ionescu (2012)

Task demand is indeed a factor that is often manipulated in studies investigating flexibility, including in language studies. Normally, in language, flexibility is often investigated in studies about, for example, bilingualism and language acquisition. However, in the context of grammatical agreement, little is known about it. Flexibility in language processing is thought to direct the system to comprehend a sentence based on the most appropriate representations, so that a response may be generated.

4.2 Cognitive flexibility in language processing

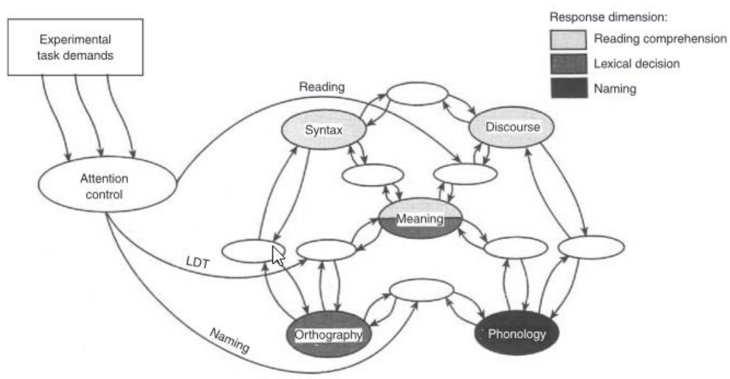
Flexibility in language is usually addressed in studies about language acquisition, bilingualism and embodied language. In children's language acquisition, flexibility is crucial because there are many cues in both linguistic and non-linguistic environments: children need to adapt to these environments and select the right cues in order to acquire language. Previous studies have examined the benefits of bilingualism: bilinguals seem to enjoy more flexibility than monolinguals (Adi-Japha et al., 2010; Bialystok & Martin, 2004; Bialystok & Shapero, 2005; Kuipers & Thierry, 2013; Marzecová et al., 2013; Wiseheart et al., 2016).

Cutler (2012) also showed that flexibility is needed by bilingual people because the phonetic rules are different in each language. Bilinguals thus need to adjust to these rules and their cognitive control and flexibility are consequently enhanced. In studies about bilingualism, cognitive flexibility has been shown to be improved through training. As flexibility is known to be one of the advantages of bilingualism, it is a major cognitive ability.

In the same line, Deák (2003) also recognized the importance of flexibility in language processing and suggested that "*Flexible language processing critically depends on selective activation and suppression of linguistic forms and meanings. Flexibility also depends on synthesizing language cues, task demands, contextual factors, and internal cognitive states*." (p. 283). In the same vein, Balota & Yap (2006) argued that flexibility is task-dependent, since the task itself seems to guide the system into finding the right pathway to complete it. They also proposed a framework of flexible lexical processor, as depicted in Figure 10. Importantly, this framework was built for visual lexical processing and it has three pathways for three different tasks: lexical decision task (LDT) (i.e., participants need to differentiate words from nonwords); naming task (i.e., participants need to name object stimuli); and reading comprehension (i.e., participants need to answer a comprehension question after reading a sentence). They suggested that these various options were highly affected by the attention requested by the task goal. For instance, in the visual lexical decision task, participants are required to discriminate words from nonwords.

Figure 10

The illustration of flexible lexical processor



Note. adapted from Balota & Yap (2006).

Figure 10. shows that the discrimination process between word and nonword requires the system to use either semantic or orthographic representation flexibly. However, Balota and Yap (2006) argued that, since the system is guided by word familiarity and meaning, the LDT task relies more on semantic representations than on orthographic representations, which is part of the sublexical pathway; in the sense that orthography is related to spelling to sound pathway. Balota et al. (1999) also agree with Ionescu (2012) that the flexibility mechanism depends on the task. For instance, it is common to observe a word frequency effect, where a high frequency word is recognized or named faster than low frequency one in a word-naming task (Balota & Spieler, 1999; Grainger, 1990) or LDT (Perea, Manuel & Rosa, 2000; Perea & Carreiras, 1998; Wagenmakers et al., 2008; Yap et al., 2008). However, Balota et al., (2000) showed the opposite effect in their naming task with regularization condition. In their experiment, they had two conditions: a normal naming task condition and a regularization condition. In the former, participants were asked to name the stimuli as fast and accurately as possible. In the latter, they were requested to apply a spelling to sound principle. Interestingly, in the regularization condition, they found that low frequency words were named faster. This result showed that the task could affect the lexical and sublexical pathways during word processing and it seemed the lexical interference could be manipulated by the task. Furthermore, the flexibility in selecting the lexical or sublexical pathway seemed to require attention-control. To further investigate the control process in accessing or inhibiting the lexical and sublexical pathways, Zevin & Balota (2000) conducted a prime-naming task in which participants were asked to pronounce the presented stimuli. In their experiment, the prime task was low frequency words or nonwords; the former to prompt lexical access, the latter to prompt sublexical access (i.e., grapheme and phonology). In their experiments, Zevin and Balota (2000) controlled word frequency and imageability, and they used both words and nonwords. They used word-naming tasks where participants were asked to read a list of nonwords followed by an exception word. The first five words were primes and the sixth word was the target. The idea was that low frequency word primes would prompt lexical access while nonword primes would prompt sublexical access and inhibit the lexical access. The results supported their hypothesis as they found that when the lexical prime was applied, a larger lexicality effect was observed: words were named faster than nonwords, high frequency words were recognized faster than low frequency ones, and highly imageable words were recognized faster than abstract ones. In short, the results confirmed that flexibility in lexical access is influenced by the task demands and is not an automatic process that employed a specific pathway for lexical

processing. Moreover, this flexibility is affected by three factors (Balota and Yap, 2006): 1.) the capability of the contextual factor to interact with the relevant task; 2.) the capability to sustain the same representation throughout the task; 3.) the influence of the pre-existing pathway.

Regarding the importance of task and attention in flexibility, Balota and Yap (2006) suggested that the lexical processing pathway was adjusted by attentional control during their experimental task. They added that lexical flexibility is the result of heuristic processing (i.e., using information that is most familiar) in solving a task where attention and control are also involved. The importance of task effect was also confirmed in visual word recognition (Chen et al., 2013; Grainger & Ziegler, 2005; McCann et al., 1992, 2000; Ruz & Nobre, 2008; West & Stanovich, 1986) and spoken word recognition (Hasson et al., 2006; Kreysa & Knoeferle, 2011; Theodore et al., 2015; Yoncheva et al., 2010). Flexibility requires attention, whether in visual or spoken language, and it seems to be goal-dependent. It thus has a heuristic nature, in that our cognitive system tries to find the most efficient way to respond to a demanded task.

Recognizing that language processing is flexible leads us to the possibility that this function also plays a role in grammatical agreement processing. Little is known about flexibility in agreement computation but some studies have examined the automaticity of agreement processing. Therefore, in the following we will look at grammatical agreement studies which used EEG method and aimed to explore the automaticity.

4.3 Flexibility vs. automaticity in grammatical agreement: evidence from electrophysiological studies

Previous research argued that syntax is processed automatically (Flores d'Arcais, 1982; Fodor, 1985; Forster, 1974) and that syntactic input is processed sequentially. The interaction between syntactic and semantic information would thus occur after the input information is integrated. Indeed, some studies have shown that syntactic processing may occur automatically during the early stage of word processing. Hence, some studies (Hahne & Friederici, 1999, 2002; Hasting & Kotz, 2008) suggested that automaticity would therefore be related to ELAN which is an ERP component that was enhanced when word category was violated. On the other hand, Gunter & Friederici (1999) showed that the LAN component is related to the automatic processing of morphosyntactic information.

As in flexibility studies where task demands are manipulated, the same method is used in automaticity studies. For instance, Hasting and Kotz (2008) conducted two experiments where they manipulated the task demands. In the first experiment, they introduced morphosyntactic violation and word category to generate two violation conditions, such as person violation [14b.] and word category violation [14c.]. In the subject-verb agreement condition, their sentence stimuli only used second and third person singular (i.e., *'du'*- you and *'er'* - he), and the verbal inflection was manipulated to create a violation condition [14b.]. For word category violation, a noun was placed after a pronoun [14c.].

[14] a. congruent: *'er kegelt'* – he bowls
b. person violation: *'er kegelst'* – he bowl
c. word category violation: *'er kegel'* – he cone

Stimuli were presented in two blocks and the order of the stimuli set was randomized. Participants were asked to listen to these sentences and perform the correctness judgment task, where they had to decide whether the sentence, they listened to was correct or not. In the second experiment, they used the same stimuli but the agreement condition set was separated from the violation condition set. Participants were asked to ignore the auditory stimuli and focus on a silent cartoon film. In both experiments, early negativity was found around 100 ms, which reflects a rapid detection of the syntactic errors. The incongruent condition increased the negative amplitude, which then decreased in the second experiment. P600 was found in the first experiment in a later time window but it was absent in the second one. Therefore, the early stage of syntactic processing appears to be automatic while the reanalysis process, reflected by P600, was more controlled. This is not surprising as P600 is known to be an index of a controlled process. Importantly, this result is in line with previous studies using mismatch negativity (MMN), which relies on the use of the oddball paradigm (i.e., sets of repetitive stimuli are irregularly interrupted by a deviant stimulus). These studies found automaticity of early-stage syntactic processing peaking around 150 ms (Hasting et al., 2007; Pulvermüller & Shtyrov, 2003). Automaticity occurred in the early stage after receiving stimuli input and was followed by a controlled process.

In contrast, Batterink et al., (2010) conducted an ERP study to investigate if there is automaticity in semantic and syntactic processing. They found N400 component related to attentional process. In their study, attentional blink paradigm (AB) was used, AB paradigm manipulates participants' awareness towards the second target (T2) by presenting stream of stimuli that consisted two targets. In this paradigm, the accuracy to recognize T2 is affected by the distance duration from the first target (T1); decreased of accuracy was reported when T2 appeared between 200 and 500 ms after T1. In the semantic block, the stimuli were primed with words that were semantically related (e.g., *'dog-puppy'*) and unrelated (e.g., *'lemon-puppy'*). In the syntactic block, words were primed with related (e.g., 'the-sky') and unrelated word category (e.g., *'we-sky'*). Their result in the semantic block elicited N400 within and outside AB time period; this component reflected a controlled process thus this component disappeared when the participants were not aware of the target stimulus. Concerning the syntactic block, they found late negativity reflected the processing of grammatical violation and that this process seemed to be controlled. Moreover, they argued that their syntactic block was morphologically impoverished thus, if it was richer, they might be able to observe automaticity.

Concerning associative representations, we explore this through statistical learning as associative frequency information was part of language statistical properties. In regards to automaticity, some studies found statistical learning is an automatic process (Fiser & Aslin, 2001, 2002; Saffran et al., 1996; Turk-Browne et al., 2005). Saffran and colleagues (1996) conducted two experiments using the familiarization-preference procedure and found that infants could extract statistical regularities from speech stream, in what seemed to be an automatic process. In both experiments, infants had a two-minute familiarization phase with artificial language, in which there were no clear boundary cues within the speech stream. In experiment one, they had to differentiate words from nonwords (i.e., words that did not appear in the familiarization phase). In experiment two, they had to differentiate words from word parts. The results showed that infants could perform differentiation in both experiments through longer listening. These findings could serve as evidence of automaticity in statistical language learning. To our knowledge, this particular topic in the language processing domain has received little attention to date.

Interestingly, in contrast to the notion of automaticity in statistical learning, a study by Toro et al. (2005) showed that attention affects statistical learning performance in speech segmentation. They did three experiments using artificial language, in which statistical regularities were distributed across syllables and participants' attention was diverted. In the first experiment, the attention was diverted by noise from another stream; in the second experiment, attention was diverted by a visual distractor; in the third experiment, attention was diverted within the same speech stream. In each experiment, participants were divided into two groups: passive listening (participants were asked only to listen and watch pictures in experiment 2) and high load attention (participants were asked to press a button when they detected word repetition in experiment 1, picture repetition in experiment 2 and pitch changes in experiment 3). After a 7-minute monitoring phase, participants had to respond to a two-alternative forced-choice task. The results suggested that attention diversion lowered participants' accuracy. This topic offers scope for investigation, considering the rarity of studies focusing on the automaticity of statistical learning. Whether attention is needed or not in statistical learning seemed to be debatable, because although it seems to occur implicitly, it was differentiated from implicit learning (Perruchet & Pacton, 2006). Nonetheless, even if attention was required, it did necessarily mean there is no automaticity, because participants normally were not aware that they extracted language statistical regularity. Since associative representations are part of language statistical properties, there is a possibility that these representations are accessed automatically.

Apart from automaticity to access the representations, a possibility for flexibility in accessing the representations need to be considered as well. Whether it is automaticity or flexibility, the system might use them in a heuristic manner to comprehend linguistic input. Ferreira & Patson (2007) suggested that to comprehend a message, the system should employ good-enough (GE) strategy processing. According to this notion the system tends to operate heuristically, which sometimes results in an inaccurate interpretation. However, this strategy allows the representations to be reanalyzed and updated, so that the expectation matches the input. This update could occur because the GE strategy also tries to integrate prediction, which is quite a common notion in the study of perception. We thus explore this notion of prediction in the following chapter.

Chapter 5

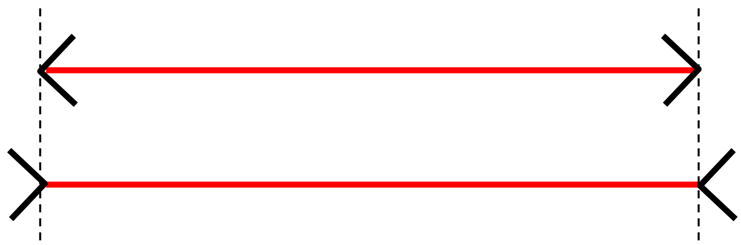
Prediction

5.1 From perception to prediction

The notion of prediction evolved from perception studies. Helmholtz researched the visual domain and showed that visual experience not only relates to sensory experience, as it also involves cognition. He argued that our mind generates unconscious inferences based on sensory input. This kind of inference can be observed in optical illusions. For example, in the Müller-Lyer optical illusion (Figure 11), people tend to judge that the line above is shorter than the one below. According to Helmholtz's unconscious inference view, this illusion is the result of previous experience that has affected the way we infer the external world.

Figure 11

The Müller-Lyer optical illusion



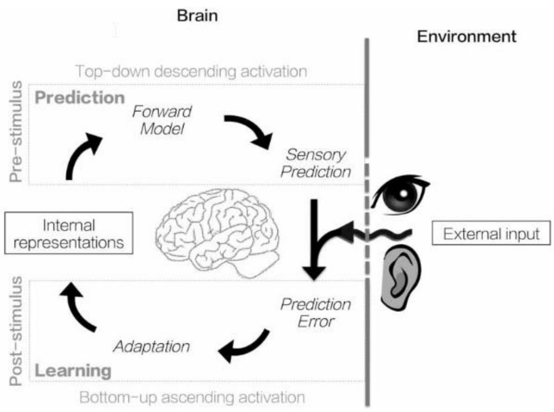
Unconscious inferences lead to interference of top-down processing, which allows us to use our knowledge to make inferences regarding the current input. This top-down processing is usually interpreted as an attempt to predict the sensory input and led to the idea of hierarchical predictive coding. The term hierarchical itself is important because the sensory input is encoded as multiple hierarchical representations in the brain (from higher representations to lower representations). This hierarchical notion is also applied in the auditory system (Bregman, 1994). This inspired other scientists to develop the predictive coding theory, as shown by the Helmholtz machine proposed by Dayan et al. (1995), where the brain is assumed to make an inference based on statistical properties. Friston (2005) proposed the notion of free energy to explain predictive processing from a neuroscientific perspective, using the unconscious inference principle. In other words, he tried to explain how neurons draw inferences using the free energy concept based on the Bayesian notion that prior knowledge is used to produce a response. Friston (2012, p.249) defined free energy as follows:

> "*Free energy is a quantity from information theory that quantifies the amount of prediction error or, more formally, it is a variational approximation to the surprise or negative log-likelihood of some data given an internal model of those data*."

In predictive coding, prediction errors are a mismatch between the predicted information and the sensory input that is encoded at any level of the representation hierarchy. Figure 12 depicts the prediction and learning process that enables representations to be updated to match the expectation generated by the system. This process could occur because our brain is not passively waiting the incoming input (Bar, 2007, 2009; Clark, 2013; Friston, 2012; Rao & Ballard, 1999), instead it actively generates expectation. When the input does not match, the system will update the representations through prediction errors and this process keeps repeating until the prediction errors are reduced and the inference is produced by the system (Friston, 2012; Jaeger & Snider, 2013; Molinaro et al., 2016; Rao & Ballard, 1999). If predictive coding is assumed to apply to the sensory-motor and cognitive systems, then it is also naturally involved in language processing as it is part of the cognitive system. The following section therefore describes what prediction is in language.

Figure 12

The illustration of prediction and learning



Note. Adapted from Molinaro et al. (2016)

5.2 Prediction in language

What is language prediction? It is not a new notion, as Van Petten & Luka (2012) indicated in their review. It arose around 50 years ago in the 1960s (Miller & Isard, 1963; Tulving & Gold, 1963), and was then overlooked in the 1980s. Nowadays, language prediction is extensively discussed (Kamide, 2008; Kim et al., 2016; Kuperberg & Jaeger, 2016; Van Petten & Luka, 2012) , as there is growing evidence suggesting that prediction is part of language comprehension (Altmann & Kamide, 1999, 2007, 2009; DeLong et al., 2005; Hintz et al., 2017, 2020; Ito et al., 2018, 2020; Kamide et al., 2003; Karimi et al., 2019; Otten et al., 2007; Van Berkum et al., 2005a; Wicha, Moreno, et al., 2003). That evidence came from behavioral and neuroimaging studies. Eye-tracking studies have shown that the context guided participants in predicting the upcoming word in a sentence (Altmann & Kamide, 1999, 2007, 2009; Hintz et al., 2017, 2020; Ito et al., 2018; Kamide et al., 2003; Karimi et al., 2019). For instance, Altmann and Kamide (1999) did an eye-tracking study in which they presented auditory sentence stimuli as in [15] and showed a semi-realistic picture that consisted of a boy, a cake, and other objects on the screen (the cake being the only edible object). They found that the verb guided the eye gaze when [15b] was presented and the saccadic eye movement to the cake was observed before the word 'cake' was heard. In [15a] however, saccadic eye movements occurred after hearing the word 'cake'.

[15] a.'the boy will move the cake'
b. 'the boy will eat the cake'

From [15b], it may be seen that the verb helps the system predict the upcoming word as the effect was observed prior to the predicted word. Perhaps an issue with this method was that participants could see the picture prior to listening to the sentence, thus this might bias the prediction effect. Apart from that, there is ERP method which is also used to study prediction in sentence comprehension (DeLong et al., 2005; Fleur et al., 2020; Ito et al., 2020; Laszlo & Federmeier, 2009; Lau et al., 2013; Otten et al., 2007; Van Berkum et al., 2005a; Wicha, Moreno, et al., 2003). In ERP studies, prediction is usually associated with N400 but it is not uncommon to have an earlier ERP component (for review see Nieuwland, 2019).

In ERP prediction studies in language comprehension, sentences are usually grouped with cloze probability. It is a method to measure the probability of a word occurring in a certain sentence, resulting in either high or low cloze probability. High cloze probability indicates a highly predictable sentence or highly constraining sentence that allows the system to predict the target word based on the context, while low cloze probability is the opposite. Sentences with high cloze probability reduce the ERP amplitude (DeLong et al., 2005; Ito et al., 2016, 2020; Otten et al., 2007; Thornhill & Van Petten, 2012; Van Berkum et al., 2005) because the sentences are highly constraining, thus the system is able to pre-activate words that are related. In contrast, sentences that are low constraining cause the system to activate more possible words thus this process was reflected through stronger ERP amplitude. The fact that the system can pre-activate words related to the incoming input indicates that the language comprehension system is not totally bottom-up. There is top-down processing where higher representations, such as semantic or contextual representations, help the system predict the upcoming input.

One of the well-known studies that demonstrated this top-down processing was by DeLong et al. (2005), where they showed that pre-activation of the upcoming input was reflected by N400. DeLong et al. (2005) conducted an ERP study in sentence processing where they manipulated article-noun cloze probability; they found evidence of pre-activation during sentence processing. In order to isolate the prediction process, they controlled the article, since in English, the article ‘an’ is followed by a vowel while ‘a’ is followed by a consonant. For example, after stimulus [16a], they had either an expected [16b] or an unexpected target [16c]. The stimuli were presented sequentially in the middle of the screen and at the end of the sentence, and the participants completed a yes/no comprehension task. Both the target article and noun were analyzed separately. A similar pattern of N400 amplitude was found in which the unpredictable article and noun increased the amplitude, while the predictable ones decreased the amplitude. The correlation between N400 and cloze probability time-locked to noun and article was also tested. The correlation result for the noun showed a negative peak over the posterior site, while the correlation result for the article showed a negative peak over the centroparietal site. As a result of lexical pre-activation that was derived from the sentential context, the N400 amplitude of the article was found reflected the system’s expectation that did not match the input. Moreover, the N400 component differed depending on cloze probability, with high cloze probability decreasing the N400 amplitude

[16] a. 'The day was breezy so the boy went outside to fly ...' - sentence stimulus
b. ‘ a kite’ - expected target
c. ‘an airplane’ - unexpected target

Misyak et al. (2009) highlighted the importance of extracting language statistical properties in language prediction. McDonald & Shillcock (2003) also showed the importance of word transitional probability (from corpus word frequency) in predicting the following word, which affects eye movements. In their study, gaze duration was longer for low probability words and skipping probability was higher for a word with higher probability.

Cloze probability is one of the most common ways to measure word probability in prediction studies. However, there is another way to measure it by using surprisal and entropy from information theory (Shannon, 1948). In sentence processing studies, surprisal measures the probability of a certain word occurring in a sentence, while entropy measures the uncertainty of that occurrence. A word that has high entropy thus has low surprisal. Surprisal and entropy are also commonly found in phonological prediction studies (Ettinger et al., 2014; Gagnepain et al., 2012; Gaston & Marantz, 2017; Gwilliams et al., 2018). In such studies, the probability and uncertainty of phonemes are measured instead of words. In the following sub-section, we explore how they are used to study prediction in spoken words and sentences.

5.2.1 Phonological prediction

Phonological prediction means the system generates a prediction based on phonological information. This prediction can be observed in both written and spoken languages (DeLong et al, 2005) as phonological representations are accessed in both language forms. Gagnepain, Henson, & Davis (2012) investigated predictive coding of the spoken word over the STG area. In their experiment, they found that the system promotes segmental prediction rather than lexical entropy. Segmental prediction is based on the frequency of occurrence of possible segments that could follow the current segment, while lexical entropy is based on word probability from a corpus after hearing a word segment. Gagnepain et al. (2012) concluded that the neural activity they observed over the STG area reflects prediction error, which is the result of unpredictable input. Inspired by these findings, Ettinger, Linzen, & Marantz (2014) conducted a study in which they investigated whether morphological complexity affects phoneme surprisal in spoken word prediction. They used monomorphemic (i.e., one morpheme) and bimorphemic (i.e., two morphemes) words. They also measured phoneme surprisal and cohort entropy, which is the distribution of all probable words that would fit the prefix; these resulted in high and low entropy. They found that bimorphemic words enhanced phoneme surprisal. Entropy affects neural activity in line with the Low-Entropy Dependent Prediction model that they proposed, in which low entropy increases brain activation at the offset of the word while high entropy increases activation at the onset of the word. This showed that morphological decomposition occurred during the processing of spoken language and that phonology prediction is affected by morphology.

5.2.2 Word prediction in spoken language comprehension

Another prominent study in sentence prediction was done by Van Berkum et al. (2005) in the spoken language comprehension. In their study, they did three experiments in Dutch. As in other sentence prediction studies, they controlled the context and cloze probability of nouns. The first two studies were EEG studies and the third one was a self-paced reading study. The sentence materials were either prediction-consistent or prediction-inconsistent and constructed as mini-stories. Sentences that were prediction-inconsistent had lower cloze probability compared to the prediction-consistent ones. Moreover, to explore the predictability of nouns in a prior article, they contrasted the suffix of the gender-marked adjectives with the syntactic gender of the following noun (see [17] for example).

[17] a. Context sentence : *De inbreker had geen enkele moeite de geheime familiekluis te vinden.*
The burglar had no trouble locating the secret family safe

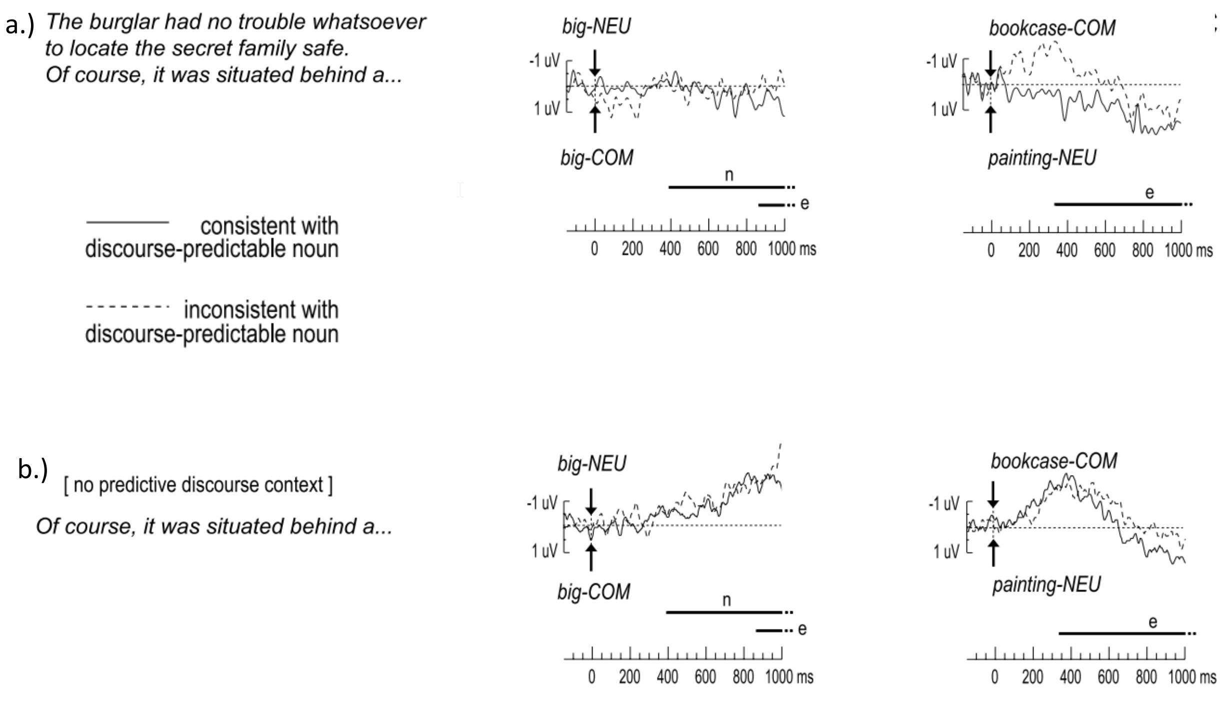
b. Prediction-consistent sentence: *Deze bevond zich natuurlijk achter een groot$_{neuter}$ maar onopvallend schilderij$_{neuter}$.*
Of course, it was situated behind a big$_{\text{neuter}}$ but unobstrusive painting$_{\text{neuter}}$

c. Prediction-inconsistent sentence: *Deze bevond zich natuurlijk achter een grote$_{common}$ maar onopvallende boekenkast$_{common}$.*
Of course, it was situated behind a big-e$_{\text{common}}$ but unobstrusive bookcase$_{\text{common}}$.

As in other languages like French and Spanish, Dutch has gender agreement, so the gender of adjectives has to agree with the noun that is being described. In the first experiment, context sentences were presented before the predictable sentences. In the second experiment, which was performed as a control experiment, context sentences were not presented. In the third experiment, around 54% of the mini-stories from the first experiment were used, to which were added comprehension questions. For the first experiment, the ERP results that were time-locked to the adjective onset inflection showed an early positive deflection (from 50 to 250 ms) elicited by the mismatch inflection with the proceeding noun gender (see Figure 13). This effect was a clear evidence of word prediction as the system pre-activate noun’s gender information. Interestingly, this effect was absent in the second experiment where context was not presented, which showed that there was anticipation when it was the case. As for the noun, a classical N400 component was observed. The third experiment also supported the findings of the two previous experiments: self-paced reading was slowed down before a noun in the inconsistent-predictive sentence. Another study in spoken language (Otten et al., 2007) used similar predictive sentence stimuli and additional prime control sentences which were less predictive. As a result, they found an inconsistent prediction effect in adjectives around 300 and 600 ms but the data was time-locked to the onset of the adjective. This effect was observed only in the predictive context condition.

Figure 13

ERP results from the study of Van Berkum et al. (2005)



Note. a.) result of experiment 1; b.) result of experiment 2. The x-axis indicates the time range in milliseconds. The first column is the sentence stimuli; the second column is the ERP for adjective inflection; the third column is ERP for the noun. Adapted from Van Berkum et al. (2005)

These studies show that context plays a crucial role in word prediction, both in spoken language and in reading (Brothers et al., 2015; DeLong et al., 2005; Dikker &

Pylkkänen, 2013; Rommers et al., 2013; Van Berkum et al., 2005a). This is due to the fact that context gives a constraint so that the system can find the best possible word to match the input. Interestingly, despite this evidence, the idea of prediction in language is still debated because prediction is thought by some to be too costly and unnecessary (Forster, 1981; Jackendoff, 2002; West & Stanovich, 1982), while others still question its importance (Huettig & Mani, 2016). Those who disagree with prediction argue that instead of prediction, they argue language comprehension occurs owing to integration (Baggio & Hagoort, 2011; Hagoort, 2003; Van Berkum et al., 1999).

Unlike prediction, which allows the system to use higher-level representations to generate a response, integration is a bottom-up process in which input is processed sequentially and combined together. Integration collects the phonological, syntactic and semantic information from the linguistic input and integrates it to the higher level representations, such as semantic representation before they generate a response. That said, integration does not recognize pre-activation. Yet, similar to prediction, integration is also affected by context, which can accelerate the process. Previous integration studies (Tanenhaus et al., 1995; Van Berkum et al., 1999; Van Den Brink et al., 2006; Van Petten et al., 1999) found an increase in N400 when integration was difficult. In integration, N400 reflect the accumulation of sentence context, thus words that occur early in the sentence would elicit larger N400 compared to words that appear late because the latter already have a context. This raised the question as to how to differentiate integration from prediction.

5.3 Prediction vs. integration

Apart from the argument that it is too costly as a mental process, there are other concerns about prediction, such as its importance and replicability. Regarding the former, studies have demonstrated prediction during language processing. However, this evidence did not directly prove the importance of prediction in language processing (Huettig & Mani, 2016). Another concern is that there is a difficulty in replicating prediction studies, such as by DeLong, Urbach, & Kutas (2005). Therefore, the debate as to whether language processing uses prediction or integration is not yet settled.

A major attempt to replicate the study by DeLong et al. (2005) was recently made by Nieuwland et al. (2018), involving several laboratories in the U.K, where the same stimuli as those of DeLong, Urbach, & Kutas (2005) were used with adjustments to British English. However, they failed to replicate the ‘a/an’ result, although the N400 effect towards the noun was replicated. DeLong et al. (2005) found a cloze probability effect, with high cloze probability reducing N400 for both article and noun. However, Nieuwland et al. (2018) were not able to replicate the cloze probability effect for the article, although a similar pattern was observed for the noun. Thus, for some researchers the idea of prediction is not convincing enough as they argued that the system would perform fast integration rather than prediction.

5.4 Studying prediction in agreement processing

Little do we know about prediction in agreement processing. Altough, in terms of syntactic context, a study by Strijkers et al. (2019) suggested that syntactic context could affect the processing of grammatical class. In regards of morphosyntactic agreement, some studies have tried to investigate prediction that involves gender agreement in a sentence (Fleur et al., 2020; Ito et al., 2020; Karimi et al., 2019; Martin et al., 2017; Otten et al., 2007; Wicha, Moreno, et al., 2003). Some studies suggested that there is syntactic prediction in the article-noun relationship within a sentence and this syntactical prediction effect can be observed in the article (Fleur et al., 2020; Ito et al., 2020; Wicha et al., 2003). If prediction occurs in gender agreement, it might also occur in subject-verb agreement, where the syntactic rule that governs how a verb is formed when paired with a pronoun can also serve as context. Furthermore, the statistical properties of language need to be considered as we have seen that they affect prediction (MacDonald, 2013; Misyak, 2010; Misyak et al., 2010). Regarding subject-verb agreement, we could draw statistical information from the co-occurrence frequency between a pronoun and its inflection. In the following chapter, we explain how we designed our studies to investigate prediction in subject-verb agreement.

Chapter 6

Aims and Hypotheses

This thesis is an attempt to investigate the underlying representations of subject-verb agreement processing. Previous studies in agreement processing have shown that abstract representations are accessed during agreement processing, in which morphosyntactic features are involved. For instance, Silva-Pereyra & Carreiras (2007), Mancini et al. (2011), Nevins et al. (2007), and Zawiszewski et al. (2016) showed that morphosyntactic violations increase the amplitude of the two ERP components (e.g., LAN and P600). Mancini et al. (2011) found that there is a topographical difference in brain response to number violation and to person violation, thus indicating that abstract morphosyntactic features are computed during the processing of subject-verb agreement. As well, previous subject-verb agreement studies (Nevins et al., 2007; Silva-Pereyra & Carreiras, 2007; Zawiszewski et al., 2016) found that there were ERP differences in amplitude between single and double violations, which means that abstract representations are stored separately. However, these empirical findings do not support the notion of hierarchy in grammatical agreement, as initially proposed by linguistics (Carminati, 2005; Greenberg, 1963; Harley & Ritter, 2002).

From the chapter on mental representations, we know that apart from abstract representations, the system can rely on associative representations and processes the language input sequentially through its statistical information from language use (Seidenberg & Macdonald, 1999; Trueswell & Tanenhaus, 1994). Little is known about whether these representations are involved in subject-verb agreement processing, although Haskell et al. (2010) investigated the topic and showed that statistical properties were involved in agreement production. This thesis thus investigates whether associative and abstract representations are used during subject-verb agreement processing in spoken language. Associative representations in subject-verb agreement are the association between a subject pronoun and its inflection, such as *'je-ai', 'tu-as', 'vous-ez'*, or *'nous-ons'*. Interestingly, access to abstract representations in subject-verb agreement in spoken language has not yet been studied.

If associative and abstract representations are indeed accessed during subject-verb agreement, it is necessary to understand whether their access is flexible. As described in

Chapter 4, flexibility is the ability to adapt to a changing situation. For instance, in the daily use of language, we can comprehend language well and effortlessly although surrounding noise is inevitable. This leads to the question of whether subject-verb agreement processing involves flexibility, or whether it is the result of automaticity. Little is known about flexibility in agreement processing, as automaticity was the focus that has received the most attention until now (Gunter et al., 2000; Hasting & Kotz, 2008; Jiménez-Ortega et al., 2014; Pulvermüller et al., 2008). Another purpose of this thesis is thus to investigate whether there is flexibility or not in accessing the underlying representations during the processing of subject-verb agreement.

A cognitive mechanism that is widely discussed in language processing nowadays is the prediction process. The previous chapter about prediction showed that studies on word prediction (Chow et al., 2016; DeLong et al., 2005; Laszlo & Federmeier, 2009; Maess et al., 2016; Ness & Meltzer-Asscher, 2018; Van Berkum et al., 2005) have shown that it occurs during sentence processing and that it is affected by sentential context. To study the predictability of a word within the context of a sentence, most studies until now have used cloze probability. They found that high cloze probability (a highly predictable word) reduces the amplitude of ERP components, such as N400 owing to semantic constraints. Prediction in agreement processing has also been not explored, particularly in subject-verb agreement. However, this is not surprising as, in grammatical agreement, the morphosyntactic relation between words could serve as context. Therefore, we hypothesize that the system can predict a verbal inflection after hearing a subject prime. Furthermore, we would like to know whether associative frequency is at the core of the inflection prediction in subject-verb agreement, as previous studies found that prediction was related to the statistical properties of language. If prediction indeed occurs during subject-verb agreement, we would like to localize the brain areas related to this process.

To sum up, the three main purposes of this thesis on subject-verb agreement in spoken language are as follows:

1. To investigate the abstract and associative representations that are accessed during subject-verb agreement processing in spoken language.

   To achieve this aim, as in previous agreement processing studies, we used the EEG technique and manipulated grammatical features to create morphosyntactic violations (i.e., number violation, person violation, and number person violation).

These violations were constructed to observe differences in processing the type of morphosyntactic violation, such as between the type of features (i.e., person vs. number violation) or number of features involved in the violations (i.e., single vs double violation). We hypothesize that these differences would reflect the accessing of the abstract representations. To investigate the role of associative representations, we analyzed the associative frequency between a subject prime and its verbal inflection by measuring their co-occurrence frequency in language use. The measures of co-occurrence frequencies were based on the pointwise mutual information (PMI) formula of Van Petten (2014). More details are presented in the method section of the following chapter about Experiment 1. If associative representations are indeed accessed during subject-verb agreement processing, we would expect the amplitude of ERP components to be affected when the data is time-locked to the verb onset. Moreover, we hypothesized that the system extracts the associative frequency information from the subject prime and uses it to predict the upcoming verb inflection. This prediction is demonstrated through the preactivation of the low level (phonology) due to the high level (associative representations) as a result of top-down processing. Previous studies (Cason & Schön, 2012; Getz & Toscano, 2019; Noe & Fischer-Baum, 2020) have suggested that there is a top-down effect during phonological processing and that N100 is related to this process. In other words, we would expect N100 to be modulated by associative frequency.

2. To investigate whether there is flexibility in accessing representations during subject-verb agreement processing.

   For this purpose, we manipulated task instructions while using the same EEG technique and the same stimuli as in our first EEG experiment. For each trial in both experiments, we presented a prime followed by a target word. In one experiment (Experiment 1), we asked participants to perform a lexical decision task (LDT) for the target word, where they had to respond if they heard a pseudoword. In another experimental task (Experiment 2), we asked them to perform a noun categorization task on a target word, where they had to respond if they heard a noun. We then compared the ERP results time-locked to the verb onset from both experiments. As a result of flexibility, we expected to observe differences between the two experiments that would affect the accessing of either associative representations or abstract features, or both (Chapter 8). If there was flexibility, we expected the ERP amplitude to be affected by the task demand. We expected to see flexibility in accessing the abstract representations during the LAN time window, where the noun categorization task would enhance the grammaticality effect. The aforementioned task probed the use of grammatical information, so we expected the system to rely more on abstract than on associative representations. Moreover, a similar effect was expected for P600 where abstract representations were accessed for the purpose of reanalysis.

3. To investigate and isolate the predictive nature of processes involved in subject-verb agreement.

   Our third aim was to isolate the brain areas related to prediction in subject-verb agreement processing. To this end, we used the MEG technique, which has better spatial resolution compared to EEG (Chapter 9). For the stimuli, we used the same stimuli as in our EEG experiments, with the classical lexical decision task where participants had to respond for both target words and non-words. Previous studies (Ettinger et al., 2014; Gagnepain et al., 2012; Gaston & Marantz, 2017; Gwilliams et al., 2018) in spoken language have demonstrated that brain areas such as TTG, MTG and STG are involved in phonological prediction. We also expected to observe activation in those areas related to phonological preactivation based on the associative frequency information during the verb phonological processing. Concerning the processing of syntactic information, we expected to observe activation related to grammaticality over the IFG area after hearing the verb inflection. Moreover, we were particularly interested in the left hemisphere, as it is traditionally known to govern language.

Chapter 7

Study 1: EEG experiment to explore the nature of representations

The purpose of Experiment 1 is to discover which representations are accessed during subject-verb agreement processing. Previous studies in this field have confirmed that abstract feature representations are accessed. In this experiment, we wanted to replicate prior findings showing the access to abstract feature representations in spoken language and consider other possible representations, such as associative representations. To this end, we presented prime and target stimuli to participants who then had to perform a lexical decision task on the target word. We recorded the brain response using EEG. This technique has high temporal resolution and can capture online agreement processing. To investigate these representations, we manipulated the type and number of morphosyntactic features to create violations and the associative frequency between a subject prime and its verbal inflection. Associative frequency helps the system predict the upcoming inflection when the subject is heard. The brain's early response would thus be modulated when the data is time-locked to the verb onset. That is why the data was not time-locked to the onset of inflection, as time-locking the data to the inflection would only show integration process rather than prediction in a sense preactivation of representations related to the agreement inflection (i.e., associative representations) prior to perceiving the inflection. Moreover, time-locking to the verb onset was also aimed to minimize the coarticulation effect which is due to the overlap phonetic cues that appear in continuous speech. In regards to the prediction of the current study, we describe it in more detail in the following section.

7.1 Predictions

1. Statistical properties of language belong to associative representations and are used to pre-activate the stimuli input during language processing. Pre-activation is a result of the top-down effect. This effect is also found during phonological processing, which is reflected by N100. We thus expected that associative frequency information, which is extracted from the subject prime, would modulate the amplitude of N100, as a result of predicting the upcoming verb inflection when the data was time-locked to the verb onset. As in previous prediction studies where

highly predictive words reduced the ERP amplitude, we expected high associative frequency to reduce the amplitude of N100.

2. We expected to observe LAN around 300 ms after the onset of the verb stimuli, when the morphosyntactic anomaly would be recognized in comparison with congruent grammatical forms. We hypothesized that LAN would be modulated by associative frequency and grammaticality. Similar to previous time window, we expect the associative frequency information would constrain the verb phonological processing. For grammaticality effect, traditionally, in grammatical agreement studies, sensitivity towards morphosyntactic features is observed reflected through LAN. As a result of accessing the abstract representations, we expected to observe differences between the type of feature violation (i.e., number vs. person) or the number of feature violations (i.e., single vs. double).
3. Following the LAN, we expected that an increase in P600 amplitude would also be observed as a result of the reanalysis process after the detection of the morphosyntactic violations. We predicted that P600 would be mainly modulated by grammaticality because the system uses the abstract representations to perform syntactic re-analysis. We particularly expect to observe differences between the type of feature violation (e.g., number vs. person) and the number of feature violations.

7.2 Methods

7.2.1 Participants

Twenty-three French native speakers (18 female), participated in this experiment. Age range was between 18 and 30 years old (mean = 21.6, SD=3.03). All of them were right-handed, as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971) and they had normal or corrected to normal vision with no self-reported hearing, language or neurological impairments. For their participation, they received a fifteen-euro remuneration or credits. They read and signed an informed consent form prior to the experiment. The ethics committee of *Université de Lille* approved this experiment. Data was collected in IrDIVE research platform.

7.2.2 Materials

990 pairs of primes and targets were selected from *Lexique*, a French corpus database (New et al., 2004). They were structured as followed: 20% of the total pairs of stimuli (264) were used as critical stimuli, while the rest were fillers (726) which aimed at distracting participants from the strategy building of the subject-verb violations and avoiding motor responses on critical stimuli. Among the critical stimuli, primes were pronominal subjects as ‘je’, ‘tu’, ‘nous’, and ‘vous’, and the verb targets were in the future tense and consisted of either two or three syllables. This tense was used because, in the case of regular verbs, the syntactic agreement forms the verb inflection by adding one phoneme after the word stem without changing it. Hence, in this study, for the critical stimuli we only used verbs in future tense with (/a/) and (/ɔ̃/) inflection.

In the critical stimuli, we manipulate two factors: grammaticality and associative frequency. For that reason, the critical stimuli consisted of four grammatical conditions and two associative frequency conditions. The former consisted of the congruent condition and three incongruent conditions. The congruent conditions had pairs of subject-verb that shared the same features, such as second person singular *‘tu’* (e.g., *‘tu montreras’* – ‘you will show’) and first person plural ‘nous’ (e.g., *‘nous montrerons’* – ‘we will show’). Three morphosyntactic violations (i.e., number, person, and number person violation) were created for the grammatical conditions (see Table 1). The number violation was introduced by pairing subject and verb that did not agree on number feature. The person violation was created by pairing subject and verb that did not agree on person feature. The number and person violation was introduced by pairing subject and verb that did not agree on either feature. To guarantee that there was no repetition of the same verbal forms ending with the ’-/a/’ and ‘-/ɔ̃/’ inflections, the selected verbs did not share the same stem. The psycholinguistic properties of the verbal forms were matched between the verbal forms ending with /a/ and those ending with /ɔ̃/.

Table 1

Examples of the stimuli in each grammaticality and associative frequency condition

Grammaticality condition	Phrase stimuli	Associative frequency condition
Congruent	***Tu***$_{\textit{2nd person-singular}}$ *montrer**as***$_{\textit{2nd person-singular}}$ - you will show	Low
	Nous$_{\textit{1st person-plural}}$ *rester**ons***$_{\textit{1st person-plural}}$ - we will stay	High
Person violation	***Je***$_{\textit{1st person-singular}}$ *montrer**as***$_{\textit{2nd person-singular}}$ - i will show	Low
	Vous$_{\textit{2nd person-plural}}$ *rester**ons***$_{\textit{1st person-plural}}$ - you will stay	High
Number & person Violation	***Nous***$_{\textit{1st person-plural}}$ *montrer**as***$_{\textit{2nd person-singular}}$ - we will show	High
	Tu$_{\textit{2nd person-singular}}$ *rester**ons***$_{\textit{1st person-plural}}$ - you will stay	Low
Number violation	***Vous***$_{\textit{2nd person-plural}}$ *montrer**as***$_{\textit{2nd person-singular}}$ - you will show	High
	Je$_{\textit{1st person-singular}}$ *rester**ons***$_{\textit{1st person-plural}}$ - I will stay	Low

Associative frequency is the co-occurrence frequency between a subject and its inflection. To identify high and low associative frequency conditions, we used the PMI formula from Van Petten (2014), as follows:

$$log_2\left(\frac{ct * corpus\ size}{c * t * span}\right)$$

c indicates the frequency of the subject pronoun, while *t* is the frequency of the inflection; *ct* thus indicates the co-occurrence frequency of the subject pronoun and its inflection. Corpus size was that of the *Lexique* database. We measured the associative frequency between the pronominal subject in the critical stimuli, 'nous', 'vous', 'je', and 'tu' with their inflections. We found that *'nous'* and *'vous'* had high associative frequency with their inflections. On the contrary, *'je'* and *'tu'* had low associative frequency with their inflections.

The fillers consisted of 726 pairs of primes and targets. The filler primes were '*je', 'nous', 'tu', 'vous',' il/s', and 'elle/s'*; the articles were, '*le', 'la', 'les'*; the targets were verbs (132), nouns (297), pseudoverbs (148) or pseudonouns (149). There was no syntactic violation in the fillers, so each verb and noun was preceded by its correct pronominal subject and article. For the verb targets, they were derived from tenses (i.e., present and past tense) other than the future tense, and the verbs were different from those used in the critical stimuli. The noun targets were feminine and masculine. The pseudoword targets were either pseudoverbs or pseudonouns and they were generated by Wuggy (Keuleers & Brysbaert, 2010). These pseudowords were needed for the task and to make sure that the pseudowords followed French phonological rules, a French native speaker checked them.

7.2.2.1 Stimuli recording

A French female native speaker pronounced all the stimuli several times in a soundproofed room. The order of the stimuli between the critical verbs, the fillers target (i.e., verbs, nouns, and pseudowords), the pronouns, and the articles was randomized during the recording session. The auditory recordings were sampled digitally at 48 kHz with 16-bits. They were selected based on the best pronunciation, natural intonation, and speaking rate. The mean intensity, the mean fundamental frequency, and the duration of the critical verbs were extracted using Praat (Boersma, 2001). The –/a/ and –/ɔ̃/ inflections had a similar mean intensity (mean for all verb targets ending with –/a/: 70.5 dB; –/ɔ̃/: 71.5 dB), mean fundamental frequency (mean for all verb targets ending with –/a/: 172 Hz; –/ɔ̃/: 174 Hz), and duration (mean for all verb targets ending with –/a/: 692 ms; –/ɔ̃/: 714 ms).

7.2.3 Experimental procedure

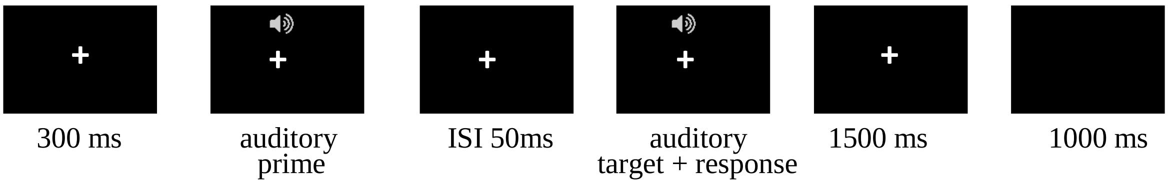
A 128-channel EEG cap was placed on the participants' head. Scalp electrodes were assigned to their designated place on the cap. Two additional electrodes were placed over the mastoids and two others on the face around the eye area to measure eye movements. When the EEG cap set-up has been done, participants were brought into a sound-attenuated, shielded chamber and were seated in front of a computer. For the stimuli presentation, Psychtoolbox (Brainard, 1997) was used and the auditory stimuli were presented binaurally through normal earphones. Before the experiment started, participants did a practice block to familiarize themselves with the task, a no-go lexical decision task, where they were asked to respond on target if they recognized a nonword by pressing the space key. This practice block consisted of 33 pairs of stimuli that differed from the experimental stimuli but had the same characteristics regarding critical stimuli and fillers. This 20% ratio for critical stimuli was also used in the training block.

There were three experimental blocks. One block lasted around 20 minutes and in between the blocks, participants could take a short break. The entire experiment therefore lasted around an hour. In each block, there were 330 stimuli, which consisted of 88 critical stimuli (20% of the total stimuli). The presentation order of the stimuli was randomized. Moreover, we also had four experimental lists, so that the four grammatical conditions have the same verbal target. Each critical verb was presented only once in each list. Fillers were always the same for all four experimental lists. Participants were randomly assigned one of the four experimental lists.

Whether it was in the practice or the experimental block, each trial began with a 300 ms white fixation cross presented at the center of a black screen. The fixation cross was followed by an auditory prime, either a pronoun or an article, then by a 50 ms interstimulus interval (ISI) prior to an auditory target: either a verb, noun, or pseudoword. During the auditory presentation, the white fixation cross remained on the screen to keep the participant's eye gaze on the screen and reduce eye movements. This fixation cross remained on the screen until 1500 ms after the offset of the target, to reduce participants' movement during the critical stimuli where participants do not need to make any responses and this was followed by a 1000-ms inter-trial interval (ITI) (for illustration see Figure 14).

Figure 14

The illustration of stimulus presentation in a trial



7.2.4 EEG data acquisition

The BioSemi ActiveTwo AD-Box system was used to record the 128-channel EEG data at a sampling rate of 1024 Hz. Bipolar electrooculograms were recorded to detect ocular movements and blinks by using two exogenous electrodes that were placed horizontally and vertically near the eye. Another two electrodes were placed on the right and left mastoids and were used for external off-line reference. The offset values (i.e., the voltage difference between each electrode and the CMS-DRL reference) of all electrodes were kept lower than 20 mV during the recording. The BioSemi system uses CMS and DRL electrodes instead of the reference and ground electrodes. CMS operates similarly to the ground electrode, while DRL operates like a feedback circuit that brings the voltage potential from the participant close to the potential value of the amplifier.

7.2.5 EEG data pre-processing

Independent component analysis (ICA), where EEG signal is decomposed into components, was performed to identify and remove ocular artifacts from EEG data using BESA software (MEGIS Software GmbH, Gräfelfing, Germany). Following that, Cartool software (Brunet et al., 2011) was used for EEG data pre-processing. Primarily, we filtered the EEG data to remove noise and artifacts. The low pass filter was set at 30 Hz and the high pass filter was set at 0.01 Hz. Epoch for each condition was started 50 ms pre-stimulus verb target onset and 1200 ms post-stimulus onset. EEG epoch was corrected 50 ms pre-stimulus onset. To remove artifacts, the threshold amplitude was set at 100 mV, so if any brain activity exceeded that value, the EEG epoch was rejected. Epochs per condition were averaged for each participant to create ERP. All data from each participant were re-referenced to the left and right mastoids. Lastly, any channel that was noisy or removed during epoch processing was interpolated. The average number of acceptance trials was matched between all experimental conditions. In more detail, for low associative frequency: congruent condition (30.6), number and person violation (30.8), number violation (30.7), and person violation (30.8); and for high associative frequency: congruent condition (30.3), number and person violation (30.5), number violation (30.3), and person violation (30.7).

7.3 ERP Analysis

To determine the time window for each component, we did a visual inspection of the ERP waves and found four time windows related to the aforementioned ERP components. For statistical analysis purposes, we extracted the mean amplitude of the ERP data in four time windows (100-160 ms, 300-600 ms, 650-850 ms, 920-1120 ms) from seven sites that represent the topographical sites from the component of interest. For each representative site, we selected nine electrodes as follows: Left Anterior (D3-D5, D10-D12, D19-D21); Right Anterior (B22-B24, B29-B31, C3-C5); Frontal (C12-C14, Afz-Fz, C25-C27); Central (Cz-CPz, B1, B2, C1, D1, D15, D16); Left mid-parietal (A6-A8, D17, D26-D30); Left mid-parietal (A6-A8, D17, D26-D30); Posterior (A5, A17-Poz, A30-A32). A three-way repeated analysis of variance (ANOVA) was conducted on the mean amplitude over each time window with three independent variables: associative frequency (i.e., low and high), grammaticality conditions (i.e., congruent condition, person violation, number & person violation, number violation) and topographical sites. To adjust for violations of sphericity, a Greenhouse-Geisser (Greenhouse & Geisser, 1959) correction was performed when there was more than one degree of freedom in the numerator. Only corrected *p*-values were reported. If a significant effect or interaction was found, post-hoc Tukey tests were performed to interpret the significance of those effects. Only the significant effects are reported in the text.

7.4 Results

7.4.1 Behavioral results

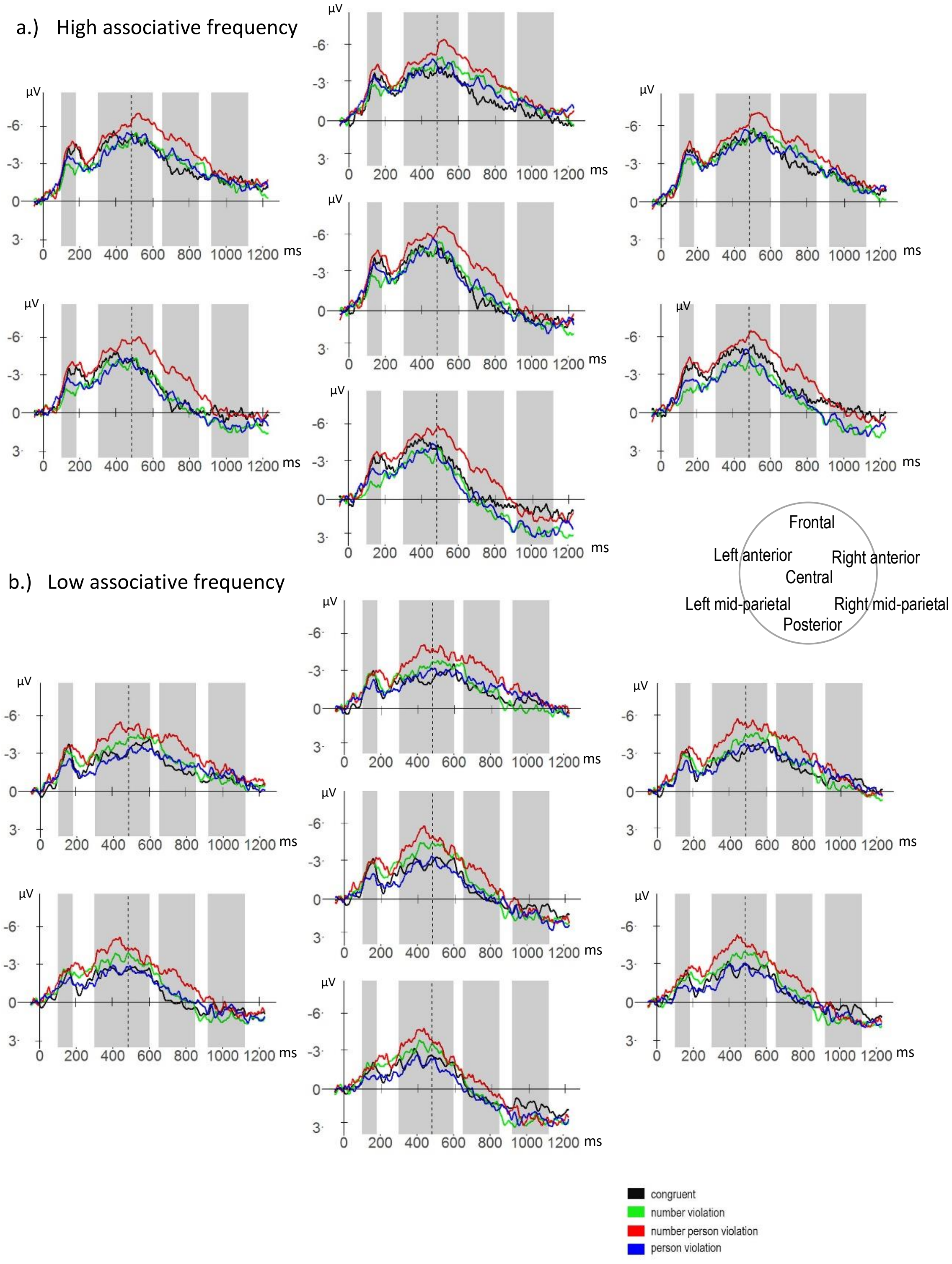
The participants performed the no-go lexical decision task accurately, as assessed by the percentage of correct responses (mean: 89%; range: 74-98%; median: 94%). The mean hit rate was 0.93 and the mean false alarm rate was 0.13. Therefore, participants paid close attention to the targets. The average reaction time was 1249 ms after the onset of pseudoword targets.

7.4.2 ERP results

The grand-average of ERP waveforms elicited by target verbs are displayed in Figure 15 across four grammaticality conditions (i.e., congruent, person violation, number and person violation, number violation) in each associative frequency condition (i.e., high associative frequency and low associative frequency). As seen in Figure 15, the N100 wave was followed by anterior negativity and late positivity in all experimental conditions. During the N100 time window between 100 and 160 ms, the amplitude by verbal targets was stronger for low associative frequency than for high associative frequency, and this pattern remained until the second time window occurring between 300 and 600ms. In this second time window, the amplitude of anterior negativity increased in the incongruent condition, involving double feature violation (number and person violation), in comparison with the congruent condition. Negativity remained in the third time window occurring between 650 and 850 ms. It seemed that the amplitude of this negativity in the third time window was stronger for the double violation, involving number and person features compared to the congruent condition; its amplitude was even enhanced in response to single violations (person violation and number violation), for low associative frequency. In the fourth time window occurring between 920 and 1120 ms, a larger amplitude of late positivity was observed in all incongruent conditions over the posterior site, in comparison to the congruent conditions. The statistical summary of each time window is presented in Table 2.

Figure 15

ERP waveform depicts four grammatical conditions



Note. Mean waveform from nine electrodes that represents seven topographical sites. X axis depict timescale in milliseconds. Y axis depict mean amplitude in microvolt (µV), the negative value is on the top. Black color represents congruent condition, green color represents number violation condition, red color represents number and person violation condition, blue color represents person violation condition. Vertical dashed line in the middle of each plot is the mean onset of the inflection (482 ms). The shaded areas are the time windows that we are focused on. First time window is from 100 to 160 ms; second time window is from 300 to 600 ms; third time window is from 650 to 850 ms; and fourth time window is from 920 to 1120 ms. a.) ERP waveform for high associative frequency condition; b.) ERP waveform for low associative frequency condition.

Table 2

Statistical results from ERP analysis over the four time windows

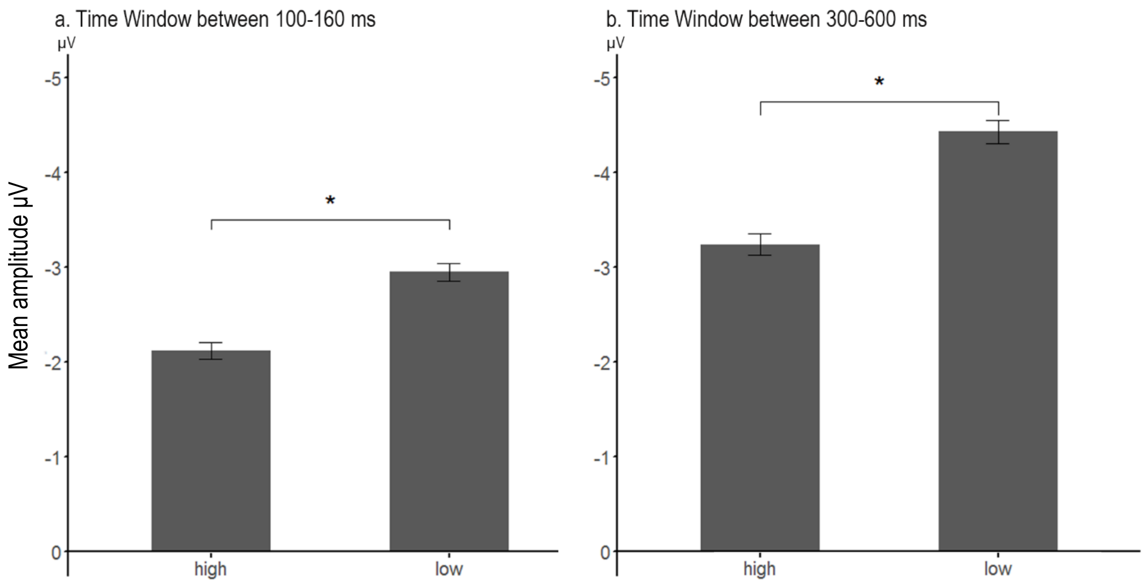
	Time window between 100-160 ms	**Time window between 300-600 ms**
Associative frequency	$F(1,22)=5.94$, $p<.05$	$F(1,22)=7.90$, $p<.05$
Grammaticality	$F(3,66)=2.15$, $p=.11$	$F(3,66)=5.65$, $p<.01$
Topographical sites	$F(6,132)= 17.01$, $p<.001$	$F(6,132)= 6.91$, $p<.001$
Associative frequency x Grammaticality	$F(3,66)=1.39$, $p>.2$	$F(3,66)=0.45$, $p>.2$
Associative frequency x Topographical sites	$F(6,132)=2.78$, $p=.06$	$F(6,132)=0.75$, $p>.2$
Grammaticality x Topographical sites	$F(18,396)=1.08$, $p>.2$	$F(18,396)=1.42$, $p>.2$
Associative frequency x Grammaticality x Topographical sites	$F(18,396)=1.79$, $p=.10$	$F(18,396)=1.27$, $p>.2$
	Time window between 650-850 ms	**Time window between 920-1120 ms**
Associative frequency	$F(1,22)=3.87$, $p=.06$	$F(1,22)=1.67$, $p>.2$
Grammaticality	$F(3,66)=3.69$, $p<.05$	$F(3,66)=0.51$, $p>.2$
Topographical sites	$F(6,132)= 35.77$, $p<.001$	$F(6,132)= 28.18$, $p<.001$
Associative frequency x Grammaticality	$F(3,66)=0.05$, $p>.2$	$F(3,66)=0.09$, $p>.2$
Associative frequency x Topographical sites	$F(6,132)=1.36$, $p>.2$	$F(6,132)=1.85$, $p=.14$
Grammaticality x Topographical sites	$F(18,396)=3.06$, $p<.01$	$F(18,396)=3.53$, $p<.01$
Associative frequency x Grammaticality x Topographical sites	$F(18,396)=2.90$, $p<.05$	$F(18,396)=1.63$, $p=.12$

7.4.2.1 Time window between 100 and 160 ms

In this time window, the ANOVA showed a main effect of associative frequency (F(1,22)=5.94, p<.05) and topographical sites (F(6,132)=17.01, p<.001). As seen in Figure 16.a, low associative frequency induced stronger negativity in comparison to that observed in high associative frequency. The paired Tukey *t-test* applied over the topographical sites revealed the classical topography of N100, in which more negative values were seen over the left and right anterior sites and the central sites compared to the right and left mid-parietal sites and posterior sites (p<.001). More negative values were also evidenced over the frontal sites than over the right mid-parietal (p<.001) and posterior sites (p<.05).

Figure 16

Mean amplitude over all topographical sites for the associative frequency condion



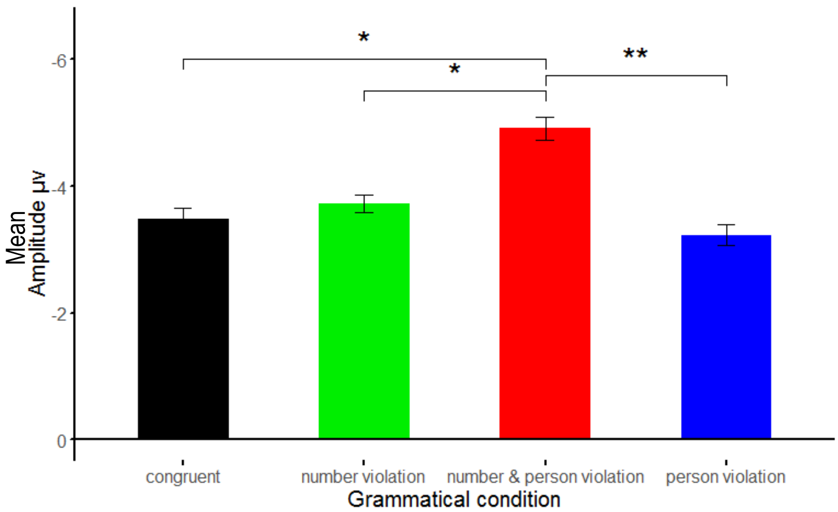
Note. *p<.05. In the y axis, the negative value of the amplitude is on the top. a) associative frequency effect for time window between 100 and 160 ms; b) associative frequency effect for time window between 300 and 600 ms. In both time window, low associative frequency elicited stronger negative amplitude.

7.4.2.2 Time window between 300 and 600 ms

As with N100, the ANOVA over the second time window showed a main effect of associative frequency, with a stronger amplitude of the anterior negativity for low associative frequency than for high associative frequency (F(1,22)=7.90, p<.05), as depicted in Figure 16.b. There were also main effects of topographical sites (F(6,132)=6.91, p<.001) and grammaticality effect ($F(3,66)=5.65$, $p<.01$), as seen in Figure 17 Concerning the topographical sites, paired Tukey *t-tests* showed that there were more negative values over the left and right anterior sites relative to the left mid-parietal and posterior sites ($p<.001$). The right anterior sites showed more negative values than the right mid-parietal sites ($p<.05$) and the central sites had more negative values than the posterior sites ($p<.05$). As for the grammaticality effect factor, Tukey *t-tests* showed that the amplitude of the anterior negativity was stronger for the number and person violation than the congruent condition ($p<.05$), person violation ($p<.01$), and number violation ($p<.05$).

Figure 17

Mean amplitude over all topographical sites for each grammaticality condition



Note. *$p<.05$, **$p<.01$. In the y axis, the negative value of the amplitude is on the top. Grammaticality effect during the second time window between 300 and 600 ms. Double violation effect is observed here, wherein it elicited stronger negative amplitude compared to other grammaticality conditions.

7.4.2.3 Time window between 650 and 850 ms

During this time window, the main effect of associative frequency was no longer observed. However, the main effects of topographical sites ($F(6,132)=35.77$, $p<.001$) and grammaticality effect ($F(3,66)=3.69$, $p<.05$) were observed. Paired Tukey *t-test* comparisons showed that there were more negative values over the right and left anterior sites and the frontal sites than over the central sites ($p<.001$), the right and left mid-parietal sites ($p<.001$), and the posterior sites ($p<.001$). There were also more negative values over both right and left mid-parietal sites than over the posterior sites ($p<.001$). Frontal negativity was thus sustained over the time window between 650 and 850 ms after the target onset. As for the grammaticality effect, Tukey *t*-test comparisons showed that the amplitude of the negativity was stronger for the double violation involving number and person features than for the congruent condition ($p<.05$).

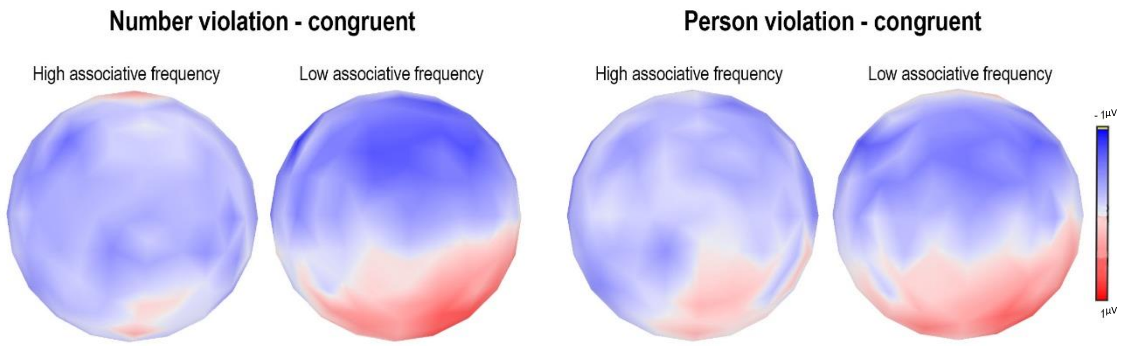
Two interactions were also found: first, a significant interaction between grammaticality and sites ($F(18,396)=3.06$, $p<.01$) ; second, a significant interaction between grammaticality, sites, and associative frequency ($F(18,396)=2.90$, $p<.05$). Tukey *t-tests* showed that the number and person violation condition induced stronger negativity when compared to the congruent condition and other incongruent conditions, such as person violation and number violation, over all topographical sites ($p<.001$). Other incongruent conditions, such as the single violations (number violation and person violation), also enhanced the negative amplitude when compared to the congruent condition over the left and right anterior sites ($p<.05$) and the frontal sites ($p<.01$). This result suggested that the detection of violations involving a single feature occurred at this stage in contrast to the previous time window.

The significant interaction between grammaticality, sites and associative frequency showed that stronger negative amplitude was induced by the number and person violation. In high associative frequency condition, the double violation that is number and person violation elicited stronger negativity compared to the congruent condition over all topographical sites ($p<.001$). Double violation also had larger negativity compared to the other single violation conditions, such as number violation and person violation over all topographical sites ($p<.05$). Yet, there was no significant differences between the congruent conditions and the other single violation condition. When the associative frequency was low, number and person violation elicited stronger negativity over all topographical sites compared to congruent condition ($p<.001$). Single violation condition, such as number violation elicited stronger negativity compared to congruent condition over the frontal site ($p<.001$). Moreover, double violation, number and person violation elicited more negative amplitude when compared to single violation, such as number violation and person violation over the left anterior, central, right and left mid-parietal, and posterior sites ($p<.001$); double violation was also more negative than person violation over the frontal sites ($p<.05$).

In short, double violation condition elicited stronger negativity compared to congruent condition over all topographical sites ($p<.001$) in both associative frequency conditions. A shift to the frontal site by single violation condition was observed in low associative frequency, in which number violation condition in low associative frequency was more negative compared with the same condition in high associative frequency over the frontal site (see Figure 18).

Figure 18

Interaction between grammaticality condition and topographical sites



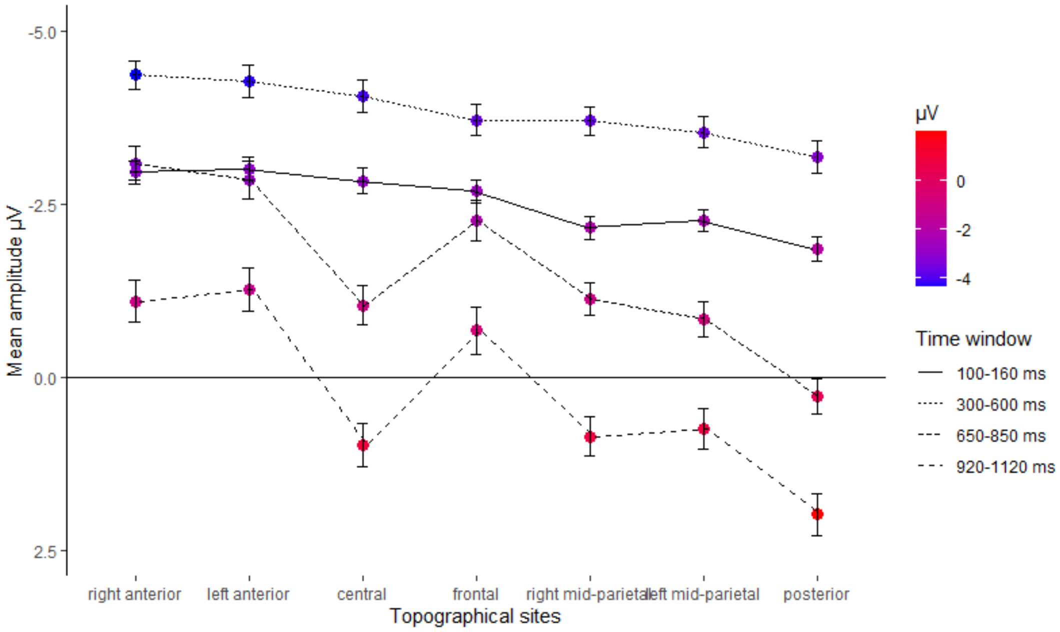
Note. Topography from 650 to 850 ms based on the subtraction between incongruent and congruent condition. Blue color indicates negative value; red color indicates the positive value. On the left is the topography for each associative frequency condition in the subtraction between number violation and congruent condition, while the right side is the topography for each associative frequency condition in the subtraction between person violation and congruent condition. In both subtraction conditions, the high associative frequency is presented on the left while the low associative frequency is on the right side.

7.4.2.4 Time window between 920 and 1120 ms

In this last time window, there was no effect of associative frequency or grammaticality. However, a main effect of topographical sites ($F(6,132)=28.18$, $p<.001$) and a significant interaction between grammaticality and topographical sites ($F(18,396)=3.53$, $p<.01$) were still observed. Regarding topographical sites, Tukey *t-test*s showed that the posterior sites had more positive values than the other sites ($p<.05$), as depicted in Figure 19. There were also more positive values over the right and left mid-parietal sites as well as the central sites than over the right and left anterior sites and the frontal sites ($p<.001$). The highest positivity amplitude was observed over the most posterior part of the scalp. As mentioned above, there was a significant interaction between grammaticality and topographical sites. Over the right mid-parietal sites, Tukey *t-test*s showed that positivity amplitude was stronger for the number violation ($p<.001$) and person violation conditions ($p<.001$) compared to the congruent condition. Over the left mid-parietal site, we found that stronger positivity amplitude was elicited by number violation compared to the congruent condition ($p<.05$) and the number & person violation ($p<.05$).

Figure 19

Mean amplitudes over each topographical site of each ERP time window



Note. In the y axis, the negative value is on the top. For N100 time window, the anterior site was more negative compared to the posterior. In the second time window, we observed increased of negativity particularly over the anterior and frontal sites. In the third time window, large negativity was observed over the anterior and frontal site. Lastly, the late P600 was observed in the last time window, where positive amplitude was mostly increased over the posterior site.

7.5 Discussion

This first study aimed at understanding the representations underlying subject-verb agreement processing. We wanted to investigate whether abstract representations or associative representations, or both, were accessed during agreement processing. The former are related to the generative syntax view (Carminati, 2005; Chomsky, 1959; Harley & Ritter, 2002), according to which morphosyntactic features such as gender, number and person are believed to be hierarchical. The latter are related to statistical regularities in language use (Seidenberg & MacDonald, 1999), which have been widely explored in studies of language acquisition in both children (Kuhl, 2004; Pelucchi et al., 2009; Saffran et al., 1996, 2001; Saffran & Wilson, 2003; Thiessen & Saffran, 2003) and adults (Conway et al., 2010; Hudson Kam, 2009; Kittleson et al., 2010; Kuppuraj et al., 2018; Mirman et al., 2008; Saffran et al., 1999). Previous studies in agreement processing have shown that the accessing of abstract representations is reflected through LAN and P600. We thus expected to replicate them as evidence that abstract representations are accessed. Concerning associative representations, we expected to see an associative frequency effect on N100, as we predicted that the system would extract this information to process the verb inflection after hearing the subject prime. Then, in the following time window, after N100, the system would use the associative frequency while processing the grammatical information by applying a constraint from associative frequency information.

Overall, our result showed that both abstract and associative representations were accessed during subject-verb processing. The accessing of associative representations was reflected through N100, a component that has often been found in auditory studies, and low associative frequency enhanced the N100 amplitude. This finding suggested that phonological processing was not only a bottom-up processing but it also uses top-down processing. We also evidenced a slight difference from the initial prediction. Earlier, we expected to observe LAN but we observed anterior and frontal negativity that reflected the accessing of abstract representations, as we found differences between grammaticality that involved single violations and double violations. The last predicted ERP component was P600, a classical ERP component that is usually found in agreement studies and is known to be an index of reanalysis. Our result showed late P600 around 920 ms over the posterior site was enhanced by grammaticality effect involving number feature. To have a better grasp on this result, we discuss the observed ERP components and their implication in subject-verb agreement processing in more detail in the following sub-section.

7.5.1 N100

This ERP component is known to be an index of perceptual auditory processing (Parasuraman & Beatty, 1980; Picton et al., 1999; Winkler et al., 1997) and phonological processing (Cason & Schön, 2012; Getz & Toscano, 2019; Noe & Fischer-Baum, 2020; Obleser et al., 2006). In spoken language comprehension and spoken word recognition, N100 also indicates top-down processing probed either by semantic constraint or lexicality (Brunellière & Soto-faraco, 2015; Getz & Toscano, 2019; Noe & Fischer-Baum, 2020). For instance, Brunellière & Soto-Faraco (2015) used Catalan stimuli whose semantic aspect was controlled by using high and low cloze probability. They found N100 reflected an early-stage processing of phonology, assisted by top-down processing with low semantic constraints facilitating the recognition of the first phonemes. The amplitude of N100 was greater for the incongruent phonological form than for the congruent one in sentences with low semantic constraints. However, this phonological sensitivy was found in sentences with high semantic constraints; this finding confirmed that semantic constraint enhanced phonological prediction. In the same vein, a study by Noe & Fischer-Baum (2020) showed that top-down processing during the early stage of phonological processing could be probed by lexicality. In their study, they had a list of words with a lexical bias effect, such as /d/-/t/ and /g/-/k. Voice onset time (VOT) was manipulated and categorized as clearly voiced, ambiguous, or clearly unvoiced. Participants were presented with a pair of phonetically close words (e.g., date-tate) in which they were asked to indicate which phoneme they perceived. The behavioral results suggested that participants perceived the stimuli as a word rather than a nonword, which is in line with the Ganong effect (Ganong, 1980), in which lexical knowledge intervenes in the recognition of the ambiguous word. The ERP results supported the behavioral results, in which lexical top-down processing affected N100 by increasing its amplitude for biased words when VOT was clearly voiced. Noe & Fischer-Baum (2020) argued that their result suggested an interaction between the perceived acoustic information and the lexical information at the early stage of phonological processing.

In line with those studies, we found a top-down prediction effect in N100. Our finding showed that this top-down processing employed the associative representations that was obtained from the associative frequency information which was extracted from the subject prime. The associative frequency information constrained the early stage of phonological processing, which caused greater N100 for low associative frequency. In short, the early stage of verb processing that was captured in N100 showed that the system did not only relied on bottom-up input but also employed information from high-level representation, such as associative representation. The accessing of associative representations appeared to facilitate the expectation of the upcoming verb inflection, as reflected in the reduction of the N100 response by high associative frequency. Furthermore, this expectation seemed to constrain the processing of the current phonological input. Owing to associative frequency information, the system is prepared to process a certain inflection depending on the subject prime. Previous studies in sentence prediction have shown that high cloze probability words reduce ERP amplitude. Our results could thus serve as evidence of a ‘proactive brain’ (Bar, 2009) in agreement processing. In line with this idea, we argue that in order to process the syntactic agreement in spoken language, the system first activates the information related to higher level representations, such as associative frequency, to constrain the processing of lower level representations, such as the phonological level.

7.5.2 Anterior and fronto-anterior negativity

Initially, we expected to observe anterior negativity over the left site (LAN), as this is the commonly found component in syntactic anomaly detection. However, the anterior negativity we observed here spread from the left to the right anterior sites, and the time windows ranged between 300 and 600 ms. For the frontal and anterior sites, it ranged between 650 and 850 ms. morphosyntactic violations increased the negative amplitude, particularly the double violation condition. Although we did not observe LAN, anterior negativity spreading from the left to the right anterior sites is not an uncommon component in agreement studies, as mentioned in Chapter 2.

In subject-verb agreement itself, anterior negativity was observed in the study by Silva-Pereyra & Carreiras (2007), who found anterior negativity instead of LAN. In their study, they used visual sentence stimuli in Spanish that were presented word by word. Their results showed anterior negativity over the right and middle anterior sites as a result of detecting the morphosyntactic violations. Interestingly, they did not find any significant differences either between number violation and person violation, but they found differences between single and double violation at a later time window (P600). Similarly, we did not find any differences for single violations between person and number violation, but we did find that double violation increased negativity. In contrast, Mancini et al. (2011a) found differences between number violation and person violation, which suggested that abstract representations were accessed during grammatical agreement processing. Like Silva-Pereyra & Carreiras (2007), Mancini et al. (2011a) also used visual stimuli. They argued that the stimuli that Silva-Pereyra & Carreiras (2007) used were more heterogeneous, in that they used the first and second persons for the pronouns, while Mancini et al. (2011a) used only the third person in their sentences.

Mancini et al. (2011) argued that the use of a person feature affects agreement processing. The use of the first and second persons involves the participants and makes them more sensitive to anomaly detection, while the third person keeps participants in a situation of observation, which might increase their sensitivity to syntactic violation (Sigurdsson, 2004). The absence of significant differences in amplitude between person and number features in our study may be due to the fact that we used the first and second persons instead of the third person, like Silva-Pereyra & Carreiras (2007). Alternatively, as mentioned earlier in Chapter 2 that third person, morphologically, has a distinct marker that differentiate it from the first and second person. As consequence, sensitivity towards the third person was higher compared to the other person feature.

Moreover, another study by Nevins et al. (2007) also showed double violation effect, however they attributed this effect to the person feature. They conducted agreement studies in Hindi, in which they had four grammatical conditions: person violation, gender violation, person & gender violation, and number & gender violation. They found that double violations, involving both person and gender features, elicited stronger P600 than the other grammatical conditions. They argued that this effect was due to the person feature, thus supporting the notion of agreement feature hierarchy. In our case, although we had an absence of person effect, which is related to the amplitude difference between the type of feature (i.e., number vs. person) after detecting the syntactic violation, we found a double violation effect, which is related to the number of feature violation (i.e., single vs. double). We, therefore, argued that the double violation effect is an evidence of the system accessing the abstract representations.

During the frontal negativity, associative representations were still accessed and affect the grammatical processing, in a way that low associative frequency increased the sensitivity towards single violation, such as number violation and person violation. The way associative frequency put a constrain on grammatical processing is similar to the concept of cloze probability. Note that they are not the same thing but they have similarity in the sense that associative frequency measures the co-occurrence between a subject and its inflection within agreement context. On the other hand, cloze probability measures the probability of a word in a sentence. Following this logic, the way associative frequency affect grammaticality, wherein low associative frequency enhanced morphosyntactic detection, was similar to previous studies (Brunellière & Soto-faraco, 2015; Connolly et al., 1990, 1992) in spoken language comprehension, in the sense that sentences with low cloze probability increased the negative amplitude compared with high cloze probability sentences.

7.5.3 Late P600

The P600 component following LAN or anterior negativity is a classical finding in agreement processing studies, with positive amplitude over the posterior site being increased after morphosyntactic violations (Mancini et al., 2011a; Nevins et al., 2007; Silva-Pereyra, & Carreiras, 2007). In our study, this effect occurred quite late, between 920 and 1120 ms. Late P600 reflects a reanalysis process by returning to the previous step and re-accessing the syntactic information to identify the irregularities from the stimuli input (Molinaro, Barber, & Carreiras, 2011). As with anterior and frontal negativity, we found no differences between the processing of number violation and person violation. Interestingly, single violation elicited stronger P600 amplitude than double violation, over the left mid-parietal site. This result confirmed once again that abstract representations were accessed. This difference between single and double violations might reflect the cost of reanalysis, in that it is easier for the system to detect double violation and thus requires less effort to repair it. Double violations are thus processed earlier as soon as 300 ms, as it requires more effort for the system to detect and reanalyze a single violation. Altogether, this result does not support the notion of hierarchical features, as we did not observe any difference between number violation and person violation.

7.5.4 The role of representations in subject-verb agreement

Regarding the issue of the representations that underlie agreement processing, our findings show that both abstract and associative representations are accessed. Note that the two representations, abstract and associative, are not opposing each other instead they are complementing. At the early stage, the verb decoding process is not solely bottom-up, as there is top-down processing from associative frequency information extracted from the subject prime in which, the phonological processing of the verb inflection in subject-verb agreement during spoken language processing was constrained by the associative frequency. This finding is in line with previous studies in spoken language showing a top-down effect, where higher-level representations (e.g., syntactic, lexical, contextual or associative information) affected processing at lower levels, such as the phonological processing level (Fox & Blumstein, 2016; Samuel, 1981; Sivonen et al., 2006). Following to that, when the system detected the syntactic violation during the agreement computation, we can see how the two representations were complementary in which the associative frequency information constrained the preactivation information from the abstract representations related to the verbal inflection. Through the interaction of both representations, the system generated an expectation of verbal inflection; low associative frequency had lower commitment in generating the inflection thus it was more sensitive towards morphosyntactic violations. Furthermore, we observed that the system using different pathway when it encountered single vs. double violations which indicated that the abstract representations were accessed.

7.6 Conclusions

The current study has showed that subject-verb agreement in spoken language employed both abstract and associative representations. The using of associative representations during subject-verb agreement processing also gives an insight that there is a prediction related to verbal inflection. Concerning abstract representations, our result showed that the system employed this system for morphosyntactic verification; and, as evidence that the abstract representations were accessed, we observed differences in grammaticality between condition involving double violations and single violation.

Concerning the nature of representations during subject-verb processing, to our knowledge, the present study is one of the first to investigate abstract and associative representations during subject-verb agreement processing in spoken language. In addition to that, the present finding, also has replicated most of the classical ERP components in agreement processing studies, such as anterior negativity and P600.

All in all, our results throw new light on the representations that are accessed during agreement processing, as agreement studies usually focus on abstract representations rather than on associative representations. These findings also provide new insights into how associative representations can be used to explore the predictive function in agreement processing. As mentioned in the chapter on prediction, studies that investigate prediction manipulate the statistical properties of words to determine their predictability. In our study, we found that after hearing a subject prime, the statistical subject-verb information contained in associative representations was used to provide information about the possible verb inflection to come.

Chapter 8

The second study: EEG Study with two experiments to explore flexibility in accessing the representations

Our first study showed that both abstract and associative representations are used in agreement processing. The purpose of Experiment 2 was to discover whether there is flexibility in accessing these representations during the processing of subject-verb agreement. As we saw in the previous chapter, flexibility is a major cognitive function (Ionescu, 2012) as we live in an ever-changing environment. This ability allows us to adapt to these changes and is also used in language acquisition (Deak, 2003), language production (Ferreira, 1996; Lester & del Prada Martin, 2016). Interestingly, little is known about flexibility during agreement processing. To investigate this issue, we used an experimental task, since flexibility is defined according to the effect of such tasks on the way the system processes verbs. The stimuli we used in this study were the same as in the previous one (Experiment 1). We asked the participants to perform a noun categorization task on target words in new experiment, called Experiment 2. We then compared the result of this experiment to those of the previous one, in which the task was a LDT on target words, in order to investigate potential flexibility in accessing the representations.

8.1 Predictions

We expected to observe similar ERP components in Experiment 2, such as N100, anterior negativity and P600, which were all observed in Experiment 1. Although we expected the same components, we also expected to observe differences in the way the ERP components were modulated by the experimental factors since the experimental task was different. The differences we predicted were the following:

1. As in the previous study, we expected that the associative frequency would modulate the amplitude of N100 as a result of the top-down effect during phonological processing, in which high associative frequency decreases that amplitude.
2. We expected to observe flexibility in accessing the abstract representations, around the time when the system starts detecting the syntactic error (around 300 ms). We specifically predicted that during this process, the system would rely more on abstract representations in Experiment 2. Given that Experiment 2 led the participants to focus on grammatical information while Experiment 1 probed lexical

information more. Whatever the task, we predicted that an increase in negative amplitude would be observed during syntactic error detection, when the system encountered a morphosyntactic violation and grammaticality factor involving double violation were expected to increase morphosyntactic sensitivity. In terms of flexibility, we predicted an increased negativity after morphosyntactic violations and the negative shift for double violation in comparison with single violation will be stronger in Experiment 2.

3. P600 was expected to be modulated by the experimental task as a result of flexibility. P600 is related to the controlled process that requires attention, as an index of reanalysis. We thus predicted that morphosyntactic sensitivity would be stronger in Experiment 2 compared with Experiment 1, because the task in Experiment 2 probed the use of grammatical information.

8.2 Methods (Experiment 2)

8.2.1 Participants

Twenty-four native speakers of French (17 females) aged between 19 and 25 years old (mean=29, SD=9.93) participated in this experiment. These characteristics were the same as in Experiment 1. All of them were right-handed, as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971), and they had normal or corrected to normal vision with neither self-reported hearing, language nor neurological impairments. For their participation, they received a 15-euro remuneration. They read and signed the informed consent form before beginning the experiment. The ethics committee of *Université de Lille* approved the experiment. The data was collected in IrDIVE platform.

8.2.2 Materials

The materials were identical to the first experiment in Chapter 7.

8.2.3 Experimental procedure

The experimental procedure was identical to that of Experiment 1, except for the experimental task. In Experiment 2, participants were asked to perform a noun categorization task, where they were asked to respond if the target word was a noun.

8.2.4 EEG data acquisition

The procedure of EEG data acquisition in Experiment 2 was identical to Experiment 1 in Chapter 7.

8.2.5 EEG data pre-processing

Cartool software was used to pre-process the data. The pre-processing procedure, including data filtering, threshold set-up for artifact rejection, data referencing to mastoids and channel interpolation, was identical to that in the previous study (Chapter 7). However, baseline correction was not applied in Experiment 2, because when it was, we found significant differences between the experimental conditions over the baseline period. In addition, ICA was not applied here, since there were fewer artifacts in the raw EEG data of Experiment 2.

For each experimental condition, there were at least 22 trials accepted from each participant. Therefore, the total number of accepted epochs was equal across the experimental conditions (low associative frequency, congruent condition: 28.8; low associative frequency, number and person violation: 29.2; low associative frequency, number violation: 29.2; low associative frequency, person violation: 29.2; high associative frequency, congruent condition: 29.4; high associative frequency, number and person violation: 28.9; high associative frequency, number violation: 29.3; high associative frequency, person violation: 28.5).

8.3 ERP Analysis

We used the same four time windows as in the previous study: 100-160 ms, 300-600 ms, 650-850 ms, and 920-1120 ms. Repeated ANOVA measures were also computed using the STATISTICA software in each time window with the following between-factors: associative frequency (low vs. high), grammaticality (congruent, number and person violation, number violation and person violation), and topographical sites (seven different topographical sites across the scalp). Participants were considered as within-factors. The seven topographical sites were the same as in the previous study: right anterior (B22-B24, B29-B31, C3-C5), left anterior (D3-D5, D10-D12, D19-D21), frontal (C12-C14, Afz-Fz, C25-C27), right mid-parietal (B3-B5, B12, B13, B16-B19), left mid-parietal (A6-A8, D17, D26-D30), central (Cz-CPz, B1, B2, C1, D1, D15, D16) and posterior (A5, A17-Poz, A30-

A32). Following the repeated ANOVA measures, *p*-values were corrected using the Greenhouse-Geisser method. When an interaction or a factor with more than two conditions was significant, posthoc Tukey *t*-tests were performed. We only reported the significant results.

8.4 Results

8.4.1 Experiment 2

8.4.1.1 Behavioral results

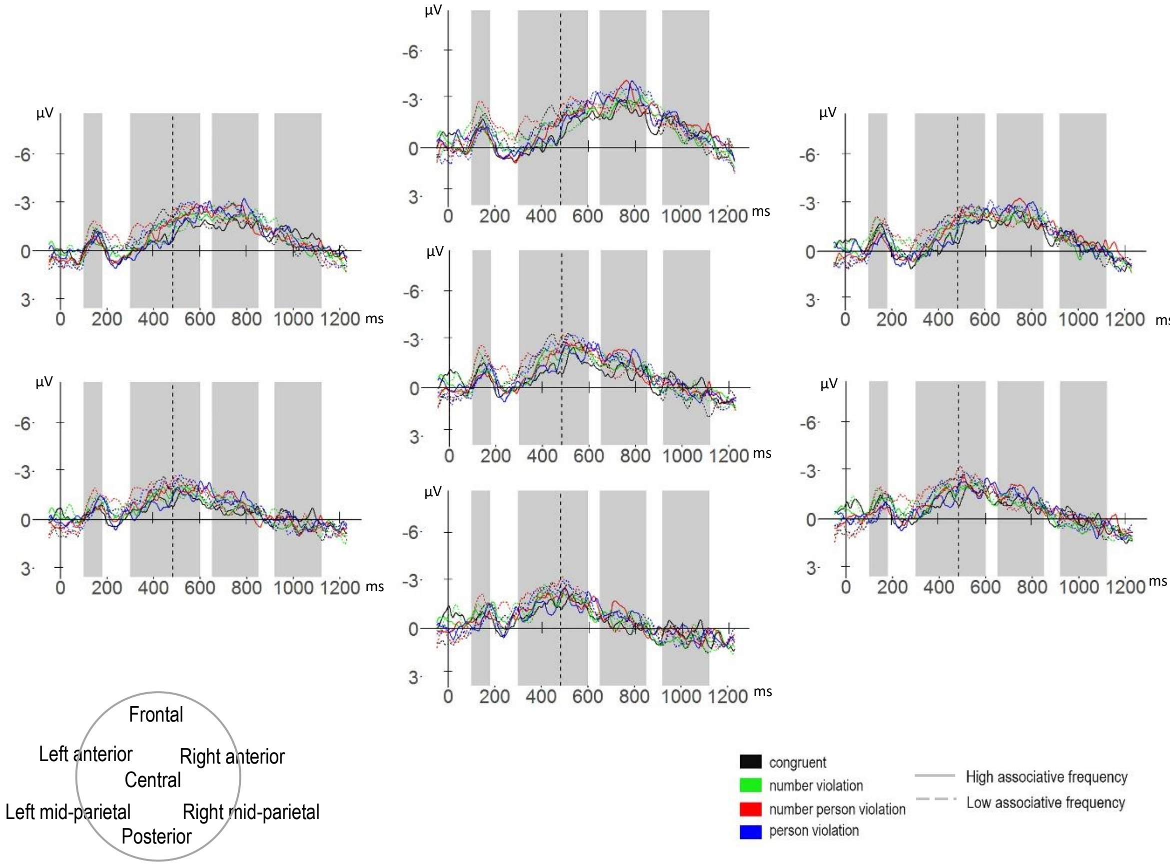
The mean accuracy of correct responses in the noun categorization task was 96% (range: 85%-99%, median: 97%). The mean hit rate was 0.95, while the mean false alarm rate was 2.61. This showed that participants performed the task accurately. The mean response time was 1135 ms after the onset of the noun target.

8.4.1.2 ERP results

After the onset of the verb, as seen in Figure 20, N100 occurring around 100 and 160 ms seemed to increase for low associative frequency. Over the second time window, the person violation and the number and person violation seemed to increase the amplitude of this negativity in comparison with the congruent condition only for low associative frequency. In the third time window between 650 and 850 ms, the negative amplitude peaked over the frontal site, as in the previous time window and it was followed by a positivity occurring between 920 and 1120 ms over the posterior site. It seemed that these two ERP components were not affected by the two factors of interest, associative frequency and grammaticality Statistical analysis was performed in these four time windows and the results are summarized in Table 3.

Figure 20

ERP waveform depicts the four grammatical conditions in each associative frequency condition



Note. Mean waveform from nine electrodes that represents seven topographical sites. X axis depicts timescale in milliseconds. Y axis depicts mean amplitude in microvolt (μV), the negative value is on the top. Solid line depicts high associative frequency, while dashed line depicts low associative frequency. Black color represents congruent condition, green color represents number violation condition, red color represents number and person violation condition, blue color represents person violation condition. Vertical dashed line in the middle of each plot is the mean onset of the inflection (482 ms). The shaded areas are the time windows that we are focused on. First time window is from 100 to 160 ms; second time window is from 300 to 600 ms; third time window is from 650 to 850 ms; and fourth time window is from 920 to 1120 ms.

Table 3

Statistical results of Experiment 2 for each time window

	Time window between 100-160 ms	**Time window between 300-600 ms**
Associative frequency	$F(1,23)=10.50$, $p<.01$	$F(1,23)=17.31$, $p<.001$
Grammaticality	$F(3,69)=1.41$, $p>.2$	$F(3,69)=1.91$, $p=.15$
Topographical sites	$F(6,138)=5.15$, $p<.05$	$F(6,138)=4.25$, $p<.05$
Associative frequency x Grammaticality	$F(3,69) = 1.75$, $p=.17$	$F(3,69) = 4.25$, $p<.01$
Associative frequency x Topographical sites	$F(6,138)=3.02$, $p<.05$	$F(6,138)=0.21$, $p>.2$
Grammaticality x Topographical sites	$F(18,414) = 1.13$, $p>.2$	$F(18,414) = 0.54$, $p>.2$
Associative frequency x Grammaticality x Topographical sites	$F(18,414)=0.93$, $p>.2$	$F(18,414)=2.64$, $p<.05$
	Time window between 650-850 ms	**Time window between 920-1120 ms**
Associative frequency	$F(1,23)=0.40$, $p>.2$	$F(1,23)=1.51$, $p>.2$
Grammaticality	$F(3,69)=1.52$, $p>.2$	$F(3,69)=0.19$, $p>.2$
Topographical sites	$F(6,138)=55.42$, $p<.001$	$F(6,138)=29.60$, $p<.001$
Associative frequency x Grammaticality	$F(3,69) = 1.08$, $p>.2$	$F(3,69) = 0.97$, $p>.2$
Associative frequency x Topographical sites	$F(6,138)=1.18$, $p>.2$	$F(6,138)=0.32$, $p>.2$
Grammaticality x Topographical sites	$F(18,414) = 1.67$, $p=.14$	$F(18,414) = 0.93$, $p>.2$
Associative frequency x Grammaticality x Topographical sites	$F(18,414)=0.75$, $p>.2$	$F(18,414)=2.02$, $p=.07$

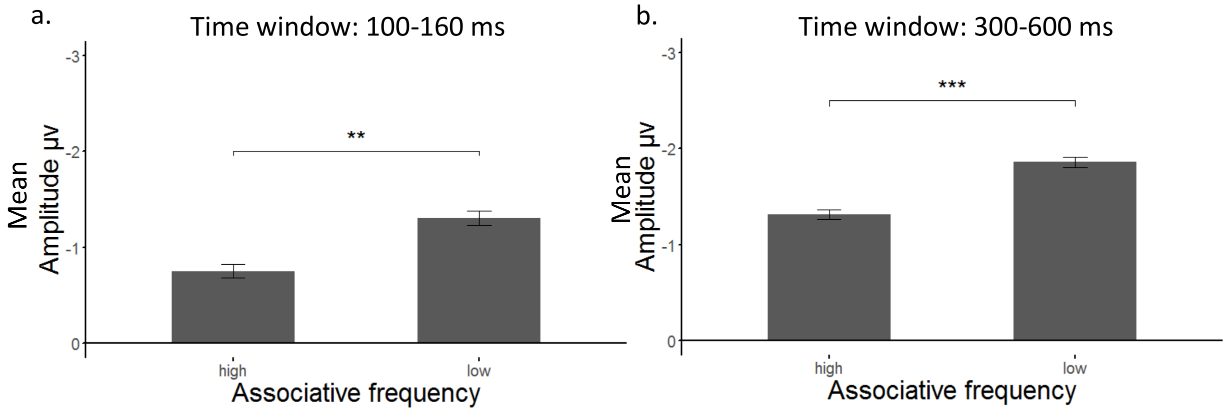
8.4.1.2.1 Time window between 100 and 160 ms

Main effects of associative frequency and topographical sites were found: $F(1,23)=10.50$, $p<.01$ and $F(6,138)=5.15$, $p<.05$, respectively. N100 amplitude elicited by low associative frequency was stronger than that elicited by high associative frequency, as depicted in Figure 21.a. Regarding the topographical sites effect, post-hoc Tukey *t*-tests showed that negativity was centralized over the frontal sites. There were more negative values over the frontal sites than over the left anterior ($p<.01$), right mid-parietal ($p<.01$), left mid-parietal ($p<.001$), and posterior sites ($p<.001$). Moreover, a significant interaction between associative frequency and topographical site was observed ($F(6,138)$, 3.03, $p<.05$).

Post-hoc Tukey *t*-tests revealed that low associative frequency elicited stronger negativity than high associative frequency in all sites (p<.001), except for the right mid-parietal site.

Figure 21

Mean amplitude over all topographical sites for the associative frequency condition in noun categorization task



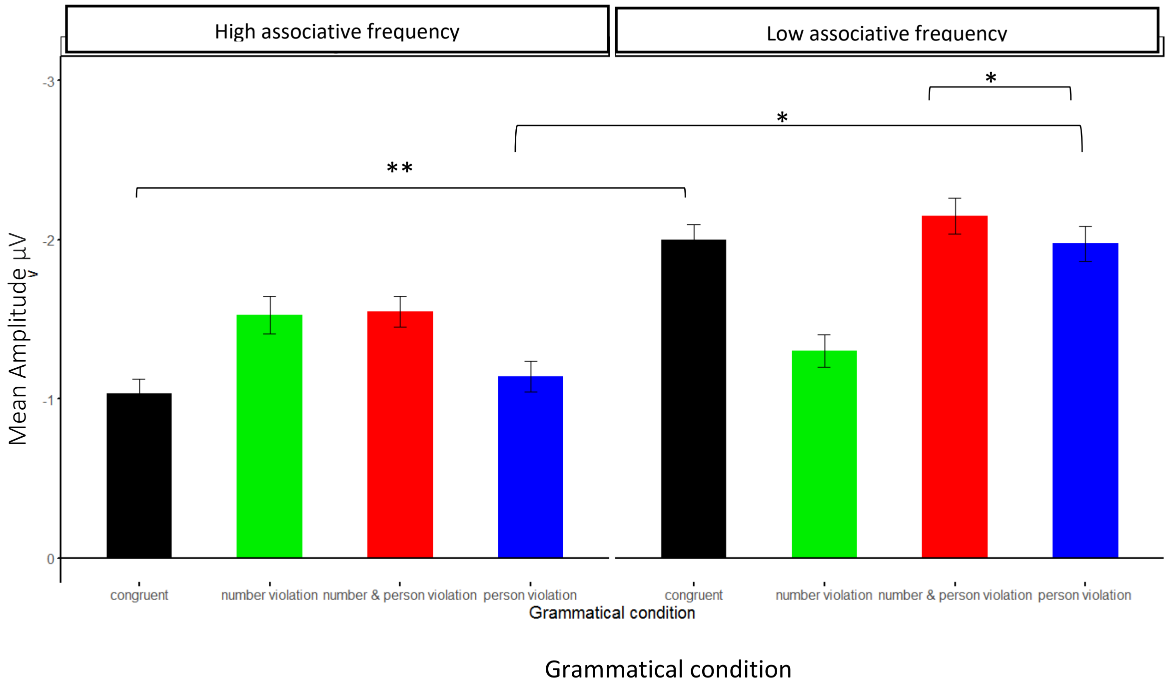
*Note.****p*< .01, ****p*< .001. In the y axis, the negative value is on the top. Low associative frequency increased the negative amplitude in the first (a.) and second (b.) time window.

8.4.1.2.2 Time window between 300 and 600 ms

In this time window, main effects of associative frequency (see Figure 21b) and topographical sites were observed: $F(1,23)=17.31$, p<.001 and $F(6,136)=4.25$, respectively, p<.05. As in the first time window, low associative frequency elicited a stronger negativity amplitude than high associative frequency. Regarding the topographical sites factor, post-hoc Tukey *t*-tests showed that there were more negative values over the central site than over the right anterior (p<.01), left anterior (p<.05), and frontal sites (p<.01). In addition, the posterior site had more negative values than the frontal site (p<.05). Although no grammaticality effect was found, two significant interactions involving the grammaticality factor were observed. First, we found a significant interaction between associative frequency and grammaticality: $F(3,69)=5.20$, p<.01, see Figure 22 . Second, we observed a significant interaction involving associative frequency, grammaticality and topographical sites: $F(18,414)=2.64$, p<.05. Post-hoc Tukey *t*-tests were run for both interactions. In the first interaction between associative frequency and grammaticality, we found stronger negative amplitude was stronger for low associative frequency than for high associative frequency only for the congruent condition (*p*<.01) and the person violation (*p*<.05). Moreover, for low associative frequency, we observed that the negativity elicited by the number and person violation was stronger than that elicited by the number violation (*p*<.05).

Figure 22

Interaction between grammaticality and associative frequency



Note. *p<.05, **p<.005, ***p<.001. In the y axis, the negative value is on the top. Low associative frequency elicited stronger amplitude for congruent and person violation condtion when compared to the same condition in the high associative frequency condition.

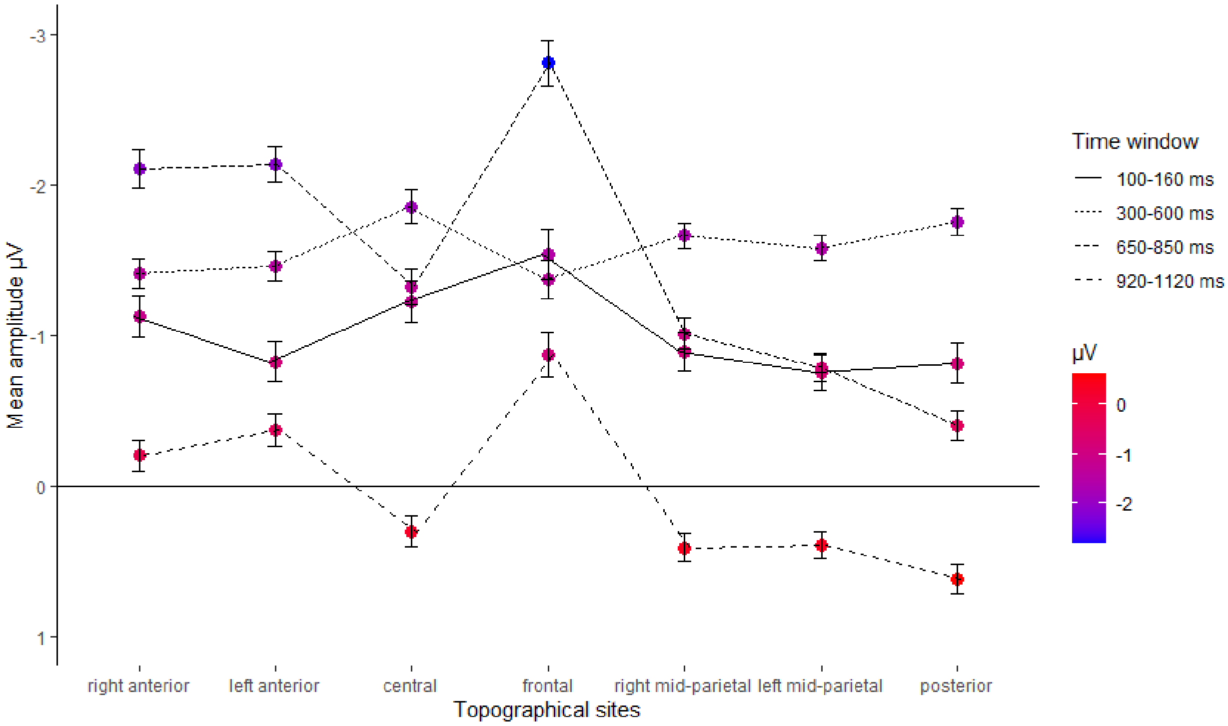
For the second interaction, we had a three-way interaction involving grammaticality, associative frequency and topographical sites. We compared the same grammaticality in each topographical sites and for each associative frequency condition. We found that high associative frequency lowered the negative values related to the processing of grammaticality over all topographical sites, for the congruent condition (*p*<.001) and the person violation condition (*p*<.001), in comparison to their counterparts in the low associative frequency condition. For the other grammaticality effect involving the number violation and the double violation, high associative frequency is reduced negativity over the frontal site (*p*<.001) in contrast to its counterpart in low associative frequency. Regarding the number and person violation, high associative frequency reduced negativity over the right anterior (p<.01), left anterior (p<.001), central (p<.01), right and left mid parietal sites (p<.01), in contrast to their counterparts in low associative frequency. Moreover, for the high associative frequency, we found that the number violation elicited stronger negativity than the congruent condition over the right anterior, central, and frontal site (p<.001), left anterior (p<.01); the person violation condition was more negative than number violation condition over the left anterior and frontal sites (p<.05). The number and person violation condition was more negative than the congruent condition over the right and left anterior, frontal sites (p<.01), and central sites (p<.001); the number and person violation condition was more negative than person violation condition over the left anterior site (p<.05). For the low associative frequency condition, we found that the congruent condition was more negative than the number violation condition over the right and left anterior, central, frontal sites (p<.001), and left mid-parietal sites (p<.01). Grammaticality effect involving double violation, such as number and person violation, were more negative than the number violation condition over all topographical sites (p<.001), except posterior sites (p<.01); number and person violation was more negative than the person violation condition over the frontal site (p<.05).

8.4.1.2.3 Time window between 650 and 850 ms

Although we expected to observe a grammaticality effect in this time window, we only observed a main effect of topographical sites: $F(6,138)=55.42$, $p<.001$, as seen in Figure 23. Post-hoc Tukey tests showed that there were more negative amplitudes over the frontal sites than over the right anterior (p<.001), left anterior (p<.001), central (p<.001), right mid-parietal (p<.001), left mid-parietal (p<.001), and posterior sites (p<.001). Right and left anterior sites had a larger negative amplitude than the central site (p<.001), right mid-parietal (p<.001), left mid-parietal (p<.001), and posterior sites (p<.001). Additionally, the central site also had more negative values than the left mid-parietal (p<.05) and posterior sites (p<.001); the right mid-parietal site had more negative values than the posterior site (p<.01).

Figure 23

Mean amplitudes over each topographical site of each ERP time window in noun categorization task



Note. In the y axis, the negative value is on the top. For N100 time window, the negativity was peaking over the frontal site. In the second time window, the negative peak shift to the central site. In the third time window, large negativity was observed over the frontal site. In the last time window, we observed positivity over the posterior site.

8.4.1.2.4 Time window between 920 and 1120 ms

In this last time window, as in the previous one, we only observed an effect of topographical sites: $F(6,138)=29.60$, $p<.001$, as depicted in Figure 23. Posthoc Tukey *t*-tests showed that the posterior site had more positive values than the right anterior ($p<.001$), left anterior ($p<.001$), and frontal sites ($p<.001$). The values over the central site were more positive than over the right anterior ($p<.01$), left anterior ($p<.001$), and frontal sites ($p<.001$). The mid-parietal, right and left mid-parietal sites had more positive values than the right anterior ($p<.001$), left anterior ($p<.001$), and frontal sites ($p<.001$). Lastly, the frontal site had more negative values than the right anterior ($p<.001$) and left anterior sites ($p<.01$).

8.4.1.3 Discussion

In Experiment 2, participants were asked to perform a noun categorization task: they had to determine whether the target they heard was a noun and respond if it was. As we looked at the same time windows as in the previous study, we found similar ERP components, such as N100, late anterior negativity, P600, and we unexpectedly observed N400 in the second time window. These ERP components seemed to have less sensitivity towards the abstract features compared to the previous experiment where participants were asked to perform LDT; at the present experiment the grammaticality effect was absent at late time windows.

The present study confirmed the results of Experiment 1 regarding N100, showing that associative representations were accessed during verb phonological processing. During this time window, the associative representations were employed after hearing the subject prime which then caused the system to pre-activate the phonological information concerning the verb inflection that constrains the phonological processing. Therefore, this result is in agreement with previous studies (Brunellière & Soto-faraco, 2015; Cason & Schön, 2012; Getz & Toscano, 2019; Noe & Fischer-Baum, 2020) that showed a top-down process in spoken language comprehension. In addition to N100, we also found N400, which we did not initially expect since we found anterior negativity in Experiment 1. N400 has indeed been observed in agreement studies involving number violation (Kutas & Hillyard, 1983; Mancini et al., 2011a; Severens et al., 2008; Tanner, 2019) and person violation (Mancini et al., 2011a, 2011b).

In regards to the N400 time window, we found that the associative representations were accessed and the way they affect the system was similar to previous studies in spoken language comprehension (Brunellière & Soto-faraco, 2015; Connolly et al., 1990, 1992). Note that those studies did not look at the associative representations but they looked at the sentential context that put a constraint in spoken word processing; and as a result of this process N400 amplitude was reduced when a sentence was highly constraint. In line with them, information from associative representations that were extracted from subject prime put a constraint on verb processing and high associative frequency reduced the sensitivity towards syntactic errors. Moreover, in agreement studies, N400 reflects the detection of syntactic error, hereby we observed that abstract representations were also accessed as we found differences between grammaticality effect involving single violation, such as number violation with double violations, such as number and person violation.

In the two following time windows over the frontal negativity and the P600, there was no sensitivity for morphosyntactic violations and for the use of associative representations. We argued that this might be due to the task instruction and the stimuli. Each noun in our stimuli was always preceded by an article, while our critical stimuli were always primed by pronoun subjects. When the critical stimuli were presented, the system may have reduced their attention because it recognized that the following stimulus would not be a noun. Therefore, the sensitivity towards the abstract features was diminished (i.e., over frontal negativity and P600) as well as the use of associative representations over frontal negativity. Furthermore, previous study by Schacht et al. (2014) showed that P600 was task-related, as it reflected the controlled process. Schacht et al. (2014) compared their study to a previous study by Martín-Loeches et al. (2006). In the 2006 study, correctness judgment task was used, while in the 2014 study, Schacht et al. used a word verification task where participants were asked to verify whether or not a presented word had appeared in the preceding sentence. They used Spanish in their stimuli and manipulated the semantic and syntactic aspects of the sentences. For the syntactic manipulation, they introduced violations involving number and gender features. They observed that P600 increased in conditions involving syntactic violation in the 2006 study, when they used the correctness judgment task. However, this effect was not observed in the 2014 study with the word verification task. They therefore concluded that P600 was task-related. The way P600 is related to the task was also studied by Gunter & Friederici (1999): they conducted two experiments with visual stimuli tasks. In one experiment, they used a physical discrimination task (i.e., differentiating upper and lower case). In the other experiment, they used a grammatical judgment task. They found that P600 was related to syntactic violation in the physical discrimination task, but it was absent in the grammatical judgment task. Similarly, we observed positivity over the posterior site with an absent of grammatical effect. We argue that the disappearance of response to morphosyntactic violations is due to the task reducing sensitivity to the abstract features. To confirm this task effect, we compared the data from Experiment 1 and from Experiment 2. This comparison could also be used to investigate whether the associative and abstract representations are accessed flexibly or automatically during subject-verb agreement processing.

8.4.2 Comparison of Experiment 1 and Experiment 2

8.4.2.1 Behavioral results

We ran a *t-test* to compare behavioral results from Experiment 1 (LDT) and Experiment 2 (noun categorization task). In terms of reaction times, participants performed the task in Experiment 2 (M=1135, SD=129) faster than in Experiment 1: $t(45)=2.16$, $p<.05$,(M=1238, SD=193). Accuracy was also higher in Experiment 2 (M=96%, SD=0.03) than in Experiment 1: $t(45)=-3.43$, $p<.01$ (M=89%, SD=0.10).

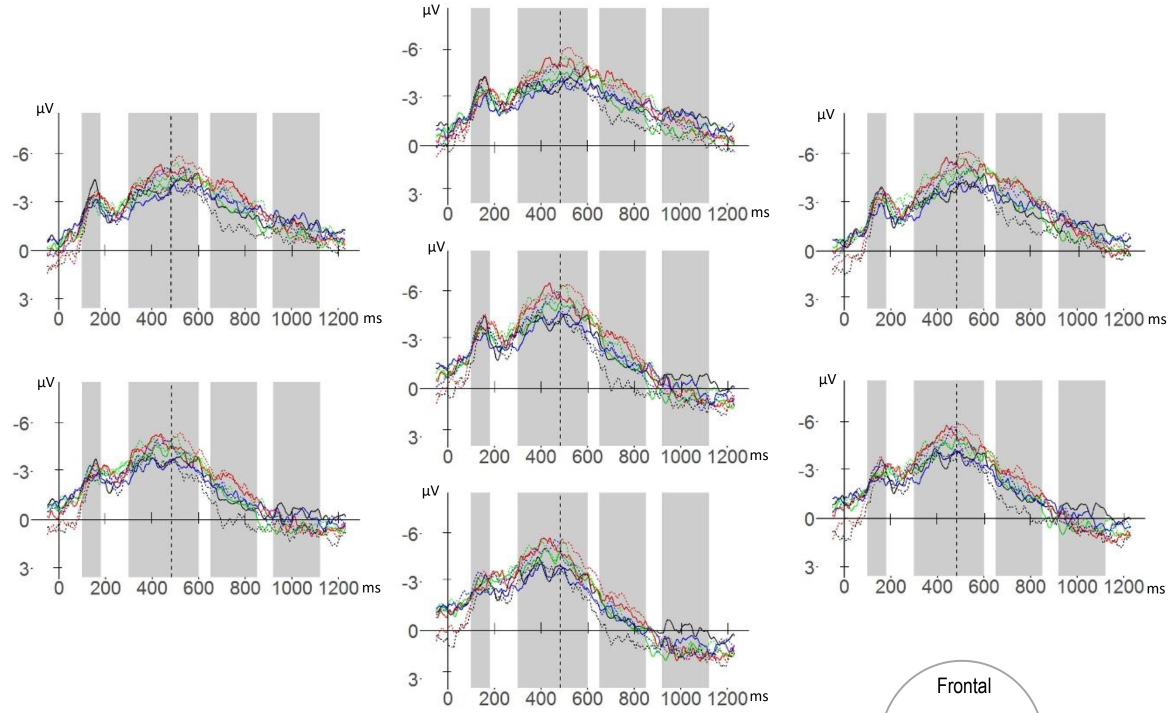
8.4.2.2 ERP results

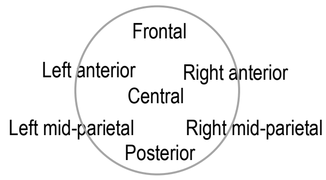
Importantly, the results of Experiment 2 (noun categorization task) are presented without a baseline correction. For the sake of comparison, we thus re-analyzed the results of Experiment 1 (LDT) after removing the baseline correction. The grand-average of ERP waveforms elicited by target verbs are displayed in Figure 24c&d, across four grammaticality conditions for each experiment and in both high and low associative frequency conditions. For grand-average of ERP comparing the associative frequency condition within the same experimental condition, see Figure 24a&b. It seemed that N100 centered over the central and frontal sites and was stronger in Experiment 1 than in Experiment 2, and it was enhanced by low associative frequency in comparison with high associative frequency. During the second time window, between 300 and 600 ms, the double violation increased the amplitude of an N400-like component negativity, especially in Experiment 2. In the following time window between 650 and 850 ms, the amplitude of negativity peaking over the frontal site increased for single violation in comparison with double violations. In the last time window, we observed the strongest positive amplitude over the posterior site. See table 4 for the statistical summary of each time window (see Appendix B for summary result of Experiment 1).

Figure 24

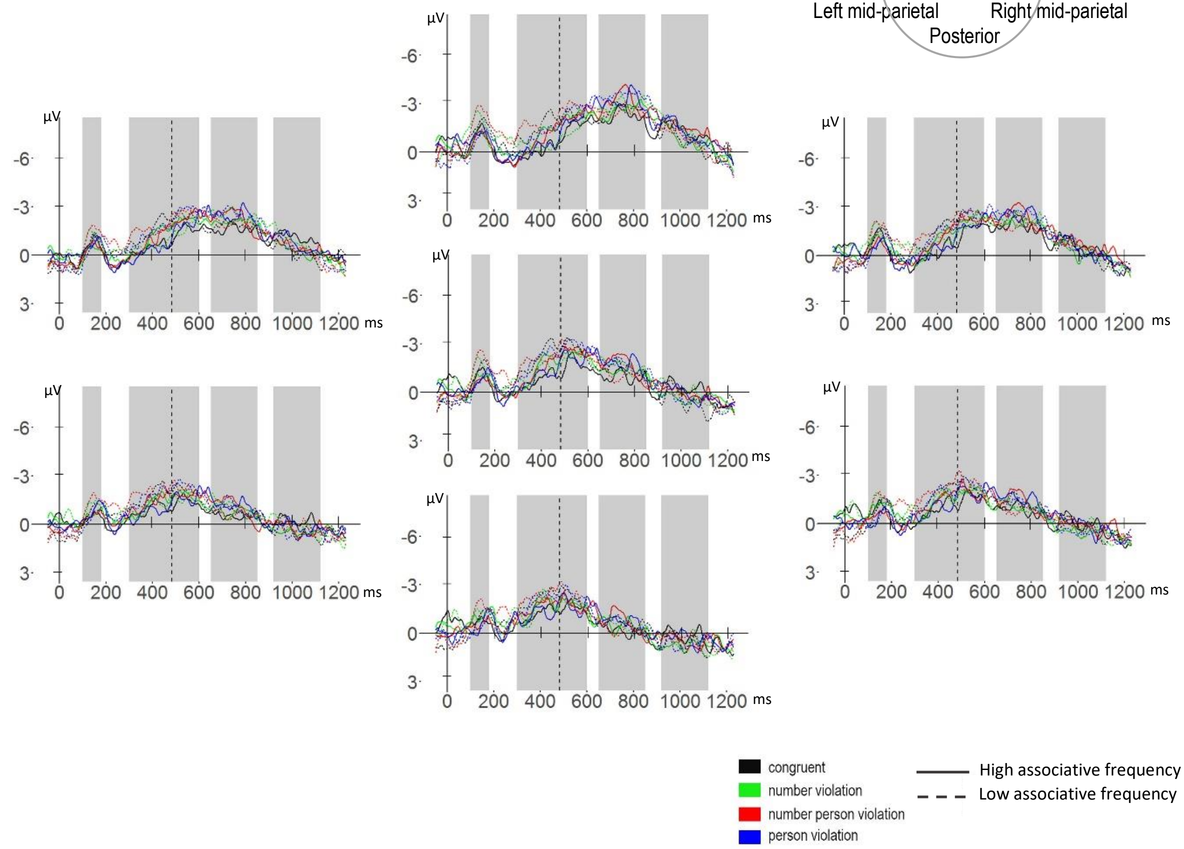
ERP waveform over seven topographical sites in the two experiments

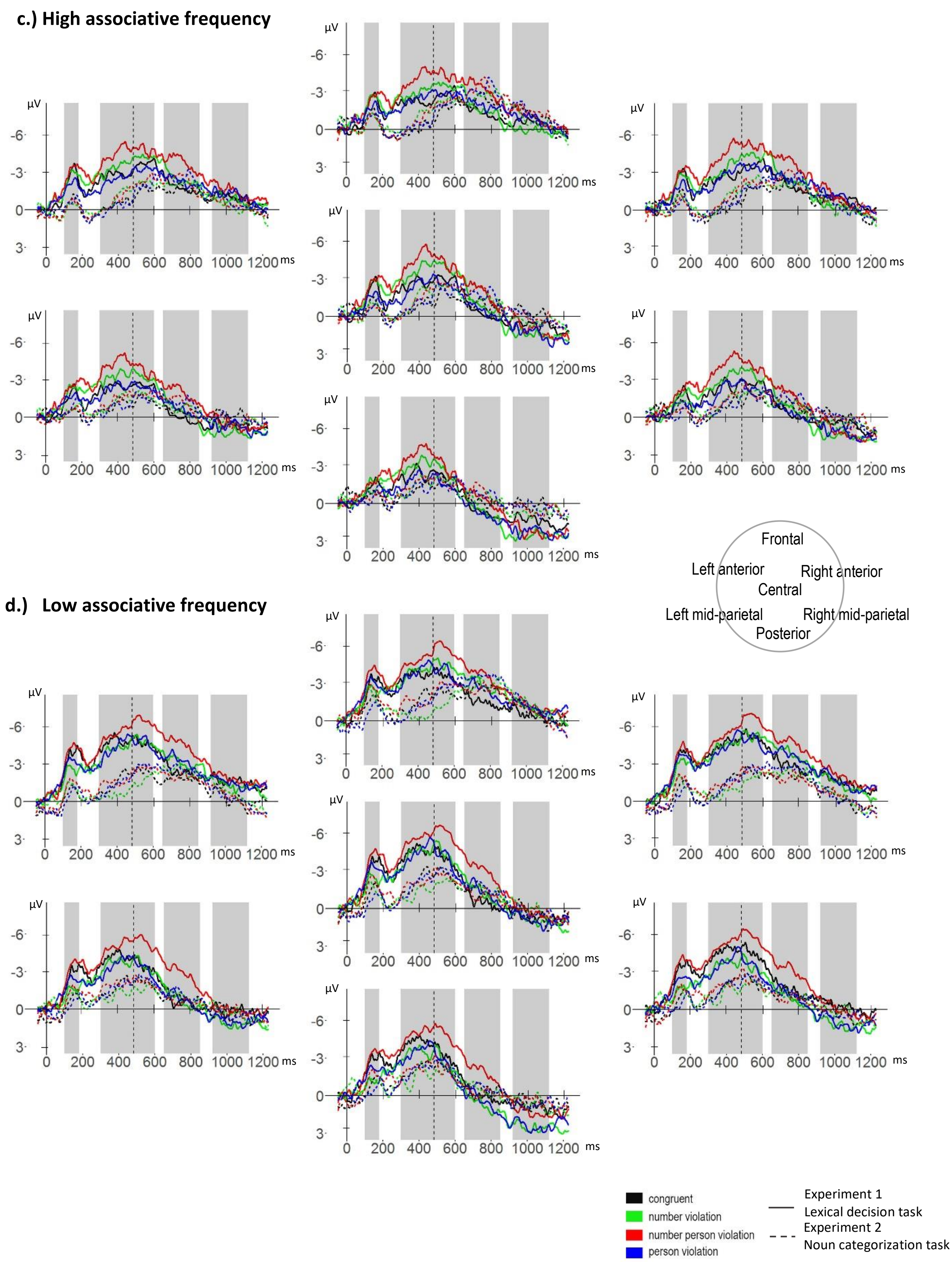
a.) Experiment : Lexical decision task





b.) Experiment 2: Noun categorization task





Note. The first two group of ERP waveforms, a. & b., are related to the experimental task. Thus, the solid line depicts high associative frequency, while dashed line depicts low associative frequency. The following two groups, c & d, compare the experimental task within each associative frequency condition. Thus, the solid line depicts Experimental 1

(Lexical decision task), dashed line depicts Experiment 2 (noun categorization task). X axis depict timescale in milliseconds. Y axis depict mean amplitude in microvolt (μV), the negative value is on the top. Black color represents congruent condition, green color represents number violation condition, red color represents number and person violation condition, blue color represents person violation condition. Vertical dashed line in the middle of each plot is the mean onset of the inflection (482 ms). The shaded areas are the time windows that we are focused on. First time window is from 100 to 160 ms; second time window is from 300 to 600 ms; third time window is from 650 to 850 ms; and fourth time window is from 920 to 1120 ms.

Table 4

Statistical result comparing Experiment 1 and Experiment 2 in each time window

	Time window between 100 and 160 ms	**Time window between 300 and 600 ms**	**Time window between 650 and 850 ms**	**Time window between 920 and 1120 ms**
Experimental task	$F(1,45)=31.32$, $p<.001$	$F(1,45)=26.95$, $p<.01$	$F(1,45)=0.97$, $p>.2$	$F(1,45)=0.16$, $p>.2$
Associative frequency	$F(1,45)=2.50$, $p=.12$	$F(1,45)=7.43$, $p<.01$	$F(1,45)=0.01$, $p>.2$	$F(1,45)=3.89$, $p=.05$
Grammaticality	$F(3,135)=0.68$, $p>.2$	$F(3,135)=6.03$, $p<.01$	$F(3,135)=6.93$, $p<.001$	$F(3,135)=0.39$, $p>.2$
Topographical sites	$F(6,270)=10.21$, $p<.001$	$F(6,270)=3.94$, $p<.01$	$F(6,270)=71.95$, $p<.001$	$F(6,270)=48.33$, $p<.001$
Associative frequency x Experimental task	$F(1,45)=2.21$, $p=.14$	$F(1,45)=0.24$, $p>.2$	$F(1,45)=0.48$, $p>.2$	$F(1,45)=0.34$, $p>.2$
Associative frequency x Topographical sites	$F(6,270)=3.25$, $p<.05$	$F(6,270)=0.38$, $p>.2$	$F(6,270)=1.05$, $p>.2$	$F(6,270)=1.35$, $p>.2$
Associative frequency x Grammaticality	$F(3,135)=1.78$, $p=.15$	$F(3,135)=1.03$, $p>.2$	$F(3,135)=1.73$, $p=.17$	$F(3,135)=2.94$, $p<.05$
Grammaticality x Experimental task	$F(3,135)=0.47$, $p>.2$	$F(3,135)=2.71$, $p=.05$	$F(3,135)=3.05$, $p<.05$	$F(3,135)=0.38$, $p>.2$
Grammaticality x Topographical sites	$F(18,810)=1.24$, $p>.2$	$F(18,810)=1.18$, $p>.2$	$F(18,810)=1.84$, $p=.07$	$F(18,810)=2.11$, $p<.05$
Experimental task x Topographical sites	$F(6,270)=1.58$, $p=.2$	$F(6,270)=1.94$, $p=.11$	$F(6,270)=2.44$, $p=.06$	$F(6,270)=5.36$, $p<.01$
Associative frequency x Grammaticality x Experimental task	$F(3,135)=1.25$, $p>.2$	$F(3,135)=2.47$, $p>.2$	$F(3,135)=2.02$, $p=.12$	$F(3,135)=0.80$, $p>.2$
Associative frequency x Grammaticality x Topographical sites	$F(18,810)=1.31$, $p>.2$	$F(18,810)=1.14$, $p>.2$	$F(18,810)=1.57$, $p=.15$	$F(18,810)=1.78$, $p=.09$
Associative frequency x Experimental task x Topographical sites	$F(6,270)=2.58$, $p<.05$	$F(6,270)=0.14$, $p>.2$	$F(6,270)=0.99$, $p>.2$	$F(6,270)=0.64$, $p>.2$
Grammaticality x Experimental task x Topographical sites	$F(18,810)=1.19$, $p>.2$	$F(18,810)=1.11$, $p>.2$	$F(18,810)=1.33$, $p>.2$	$F(18,810)=1.52$, $p=.15$
Associative frequency x Grammaticality x Experimental task x Topographical sites	$F(18,810)=0.51$, $p>.2$	$F(18,810)=1.47$, $p=.16$	$F(18,810)=1.19$, $p=.31$	$F(18,810)=0.99$, $p>.2$

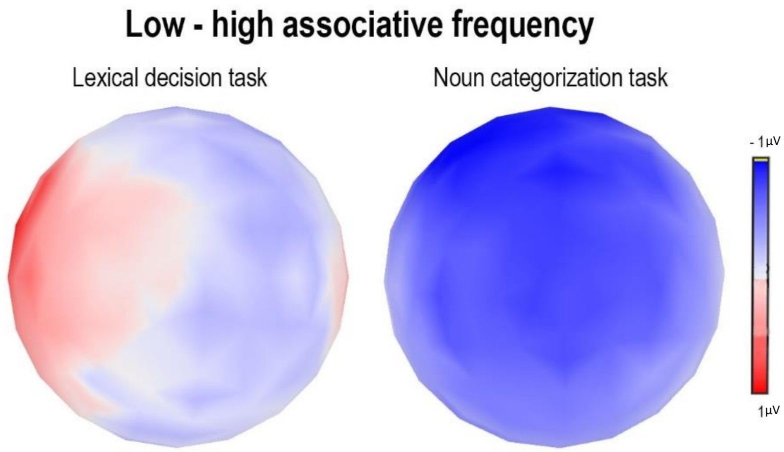
8.4.2.2.1 Time window between 100 and 160 ms

In this time window of N100, we observed a main effect of experimental task where greater negativity was induced by Experiment 1 (LDT) than by Experiment 2 (noun categorization task), $F(1,45)=31.32$, $p<.001$. A main effect of topographical sites was also noted, $F(6,270)=10.21$, $p<.001$. Post-hoc Tukey *t*-tests showed that the central and frontal sites had significantly more negative values than the left anterior ($p<.01$), right mid-parietal ($p<.001$), left mid parietal ($p<.001$) and posterior sites ($p<.001$). Two interactions involving associative frequency were observed: first, a significant interaction between associative frequency and topographical sites ($F(6,270)=3.25$, $p<.05$); second, a significant interaction between associative frequency, topographical sites and experimental task ($F(6,270)=2.58$, $p<.05$). In terms of the two-way interaction between associative frequency and topographical sites, we found that low associative frequency, enhanced negativity in comparison with high associative frequency, over the right anterior ($p<.01$), central ($p<.001$), frontal ($p<.001$) and posterior sites ($p<.01$).

For the second interaction involving associative frequency, topographical sites and experimental task, it was found the amplitude of negativity was greater in Experiment 1 than in Experiment 2 over the right anterior ($p<.05$), left anterior ($p<.01$), central ($p<.01$), frontal ($p<.05$), left mid-parietal ($p<.01$) and posterior sites ($p<.05$) in high associative frequency. This negativity was also greater in Experiment 1 only over the central site ($p<.05$), when compared to Experiment 2 in low associative frequency. When we looked at the comparison between high and low associative frequency condition within Experiment 1, we found no significant differences amongst the topographical sites. Moreover, we also compared each associative frequency in each experimental task (see Figure 25). In Experiment 1, we did not find significant differences between high and low associative frequency. Nevertheless, comparison within the same associative frequency condition, whether in high or low associative frequency condition, the central site has more negativity compared to right anterior, right mid parietal, left mid parietal, and posterior sites ($p<.001$). On the other hand, in Experiment 2, we found low associative frequency was more negative than high associative frequency over right anterior, left mid-parietal, and posterior sites ($p<.01$), left anterior, central, and frontal sites ($p<.001$).

Figure 25

Interaction between associative frequency, topographical sites, and experimental task



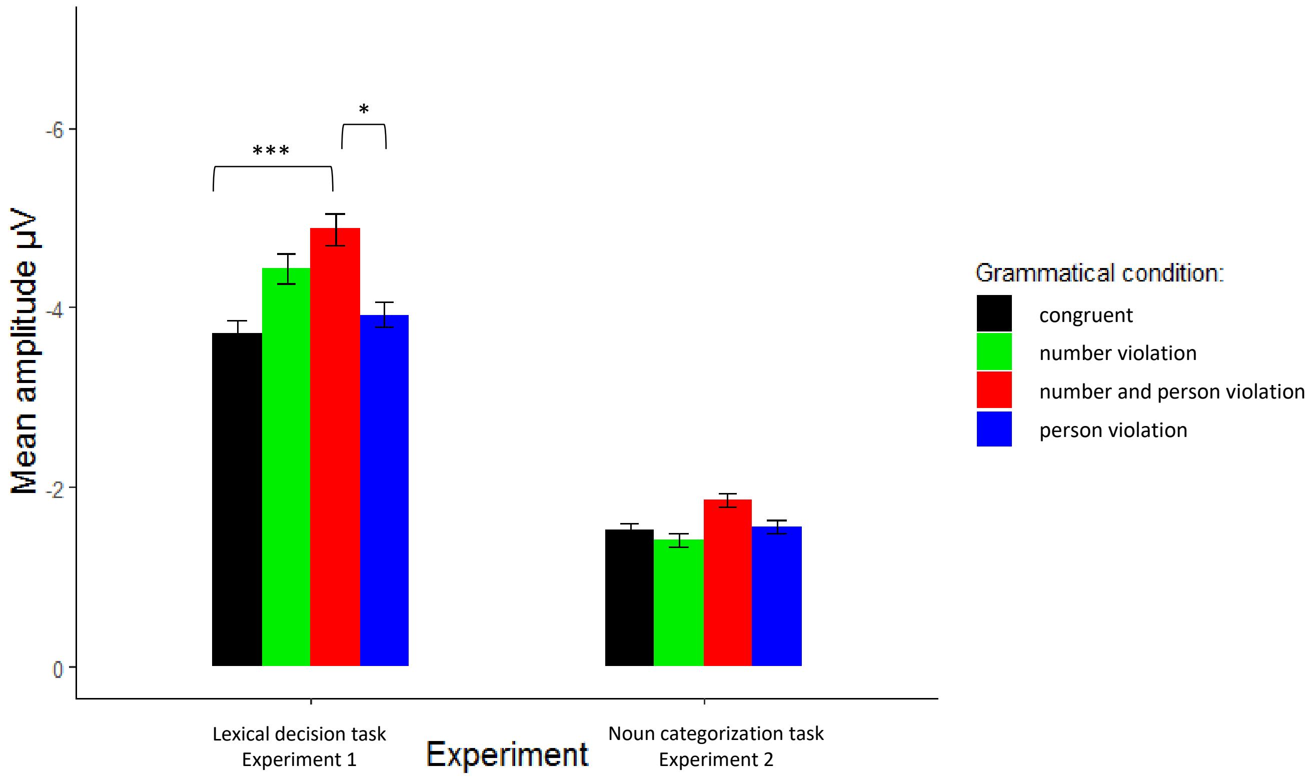
Note. Topography from 100 to 160 ms based on the subtraction between low and high associative frequency. Blue color indicates negative value, red color indicates the positive value. On the left is the topography from Experiment 1 which is the LDT, while the right side is the topography from Experiment 2 which is the noun categorization task.

8.4.2.2.2 Time window between 300 and 600 ms

In this time window, we observed a main effect of experimental task ($F(1,45)=26.95$, $p<.001$) where the amplitude of negativity was greater in Experiment 1 than in Experiment 2. A main effect of associative frequency ($F(1,45)=7.43$, $p<.01$) was also observed and the low associative frequency induced stronger negativity in comparison with high associative frequency. Other main effects that were observed were main effects of grammaticality ($F(3,135)=6.03$, $p<.001$) and of topographical sites ($F(6,270)=3.94$, $p<.01$). A post-hoc Tukey *t*-tests showed that the double violation elicited greater negativity than the congruent condition ($p<.001$) and the person violation ($p<.01$). Post-hoc Tukey *t*-tests over the topographical sites revealed that there were more negative values over the central sites than over the right anterior ($p<.05$), left anterior ($p<.01$), frontal ($p<.01$), right mid-parietal ($p<.05$), left mid-parietal ($p<.01$) and posterior sites ($p<.05$). An interaction between grammaticality and experimental task was observed ($F(3,135)=2.71$, $p=.05$), as illustrated in Figure 26. If we look at the differences between various grammaticality within the same experiment, we observed that in Experiment 1, number and person violation induced stronger negative amplitude than the congruent condition ($p<.001$) and the person violation condition (p<.05). In Experiment 2, there were no significant differences within grammaticality factor.

Figure 26

Interaction between grammaticality and experimental task



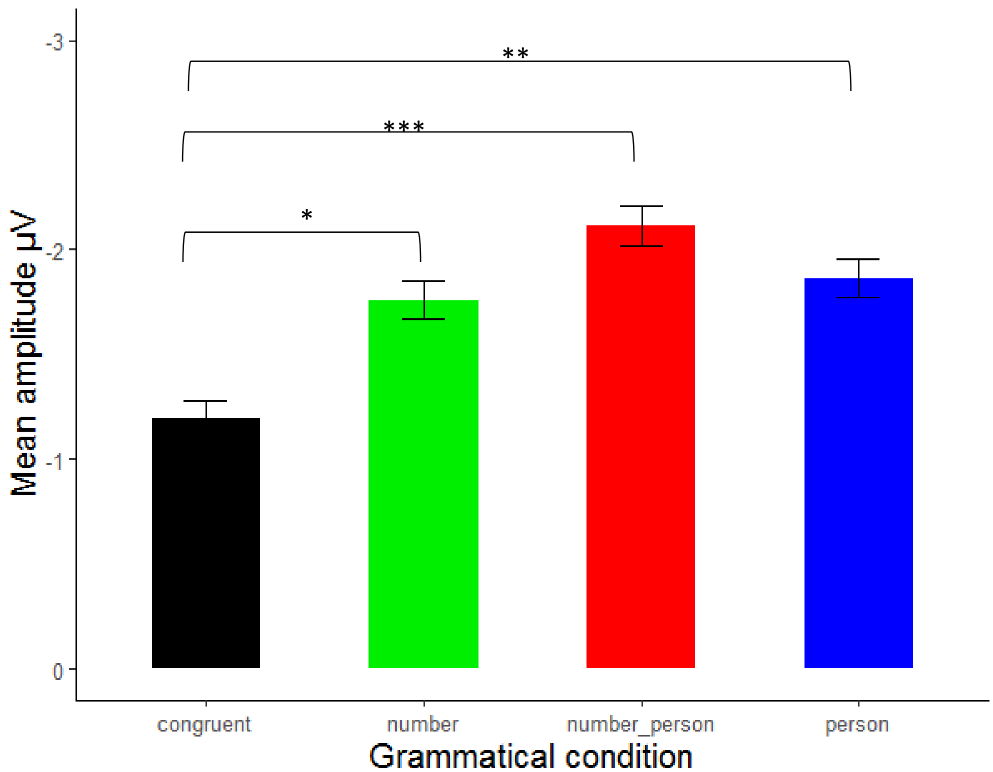
Note. *p<.05, ***p<.001. In the y axis, the negative value of the mean amplitude is on the top. Here we only observed double violation effect in Experiment 1, in which double violation was stronger than congruent and person violation.

8.4.2.2.3 Time window between 650 and 850 ms

In this time window, we observed main effects of grammaticality ($F(3,135)=6.94$, p<.001), as seen in Figure 27, and topographical sites ($F(6,270)=71.95$, p<.001). For the grammaticality effect, we found that all incongruent conditions, such as number violation (p<.05), number and person violation (p<.001) and person violation (p<.01), elicited stronger amplitude than the congruent condition. In terms of topographical sites effect, post-hoc Tukey *t*-tests revealed that there were more negative values over the right and left anterior sites and frontal sites than over the central (p<.001), right mid-parietal (p<.001), left mid-parietal (p<.001) and posterior sites (p<.001). The central sites had more negative values than the left mid-parietal sites (p<.05) and posterior sites (p<.001). We also observed a significant interaction between grammaticality and experimental task ($F(3,135)=3.05$, p<.05). Nevertheless, the posthoc Tukey's t-test did not show any significant differences between Experiment 1 and Experiment 2. The only significant difference in Experiment 1 was that the double violation elicited higher amplitude than the congruent condition (p<.001); no grammatical effect was found in Experiment 2.

Figure 27

Mean amplitude over all topographical sites for the grammaticality condition in the two experiments



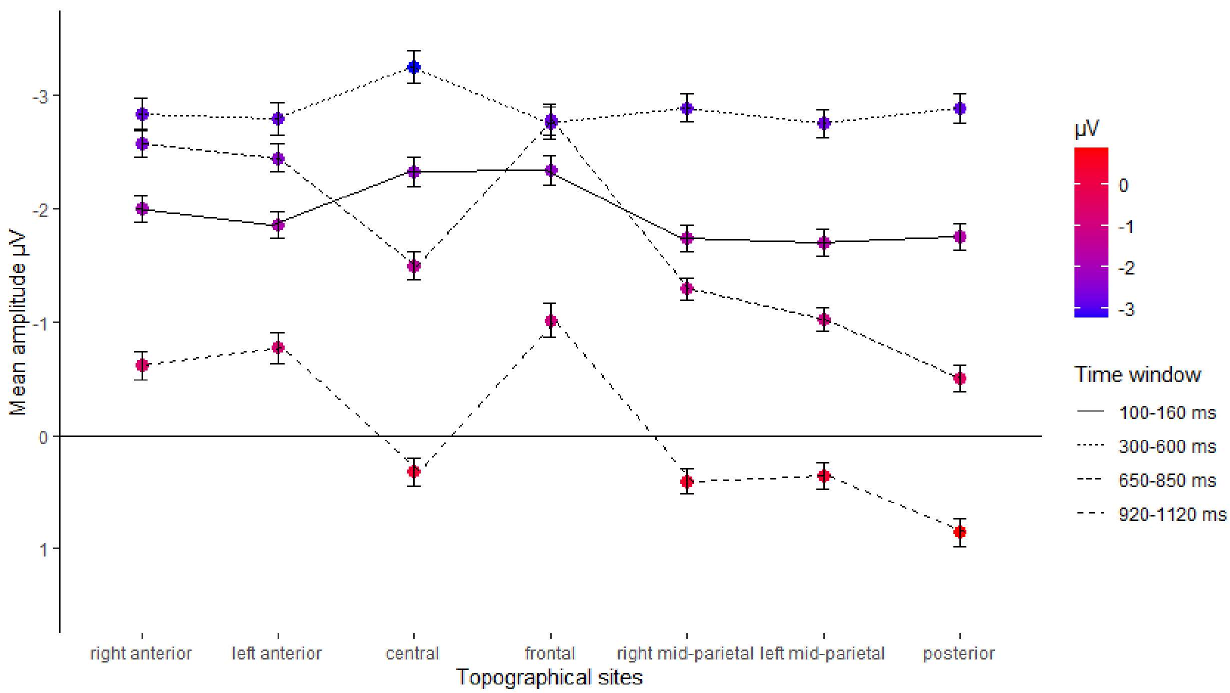
*Note. *p<.05, **p<.01, ***p<.001*. In the y axis, the negative value of the mean amplitude is on the top. Here we observed the incongruent conditions were significantly stronger than congruent condition.

8.4.2.2.4 Time window between 920 and 1120 ms

In this last time window, we found a main effect of topographical sites (*F(*6,270)=48.33, *p*<.001)), see Figure 28. Post-hoc Tukey *t*-tests revealed that there were more positive values over the central sites than over the right anterior (*p*<.001), left anterior (*p*<.001) and frontal sites (*p*<.001). The right and left mid-parietal sites were more positive than the left anterior (*p*<.001), right anterior (*p*<.001) and frontal sites (*p*<.001). Lastly, the posterior site was more positive than the right anterior (*p*<.001), left anterior (*p*<.001), frontal (*p*<.001), central (*p*<.01), right mid-parietal (*p*<.05) and left mid-parietal sites (*p*<.05). A main effect of associative frequency was almost significant (*F(*1,45) =3.89, *p*=.05), being slightly more negative in high associative frequency than in low associative frequency.

Figure 28

Mean amplitudes over each topographical site of each ERP time window in the two experiments



Note. The mean amplitude from Experiment 1 and Experiment 2 of each time window over the seven topographical sites. During the N100 time window, the negativity was peaked over the central and frontal site. In the second time window, the largest negativity was observed over the central site. In the third time window, the strongest negativity was observed over the anterior and frontal site. In the last time window, P600, the positivity was peaked over the posterior site.

Furthermore, we observed three interactions in this time window: 1) between topographical sites and experimental task ($F(6,270)=5.36$, $p<.01$); 2) between associative frequency and grammaticality ($F(3,135)=2.94$, $p<.05$); 3) between grammaticality and topographical sites, ($F(18,810)=2.11$, $p<.05$). Post-hoc Tukey *t*-tests were performed for each interaction. For the first interaction, we did not observe any significant differences between Experiment 1 and Experiment 2 over all topographical sites. For the second interaction, post-hoc Tukey *t*-tests did not reveal any significant differences. For the third interaction, we found that number violation ($p<.05$) and number & person violation ($p<.01$) increased the amplitude of positivity over the posterior sites when compared to the congruent condition.

8.4.2.3 Discussion

First, we would like to comment on the fact that the data in Experiment 1 is similar to the data in Chapter 7. The main difference is that in the present chapter, the baseline correction was removed, which induced differences between the results of Experiment 1 here and those described in Chapter 7. We found significant differences for grammaticality and associative frequency in the baseline of Experiment 2, which led us to remove it altogether so as to have no baseline at all. Zero baseline is indeed preferable but a non-zero baseline is unavoidable and it may affect topography distribution and data interpretation (Urbach & Kutas, 2002, 2006). To bring the baseline to zero, a baseline correction, which consists in subtracting the mean of the baseline from the entire data waveforms (Luck, 2014), is recommended. Alday (2019) suggested that baseline correction may shift the prestimulus effect to post-stimulus. In our case, the effect in Experiment 1 carried information regarding the extraction of associative frequency information from the subject prime, so it was not just the noise.

The purpose of comparing the Experiments was to investigate the cognitive flexibility in accessing the mental representations during the subject-verb agreement processing in spoken language. Indeed, there may be a shift from one representation to another to adapt to the current situation (Deak, 2003). In the context of this study, flexibility is the ability to process subject-verb agreement depending on task instructions: the task in Experiment 1 was a lexical decision task (LDT), while that in Experiment 2 was a noun categorization task. Initially, we predicted that the task in Experiment 2, which probed grammatical processing, would increase sensitivity towards the morphosyntactic features. We argued that this was due to the task. The task in Experiment 1 allowed a verification strategy between prime and target to determine whether a target was a word or a nonword (Becker, 1980; McNamara, 2005; Yap et al., 2013), by checking if the target was part of the word set that had been activated after the system received the prime. This process was reflected by a stronger amplitude in Experiment 1 than in Experiment 2. In addition, the system needs to check the shared features between a subject and a verb, for the sake of forming agreement when the verb input is received; this process seemed to be enhanced by LDT in Experiment 1.

The reader is reminded that flexibility is reflected by the experimental task effect that interacted with grammatical and/or associative frequency conditions, meaning that the experimental task affects the processing of either associative or abstract features in agreement processing. On the other hand, automaticity is defined by the main effect of associative frequency that was reflected through N100 despite the experimental task, in the sense that the accessing of associative representation is stable. The result from our comparison suggests that we evidenced an experimental task effect during the N100 time window. However, this effect not only reflects flexibility, it may also reflect automaticity, as we will see in the following sub-section. Furthermore, an interaction between experimental tasks and grammaticality was reflected by N400. In N400, this interaction indicated flexibility in accessing the abstract representations: Experiment 1 increased the sensitivity to syntactic error detection in comparison to Experiment 2. Following that, we also observed that negativity spread over the anterior site and peaked over the frontal site, and that Experiment 1 seemed to increase morphosyntactic sensitivity. In the last time window, we observed positivity over the posterior site that was enhanced during Experiment 1. The fact that morphosyntactic sensitivity was increased in Experiment 1 compared to Experiment 2 indicated that there was flexibility in processing the subject-verb agreement. In the following sub-section, we discuss these ERP components in more detail.

8.4.2.3.1 N100

As predicted, N100 reflects the used of associative representations that was extracted from the subject pronoun to constrain the phonological processing of the verbal inflection. Interestingly, N100 seemed to reflect process that was both automatic and flexible. Regarding flexibility, it was flexible in the sense that the way associative representation employed was depended on the task and this was reflected through the topographical differences between Experiment 1, lexical decision task, and Experiment 2, noun categorization task. In Experiment 1, the usage of associative representation seemed to enhanced negativity over the central sites; while in Experiment 2, the negativity was increased in almost all sites, except in right mid-parietal site. Moreover, lexical decision task seemed to increase the negative amplitude and the fact that there was flexibility suggests that top-down processing can be shaped by task strategies.

Concerning automaticity, the associative representations were accessed after hearing the subject pronoun in both tasks. In Experiment 2, where participants performed the noun categorization task, we found that the system still accessed the associative representations, even though the task did not probe the lexical level of the words. This raises the possibility that accessing associative representations might be an automatic process. Additionally, previous studies have suggested that the collecting of statistical information, such as co-occurrence information which is part of statistical learning, occurs incidentally or without instruction (Aslin & Newport, 2012; Christiansen, 2019). We therefore believe that automaticity is also involved in accessing the associative representations between subjects and verbal inflections. Associative representations are built from statistical learning strategies, which are implicit and devoid of intention. For instance, a study by Toro, Sinnet, & Soto-Faraco (2005) showed that high attentional focus was not required to use statistical information in speech segmentation. Likewise, the usage of associative representations does not need high attentional focus, thus automaticity in accessing associative representations were not surprising.

8.4.2.3.2 N400 and late anterior negativity

We found that N400 was affected by the task demand, which seemed to be in line with previous studies (Chwilla et al., 1995; Gunter & Friederici, 1999; Hahne & Friederici, 2002; Schacht et al., 2014). The associative frequency effect, which persisted during the N400 time window, was not affected by the experimental task. At this stage, it seemed that the use of associative representations was automatic. On the other hand, the accessing of abstract representations seemed to be flexible. The flexibility was reflected through higher morphosyntactic sensitivity in in lexical decision task, Experiment 1, than noun categorization task, Experiment 2. Moreover, the double violation effect was only observed in Experiment 1, wherein number and person violation had larger negativity compared with single violation with person feature.

Perhaps the morphosyntactic sensitivity was higher in Experiment 1 beause the task there required the participants to keep their focus during the processing of targets, as there were no cues from the prime about whether the target would be a word or a pseudoword. In Experiment 2, participants could predict whether the target was a noun or not based on the prime, meaning they did not need to be alert at all times during the processing of targets. In line with this, previous studies (Batterink et al., 2010; Friederici & Gunter, 1999) found that there was a reduction or absence of N400 in semantic and syntactic processing when attention was reduced.

Apart from finding N400 related to flexibility which seemed to be related to attention, we also found that N400 was related to automaticity. So flexibility was found for abstract representations, while automaticity was found in using associative representations. Therefore, whether N400 reflects automaticity or a controlled process is still an open question. A previous study (Kutas & Federmeier, 2011) showed that N400 required attention, although not the high-level attention that is needed for controlled processing. Therefore, when we hypothesized the role of automaticity in this time window, it did not mean that attention was absent but that the attention level decreased depending on the task demand. This varying level of attention was also demonstrated in the behavioral task, which participants performed faster and more accurately in Experiment 2 than in Experiment 1.

Following N400, we observed late negativity over the anterior and frontal sites occurring between 650 and 850 ms. This late anterior negativity indicates the accessing of abstract representations and this effect may reflect the difficulty in integrating the morphosyntactic information from the system with the current verb input. Integration is a bottom-up process, which might be a continuation of the process we found in N400 related to accessing abstract representations after detecting a syntactic error. We then observed late positivity, known as P600, which is an index of the reanalysis process.

8.4.2.3.3 Late P600

Unexpectedly, the amplitude of P600 was independent of the task demands, indicating that the process of reanalyzing morphosyntactic errors might be automatic. Even though this component is usually considered to be associated with controlled processes, Gunter & Friederici (1999) also suggested that it might occur automatically. Although there is this possibility of automaticity, we did not suggest that attention was not required at all in this process. In both experiments, the experimental task still required attention, as reflected by the high level of accuracy in the behavioral task. This indicated that the participants still paid attention to the task in both experiments. The degree of attention might have been reduced in Experiment 2, since the system could prepare the response when a prime was recognized. When the system recognized a subject prime instead of an article, it might lower attention because a noun is always primed by an article.

8.4.2.2.4 Flexibility in agreement processing

Ionescu (2012) proposed a framework of cognitive flexibility in which she suggested that flexibility was the result of an interaction between sensorimotor functions (with several cognitive mechanisms such as representations, attention and perception) and task demands. The latter is an important aspect when studying cognitive flexibility, as task demands are usually manipulated by using a switching task or a dual task (Fischer & Hommel, 2012; Hermer-Vazquez et al., 1999, 2001; Koch et al., 2018; Ravizza & Carter, 2008). Language studies have shown that flexibility in accessing syntactic information occurs in language production (Ferreira, 1996; Lester & del Prada Martin, 2016). Syntactic flexibility is needed to produce utterances, it reduces syntactic errors and speeds up language production. In agreement, our study suggests that flexibility is observed in the processing of subject-verb agreement.

Flexibility in accessing associative representations became apparent in the early stage of verb processing, as demonstrated by the differences in topographical distribution in N100 between Experiment 1 and Experiment 2. This seemed to be a more automatic process, as the associative frequency affected the processing of verbs over the N100 and around 300 ms independently of the experimental task. As for flexibility in accessing the abstract representations, it was reflected by N400, late anterior negativity, and P600, which increased in Experiment 1 where more attention was required than in Experiment 2 due to the lexical decision task. Note that French verbs are also known to be processed by morphological decomposition (Estivalet & Meunier, 2016). The morphosyntactic verification process that check the shared features between subject and verb was emphasized by the strategy in lexical decision tasks. The strategy of this task requires the system to verify whether targets are words or nonwords by checking the prime (Becker, 1980; Lorch et al., 1986; McNamara, 2005; Yap et al., 2013), therefore, the grammatical effect was stronger in Experiment 1 than in Experiment 2. Moreover, at a later stage of late anterior negativity and late P600, we found an interaction involving the experimental task. However, the effect was not significant so we could not hypothesize any flexibility in these time windows. Thus, further studies are needed to confirm the significance of this effect.

8.5 Conclusions

The results of the present study confirm our previous findings that abstract and associative representations are accessed during the processing of subject-verb agreement in spoken language. N100 that reflect the top-down processing by associative representations was observed here. We also replicate those of previous studies in agreement processing, as we found N400, late anterior negativity and P600. We found that associative representations were used flexibly and automatically to constrain phonological processing of verbal inflection. Flexibility was observed in N400 time window in which Experiment 1 with lexical decision task seemed to rely more on abstract representations compared to Experiment 2. As evidence, double violation effect that increases negative amplitude more than single violation with person feature, was only found in Experiment 1. Flexibility is mainly observed during the accessing of abstract representations, as this process depends on the level of attention and task demand. These results therefore extend the importance of flexibility in language to the processing of subject-verb agreement in spoken language. To sum up, these findings shed light on the subject-verb agreement processing by showing that automaticity and flexibility are involved in using associative representations and that flexibility is involved in accessing abstract representations.

Chapter 9

Study 3: MEG study to investigate prediction in agreement processing

In our previous experiments, we found that both associative and abstract representations are accessed during agreement processing. Our findings also showed that associative representations affect the early stage of verb processing at the phonological level. After recognizing the pronominal subject, the system accesses the associative representations between this subject and its inflections, which constrains the early processing of the verb. The top-down effect at the early stage before the recognition of the verbal inflection shows that a predictive mechanism intervenes during agreement processing. In Experiment 3, we thus sought to identify this mechanism by localizing the brain areas involved. To this end, we used the same stimuli as in the previous experiment. However, we used the MEG technique instead of EEG, since it has better spatial resolution.

9.1 Predictions

1. As we used the same stimuli as in the previous experiment, we expected to find an influence of associative frequency and grammaticality over the same time windows as those in Experiment 1, since the same task was used in this new experiment. As in previous experiments, we time-locked the data to the onset of the verb and focused on four time windows. We thus expected the following pattern: 1) stronger N100 for low associative frequency than for high associative frequency during the early time window around 150 and 210 ms 2) a grammaticality effect in which double violation would increase brain activation in comparison with congruent condition, between 350 and 650 ms after the onset of the verb, when verbal inflection starts to be recognized. In line with studies 1 and 2, we expected to see differences in brain activation related to grammatical processing between double and single violations, as a result of accessing abstract representations; 3) around 700 and 900 ms, we expected to observe a grammaticality effect, in which incongruent conditions would elicit a stronger activation than the congruent condition, and double violation would elicit a stronger activation as than single violation; 4) around 970 and 1170

ms, we expected to observe a grammaticality effect related to the reanalysis process, in which incongruent conditions (particularly double violation) would increase brain activation around verb offset in comparison with congruent condition. We also expected to observe an effect of associative frequency, where low associative frequency would increase neural activation compared with high associative frequency. This expectation was based on Ettinger et al. (2014), according to whom low associative frequency reduces neural activity around the onset of the verb, as a result of less commitment in generating prediction and increases that activity around the offset of the verb.

2. In terms of functional organization of the brain, we investigated the aforementioned time windows over several regions of interest (ROIs) in the left hemisphere. Experiments 1 and 2 showed top-down processing in which associative representations constraint the phonological processing. We thus expected to find an associative frequency effect in brain areas related to auditory processing. Previous studies investigating prediction in spoken word processing also showed activation over these areas: the primary auditory cortex (BA 41), the transverse temporal gyrus (BA 41, BA 42) and the superior temporal gyrus (BA 38, BA 22, BA 41, BA 42). We expected to observe low associative frequency enhancing the activation of these ROIs around the onset of the verb, since activation in ROIs results from the prediction of verbal inflection from associative representations. A grammaticality effect was expected in areas related to grammatical processing, such as the inferior frontal gyrus (BA44, BA 45), the middle temporal gyrus (BA 21, BA 37), and Wernicke's area (BA 22, BA 39, BA 40), since they are connected to high-level processing related to abstract representations. To conclude, we expected to observe greater brain activation over these areas after morphosyntactic violations, particularly for the double violation as compared to single violations, which would confirm the use of separate abstract features.

9.2 Method

9.2.1 Participants

Thirteen French native speakers (9 female) aged between 19 and 51 years old (mean = 29, SD=9.93) participated in this experiment. The use of French in their daily life was quite varied because this experiment was conducted in New York University (NYU), Abu Dhabi[1]. Most

[1] This experiment was done in collaboration with Prof Alec Marantz from NYU, Abu Dhabi.

participants therefore used other languages in their daily life, such as English or German. As in Experiments 1 and 2, all participants were right-handed, as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971) and they had normal or corrected to normal vision. All declared no self-reported hearing, language or neurological impairments. Participants received monetary compensation for their participation (30-AED[2] remuneration per 30 minutes). Prior to the experiment, they read and signed an informed consent form. The institutional review board of NYU Abu Dhabi approved this experiment.

9.2.2 Materials

The stimuli were identical as those in Experiments 1 and 2 but there were differences in the procedure.

9.2.3 Procedure

As in Experiments 1 and 2, there was a practice block before the main experiment started, in order to familiarize the participants with the lexical decision task. Instead of the no-go lexical decision task, participants did a classical lexical decision task in the MEG experiment, during which they were asked to respond as quickly and accurately as possible, for decisions on words and non-words. By pushing one of two buttons (blue or yellow button) on a response box, participants indicated whether the target was a French word or not. The response buttons were counterbalanced across all participants. Moreover, contrary to the two ERP experiments, 12 blocks provided experimental trials and each block lasted around 5 minutes, so that participants would not get too tired or lose their focus from lying down in the machine. After each block, participants could take a short break before continuing to the next block. The total duration of the experiment was therefore around an hour. Stimuli were displayed using the Presentation software (Neurobehavioral systems, CA, USA). They were presented on a grey screen (150,150,150) and a black fixation cross was displayed at the center of the screen, at the end of the target word. Every trial consisted of a prime, which was either a subject or an article, followed by a target word which was either a verb, a noun or a pseudoword. The fixation cross was displayed after the offset of the target word and it remained on the screen until the participant responded. If he/she did not respond,

[2] AED is an abbreviation for United Arab Emirate DIrham

the fixation cross remained for 1500 ms before the inter-trial interval, which was randomized between 500 to 100 ms. The visual presentation of the experimental materials (i.e., instruction and fixation cross) was projected on a screen above the participants' heads, while the auditory stimuli were presented through earphones over the participants' ears.

9.2.4 MEG data acquisition

Prior to the experiment, the optical FastSCAN (Polhemus) scanner was used to digitize the participants' head shapes and record their fiducial points (nasion, left and right tragus). Participants were then taken into a magnetically shielded room, where they were asked to lie down in a supine position with their head in a SQUID helmet. Before this, five marker coils were placed on the participants' heads and remained there until the end of the experiment. At the beginning and end of the experiment, the marker coils were calibrated and recorded according to the position of the MEG sensors. The information from these coils was then used for the head co-registration process and source localization. MEG data were recorded using a 208-channel axial gradiometer system (Kanazawa Institute of Technology, Kanazawa, Japan). The sampling rate was 1000 Hz and it was applied online with a high-pass filter of 0.1 Hz and a low-pass filter of 200 Hz.

9.2.5 MEG data pre-processing

The first step was to remove noise from the MEG data using the Continuously Adjusted Least-Square (Adachi et al., 2001) implemented in MEG160 software (Yokohawa Electric Corporation and Eagle Technology Corporation, Tokyo, Japan). The noise-reduced MEG data, the digitized head shape and sensor location data were all imported into MNE-Python and converted to FIFF format. MNE-Python (Gramfort et al., 2014) was also used for the following steps of the pre-processing procedure. For instance, we applied a high-pass filter at 0.1 Hz and a low-pass filter at 40 Hz. An independent component analysis (ICA) was performed to remove artifacts, including eye-blinks, movement activities and heartbeats. The data were then segmented into epochs starting from 50 ms before the onset of the verb and up to 1200 ms after verb onset. No baseline correction was applied. Epoch was automatically removed when it contained a signal exceeding 2000 femto-tesla peak to peak threshold. Each epoch was inspected visually and noisy data were rejected. The remaining epochs were averaged to create an evoked response per experimental condition and participant. The average number of accepted epochs for each condition was equivalent across the experimental conditions (for high associative frequency, congruent condition, 28.4; number and person violation, 30.2; high number violation, 30.2; and person, 30.5; for low associative frequency, congruent condition, 30.3; number and person violation, 30; number violation 30.5; and person violation, 30.5). With Eelbrain (https://github.com/christianbrodbeck/eelbrain), an open-source Python package, the forward solution (i.e., calculating the estimation of field distribution from a head model), along with the evoked response, was used to compute an inverse solution with "fixed" orientation (i.e., the polarity of the source estimation was signed) on the MRI coordinate system. The next step was co-registration, which was achieved by scaling and fitting the average brain surface from FreeSurfer (Fischl, 2012) to the participants' head shapes, aligning the fiducial points and manually adjusting them to minimize gaps. For each participant, a source space consisting of 2562 electrical source points per hemisphere was generated. The neural activity was computed at each source for the forward solution with the Boundary Element Model (BEM) method. The latter is generally used to estimate the magnetic field in response to a current dipole for each source of each MEG sensor.

9.3 Statistical analyses

We first performed the MEG statistical analysis over the whole brain area for exploration purposes and then in the ROIs (regions of interest).

9.3.1 Whole-brain analysis

We performed a cluster-based permutation test (Maris & Oostenveld, 2007) from the onset of the verb until 1200 ms after, over the left and right Brodmann areas, using the PALS B12 map (Van Essen, 2005) with 10,000 random permutations. With such a method, the experimental conditions of each participant were randomly permuted. The parameter for the permutation was as follows: *p*-value threshold for each cluster to be considered significantly different was 0.05 and the minimum duration of activation was 10 ms. We reported only those clusters that met these criteria and showed a significant effect. If the cluster fulfilled these requirements, we then performed the statistical analysis in the form of a pairwise *t*-test for associative frequency and grammaticality.

9.3.2 fROI analysis

We performed a temporal analysis in which we did not consider the spatial factor or the region as it had already been defined. Basically, the analysis here is similar to the previous spatiotemporal analysis wherein both spatial and temporal data were used for the whole brain analysis. Thus, the permutation parameter was the same as the spatiotemporal analysis: *p*-value threshold for each cluster was 0.05 and the minimum duration was 10 ms. Clusters that did not meet this requirement were removed. The permutation was done to compare the null hypothesis with the cluster data. There were 10,000 random permutations, which means they were performed randomly for each cluster, each participant and each condition. We defined the ROIs based on previous studies (e.g., Gagnepain et al., 2012; Ettinger et al., 2014; Gaston & Marantz, 2017) which had indicated several ROIs related to spoken language processing, such as TTG, MTG, and STG. The previous spatiotemporal analysis had confirmed that several areas related to the ROIs were activated either in the right or left hemisphere. We then performed a temporal analysis over the ROIs in the left hemisphere of the PALS-B12 surface. Based on the root mean square (RMS) from evoked responses to each condition in each ROI, time windows of interest were also determined. We observed that there were peaks on RMS that were time windows similar to those used in the data analyses of our EEG studies. They were: 150-210 ms, 350-650 ms, 700-900 ms and 970-1170 ms. Statistical analysis using a cluster-based permutation test (Maris and Oostenveld, 2007) was performed on these time windows using Eelbrain.

9.4 Results

9.4.1 Behavioral results

As a reminder about Experiment 3, participants were asked to perform classical lexical decision tasks on targets, during which they had to respond by pressing a button when recognizing a word and another button for a pseudoword. This indicated their behavioral response to critical stimuli. The mean accuracy of the 13 participants' behavioral data was 90%, and their mean reaction time (RT) for correct responses was 1118 ms after the onset of the verb. Moreover, we conducted a repeated measures ANOVA on the correct RT to critical stimuli (see Table 5 for RTs in each experimental condition). A main effect of grammaticality was found on RT ($F(3,36)=22.83$, $p<.001$): reaction times to the congruent condition were faster than those for the number violation ($p<.001$), the number and person violation ($p< .001$) and the person violation

(p<.001). There was also a significant interaction between grammaticality and associative frequency: $F(3,36)=7.26$, p<.001. A post-hoc Tukey *t*-test showed response in the congruent condition was faster in low associative frequency than in high associative frequency (p<.05).

Table 5

Mean reaction times for correct responses to critical stimuli

Associative frequency	Grammaticality	Mean RT
High	Congruent	1076 ms
	Number violation	1120 ms
	Person violation	1148 ms
	Number and person violation	1134 ms
Low	Congruent	1013 ms
	Number violation	1169 ms
	Person violation	1132 ms
	Number and person violation	1149 ms

9.4.2 MEG results

9.4.2.1 Results from the whole-brain analysis

A cluster-based permutation test was performed over all brain areas, from both left and right hemispheres, for exploratory purposes. We reported only those clusters with significant effects (Table 6).

9.4.2.1.1 Left hemisphere

Over the left hemisphere, we found significant clusters over premotor area BA6, around 78 to 488 ms (p< .05) with a main effect of associative frequency (p<.01), in which low associative frequency elicited stronger neural activity than high associative frequency. Another cluster was found over BA 41, also known as the primary auditory cortex (PAC). The duration of the cluster was from 29 to 265 ms (p= .05); in this cluster, we also observed a main effect of associative frequency, where low associative frequency enhanced neural activation once again (p< .05). Other significant clusters were found in BA 42, which is part of the transverse temporal gyrus, in two different time windows: the first cluster was found around 0 to 324 ms (p<.05), when low associative frequency elicited stronger activation than high associative frequency (*p*<.01). The second significant cluster appeared in a late time window occurring between 840 and 1136 ms (*p*<.05). A main effect of associative frequency (*p*<.01) was observed, but there was a reverse pattern of activation where high associative frequency elicited stronger activation than low associative frequency. We also observed cluster activation over the anterior part of the temporal lobe, BA 38, during a time window ranging between 222 and 416 ms (*p*<.05). Again, a main effect of associative frequency was observed (*p*<.01), in which low associative frequency elicited stronger activation than high associative frequency. The same pattern was also found over the anterior cingulate cortex (ACC), BA 24, and occurred between 505 and 947 ms (*p*<.01).

9.4.2.1.2 Right hemisphere

We also found significant clusters with a main effect of associative frequency over the right hemisphere, one of which occurred in sensory-motor related area BA 2. Its duration ranged from 500 to 783 ms (*p*<.05) and we observed that low associative frequency elicited stronger activation than high associative frequency. Another significant cluster was found in BA 5, located around the parietal lobe. Its duration ranged from 215 to 837 ms (*p*<.01) and it was also associated with a main effect of associative frequency (*p*<.01). Low associative frequency elicited stronger activation than high associative frequency. In BA 6, we found two clusters. The first cluster occurred between 51 and 413 ms (*p*< .05), and once again, low associative frequency elicited stronger activation than high associative frequency (*p*<.001). The second cluster was observed between 636 and 1200 ms (*p*< .05) with a main effect of associative frequency (*p*< .001). However, unlike what was observed in the previous time windows, high associative frequency elicited stronger activation than low associative frequency. A significant cluster was also observed over BA 7, in the somatosensory area, in a late time window ranging from 938 to 1200 ms (*p*< .05). In this position, high associative frequency elicited stronger activation than low associative frequency condition (*p*<.001).

Two other significant clusters were observed in the right hemisphere over BA 41, the primary auditory cortex. The first significant cluster was found between 147 and 399 ms (*p*<.05) and a main effect of associative frequency was observed (*p*<.001), with stronger activation for low associative frequency than high associative frequency. Surprisingly, the second cluster in the primary auditory cortex occurred during a time window between 197 and 427 ms (*p*<.01), where we observed a main effect of grammaticality. The activation of this area was stronger for a single violation involving a number feature than for the congruent condition (p<.01) and a double violation involving number and person features (p<.05). Another single violation involving a person feature also elicited stronger activation than the congruent condition (p<.05). Two other significant clusters were observed in BA 42: the first one was found in the early time window from 27 to 558 ms (p< .001) and high associative frequency elicited stronger activation than low associative frequency (p< .001); the other one was in a later time window between 563 to 920 ms (p< .05) and low associative frequency elicited stronger activation than high associative frequency (p<.001). Another significant cluster was observed in BA 46, located in the middle frontal gyrus area, between 191 and 480 ms (p< .05). There was a main effect of associative frequency (p<.05), with low associative frequency eliciting stronger activation than high associative frequency.

The activation of BA 31 in the medial parietal cortex (MPC) occurred between 682 to 1200 ms (p< .05) and was stronger for low associative frequency than for high associative frequency (p<.01). Two other significant clusters were found over BA 24, in the anterior cingulate cortex (ACC): the first one was found around 462 to 799 ms (p< .05), where low associative frequency elicited stronger activation than high associative frequency (p< .001); the second one had the same pattern and occurred between 813 and 1106 ms (p< .05). Taken together, these results suggest low sensitivity towards grammaticality effect and a major effect of accessing associative representations. However, there were only 13 participants in this experiment, which may explain why no grammaticality effect was evidenced. This effect was observed in the behavioral results and our previous EEG studies also indicated the accessing of abstract representations. The results of this whole-brain analysis are summarized in Table 6 and confirm the findings of the previous EEG studies, which showed that associative representations are accessed during subject-verb agreement in spoken language.

Table 6

Significant clusters found in the whole-brain analysis from 0 to 1200 ms after verb onset

Left Hemisphere **BA 4** 468-781 ms (*p*< .05) Associative frequency ns Grammaticality ns Associative frequency x grammaticality ns **BA 6** 78-488 ms (*p*<.05) Associative frequency, high < low (*p*< .0)1 Grammaticality ns Associative frequency x grammaticality ns **BA 3** 33-504 (p<.05) Associative frequency ns Grammaticality ns Associative frequency x grammaticality ns 797 -1159 ms (*p*<.05) Associative frequency ns Grammaticality ns Associative frequency x grammaticality ns **BA 24** 505-947 ms (*p*<.01) Associative frequency, high < low (*p*< .01) Grammaticality ns Associative frequency x grammaticality ns	**BA 38** 222-416 ms (*p*< .05) Associative frequency, high < low (*p*< .01) Grammaticality ns Associative frequency x grammaticality ns **BA 41** 29-265 ms (*p*=.05) Associative frequency, high < low (*p*< .05) Grammaticality ns Associative frequency x grammaticality ns **BA 42** 0-324 ms (p<.05) Associative frequency, high < low (*p*< .01) Grammaticality ns Associative frequency x grammaticality ns 840-1136 ms (p<.05) Associative frequency, low < high (*p*< .01) Grammaticality ns Associative frequency x grammaticality ns
Right Hemisphere **BA 2** 500-783 ms (*p*<.05) Associative frequency, high < low (*p*<.001) Grammaticality ns Associative frequency x grammaticality ns **BA 5** 215-837 ms (*p*< .01) Associative frequency, high < low (*p*<.01) Grammaticality ns Associative frequency x grammaticality ns **BA 6** 51-413 ms (p< .05) Associative frequency, high < low (p<.001) Grammaticality ns Associative frequency x grammaticality ns 636-1200 ms (*p*<.05) Associative frequency, low<high (*p*< .001) Grammaticality ns Associative frequency x grammaticality ns **BA 7** 938-1200 ms (*p* <.05) Associative frequency, low<high(*p*< .001) Grammaticality ns Associative frequency x grammaticality ns **BA 24** 462-799 ms (*p*< .05) Associative frequency, high < low (*p*< .001) Grammaticality ns Associative frequency x grammaticality ns 813-1106 ms (*p*< .05) Associative frequency, high < low (*p*< .05) Grammaticality ns Associative frequency x grammaticality ns	**BA 31** 682-1200 (*p*<.05) Associative frequency, high<low, (*p*<.01) Grammaticality ns Associative frequency x grammaticality ns **BA 41** 197-427 (*p*<.01) Associative frequency ns Grammaticality Congruent –number *p*<.01 Congruent – person *p*<.05 Number – number person *p*<.05 Associative frequency x grammaticality ns 147-399 (*p*<.05) Associative frequency, high < low (*p*<.001) Grammaticality ns Associative frequency x grammaticality ns **BA 42** 24-558 (*p*<.001) Associative frequency, low<high (*p*<.001) Grammaticality ns Associative frequency x grammaticality ns 563-920 (*p*<.05) Associative frequency, high < low (*p*<.001) Grammaticality ns Associative frequency x grammaticality ns **BA 44** 644-1200 (*p*<.01) Associative frequency ns Grammaticality ns Associative frequency x grammaticality ns **BA 46** 191-480 (*p*<.05) Associative frequency, high<low (*p*<.05) Grammaticality ns Associative frequency x grammaticality ns

9.4.2.2 Results from the fROIs analysis

Based on our hypothesis, we conducted a temporal analysis over the left hemisphere of several ROIs for four time windows after the onset of the verb: 150-210 ms, 350-650 ms, 700-900 ms, and 970-1170 ms (Table 7). These time windows were the same as in our previous EEG experiments (see Chapters 6 and 7). In the first one (150-210 ms, see Figure 29.a), we found a significant cluster over the primary auditory cortex (PAC), between 150 and 180 ms (p<.05). A pairwise t-test revealed a main effect of associative frequency (p<.05), with low associative frequency eliciting stronger activation than high associative frequency. A similar associative frequency effect was observed in the inferior frontal gyrus (IFG), with a longer cluster duration between 150 and 210 ms (p<.001). Contrary to the pattern found in the primary auditory cortex, the cortical activation in the IFG was stronger for high associative frequency than for low associative frequency (p<.01).

In the second time window between 350 and 650 ms (Figure 29.b), we observed a significant cluster over Wernicke's area that lasted from 385 to 425 ms (p<.05). We found a main effect of associative frequency (p<.05), with low associative frequency eliciting stronger activation than high associative frequency. Two other clusters were found in the IFG: the first one lasted from 350 to 405 ms (p<.05), the second one from 415 to 455 ms (p<.05). In these two clusters, a main effect of associative frequency was observed (p<.05), with low associative frequency eliciting stronger activation than high associative frequency.

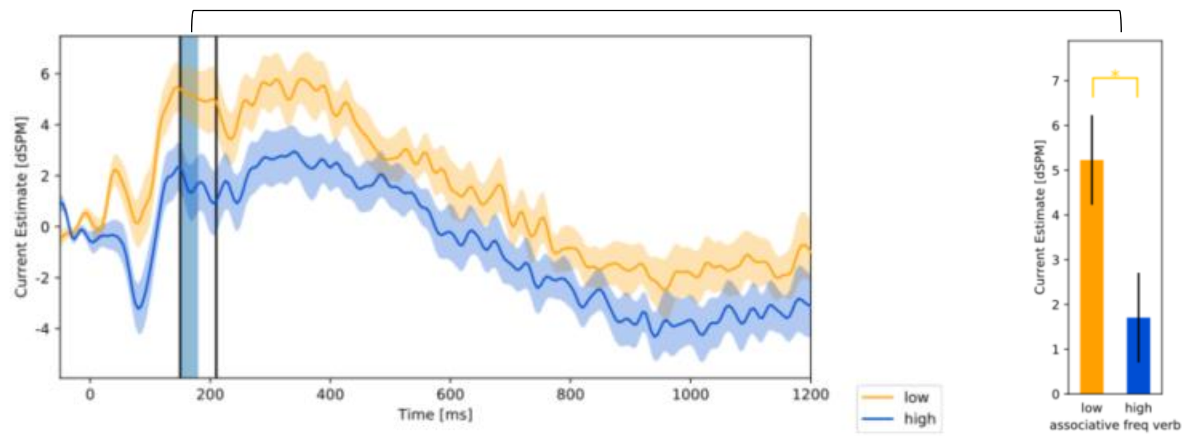
In the third time window between 700 and 900 ms (Figure 29.c), a significant cluster was found in IFG, which lasted from 840 to 885 ms (p<.05). A main effect of associative frequency was observed (p<.05) with a similar pattern as that of the first time window. The last time window we observed was between 970 and 1170 ms (Figure 29.d). We found two clusters in the IFG: the first cluster in the IFG lasted from 970 to 1075 ms (p<.01), and low associative frequency elicited stronger activation than high associative frequency (p<.05); the second IFG cluster occurred between 1085 and 1150 ms (p<.05), and the same associative frequency pattern (p<.01) was observed. We also observed two clusters in the transverse temporal gyrus (TTG): the first cluster occurred between 970 and 1085 ms (p<.001), with high associative frequency enhancing cortical activation (p<.001); the second cluster occurred between 1100 and 1135 ms (p<.05), with the same associative frequency pattern (p<.01).

Figure 29

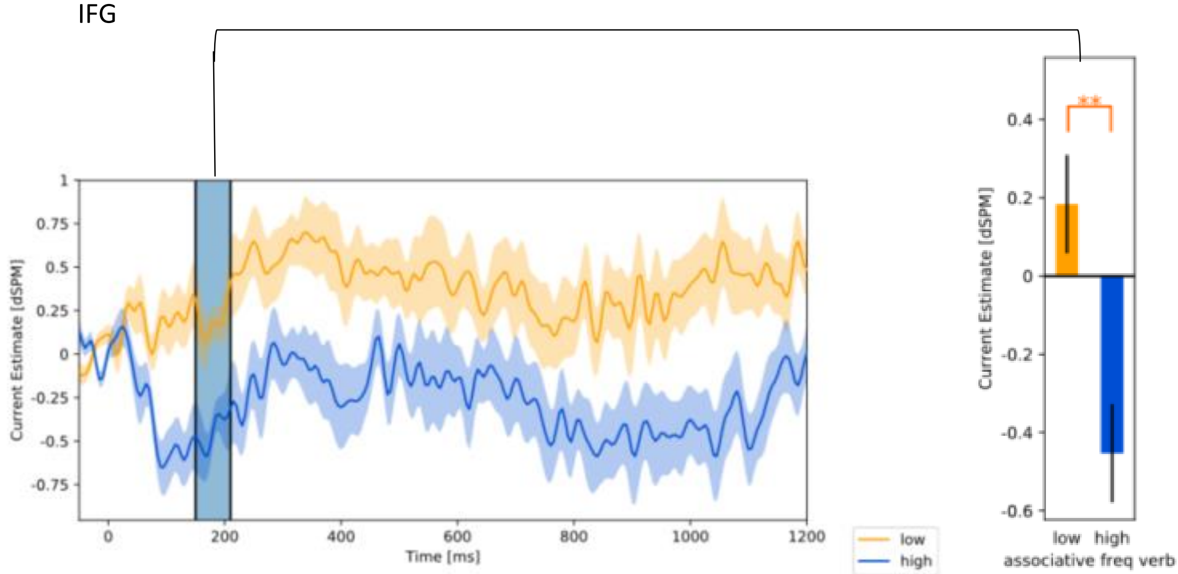
Significant clusters that were found in the ROIs

a. Time window between 150 and 210 ms

PAC

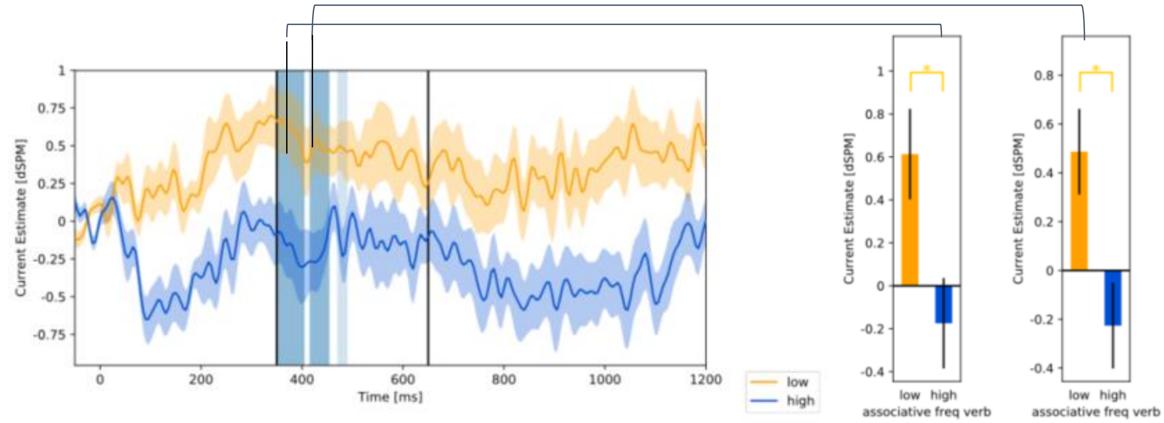


IFG

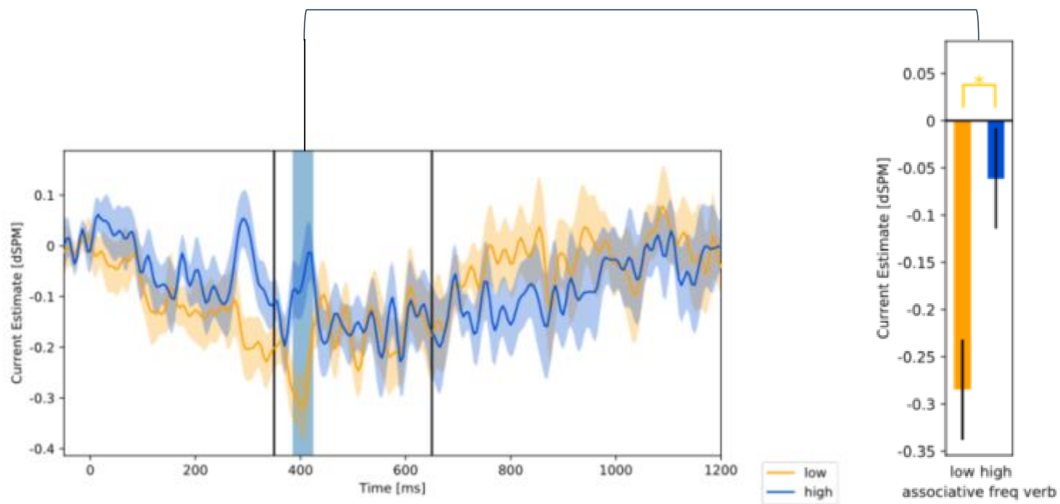


b. Time window between 350 and 650 ms

IFG

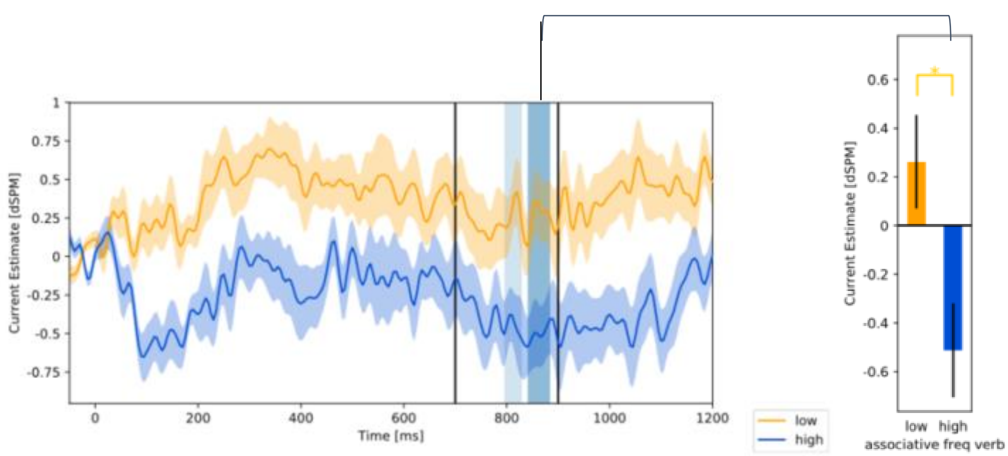


Wernicke's area



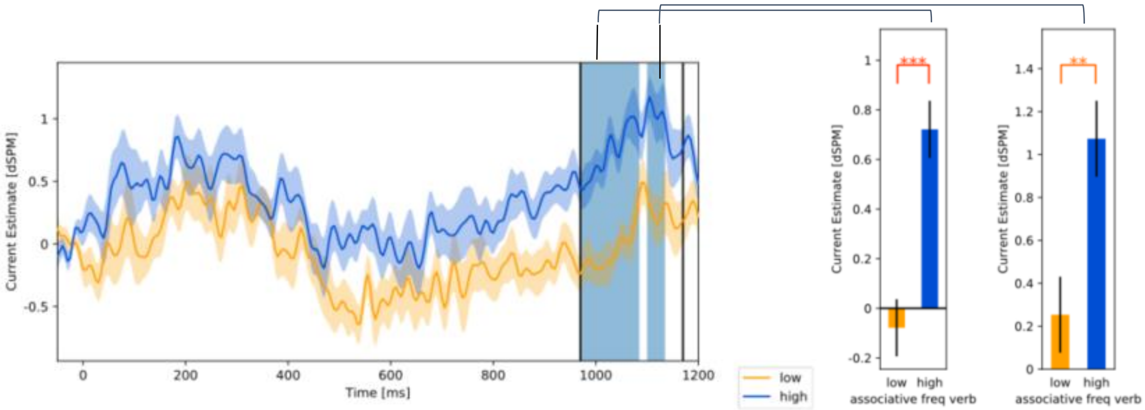
c. Time window between 700 and 900 ms

IFG



d. Time window between 970 and 1170 ms

TTG



Note. **a.)** The first row shows a significant cluster in the PAC, 150-180 ms (p<.05), with a main effect of associative frequency, p<.05. The second row shows a significant cluster in the IFG, 150-210 ms (p<.001), with a main effect of associative frequency, p<.001. **b.)** The first row shows two significant clusters in the IFG: 1) 350-405 ms (p<.05), 2) 415-455 ms (p<.05), both with a main effect of associative frequency, p<.05; the second row shows a significant cluster in Wernicke's area, 358-425 ms (p<.05), with a main effect of associative frequency, p<.05. **c.**) A significant cluster in the IFG, 840-885 ms (p<.05), with a main effect of associative frequency, p<.05. **d.**) Two significant clusters in the TTG: 1) 970-1085 ms (p<.001) with a main effect of associative frequency, p<.001, 2) 1100-1135 ms (p<.05) with a main effect of associative frequency (p<.01).

Table 7

Significant clusters found from the fROIs analysis from 0 to 1200 ms after verb onset

PAC	TTG	MTG
Time window 150-210 ms 150-180 ms ($p<.05$) Associative frequency High<low $p<.05$ Time window 350-650 ms ns Time window 700-900 ms ns Time window 970-1170 ms ns	Time window 150-210 ms ns Time window 350-650 ms ns Time window 700-900 ms ns Time window 970-1085 ms 970-1075 ms ($p<.001$) Associative frequency Low<high $p<.001$ 1100-1135 ms ($p<.05$) Associative frequency Low<high $p<.01$	Time window 150-210 ms ns Time window 350-650 ms ns Time window 700-900 ms ns Time window 970-1170 ms ns
STG	IFG	Wernicke's area
Time window 150-210 ms ns Time window 350-650 ms ns Time window 700-900 ms ns Time window 970-1170 ms ns	Time window 150-210 ms 150-210 ms ($p<.001$) Associative frequency Low<high $p<.001$ Time window 350-650 ms 350-405 ms ($p<.05$) Associative frequency High< low $p<.05$ 415-455 ms ($p<.05$) Associative frequency High< low $p<.05$ Time window 700-900 ms 840-885 ms ($p<.05$) Associative frequency High<low $p<.05$ Time window 970-1170 ms 970-1075 ms ($p<.01$) Associative frequency effect High< low $p<.05$ 1085-1150 ($p<.05$) Associative frequency effect High< low $p<.01$	Time window 150-210 ms ns Time window 350-650 ms 358-425 ms ($p<.05$) Associative frequency High< low $p<.05$ Time window 700-900 ms ns Time window 970-1170 ms ns

9.5 Discussion

The purpose of this experiment was to investigate the prediction mechanism that intervenes during the computation of subject-verb agreement. We thus conducted an MEG experiment where participants were asked to perform an LDT. Unlike the previous experiments, participants had to respond for both words and nonwords. We therefore obtained behavioral results for the critical stimuli which showed grammaticality effect in which congruent condition was respond faster than the other incongruent conditions.

Concerning the MEG results, we conducted two analyses: the first over the whole brain and the second over the left hemisphere of the ROIs. Unexpectedly, these results did not show high sensitivity towards abstract representations and a sensitivity to morphosyntactic violations was rarely observed, except in the right hemisphere over BA 41. Nonetheless, the data seemed to be sensitive to associative representations, as we mainly observed an associative frequency effect, notably in the PAC and the IFG. We expected to see neural activation differences at the onset and offset of the verb, elicited by associative frequency on the ROIs as a result of prediction. Importantly, Ettinger et al. (2014) examined phoneme prediction in a word, so they used surprisal and entropy in their study to measure the probability of the upcoming phonemes. In our study, we observed prediction mechanisms in subject-verb agreement and we used associative frequency. Ettinger et al. (2014) tried to measure the probability of all possible words that could follow a phoneme using an inverse log: for associative frequency, we used a log to measure the probable correct inflection following a subject pronoun. Ettinger et al. (2014) showed that high entropy decreased neural activity at the onset of the word as a result of the delay in phoneme prediction, but it increased neural activity at the offset of the word. High entropy indicates high uncertainty due to the possibility of many options following the heard phoneme. If we translate entropy into associative frequency, high entropy is akin to low associative frequency. Therefore, we expected to observe high associative frequency increasing neural activation at word onset and decreasing it at word offset. However, the pattern that we found was different in the sense that in the activation that we observed was mostly reduced by high associative frequency. To have better understanding on the effect that we observed in the initial ROIs and activation over the other brain areas that we found through whole-brain analysis, and their implication to subject-verb processing, we discuss them in the following.

9.5.1 Abstract representations in temporal lobe

As mentioned earlier, we observed that it is the primary auditory cortex (PAC) that was related to the accessing abstract representations around the onset of the verb inflection. This was unexpected since previous studies had suggested that the PAC was sensitive to phonological processing (Dewitt & Rauschecker, 2012; Fiez et al., 1995; Ryskin et al., 2020; Whalen et al., 2006). However, a growing number of studies have shown that the temporal lobe is also sensitive to syntactic processing, particularly the anterior temporal lobe (ATL) (Brennan et al., 2012; Dronkers et al., 2004; Henderson et al., 2016; Pylkkänen, 2019; Rogalsky & Hickok, 2009), which is part of the STG. While most of those studies mentioned the left anterior temporal lobe, we found a grammaticality effect over the right hemisphere; perhaps this might be because right hemisphere is more sensitive to integration than prediction (Federmeier et al., 2008; Wlotko & Federmeier, 2007). Note that the time window of the grammaticality effect that we found was around the onset of the inflection, which means that the system has already recognized /a/ or /ɔ̃/ sounds and detect the error. Furthermore, the result also showed that the system has detect the morphosyntactic error as single violation involving number feature elicited stronger activation compared to other conditions. That said, our findings seemed to support the notion that right hemisphere is sensitive to integration process (Federmeier et al., 2008; Wlotko & Federmeier, 2007). Nevertheless, further research is needed to confirm these observations.

9.5.2 Associative representations and prediction

Prediction is a top-down process where the system uses information from higher-level representations to generate an expectation about the upcoming input. Studies in language prediction have shown that the way prediction affects brain activation depends on how predictable a word is. Word predictability is usually measured by cloze probability or surprisal; in our case, we used associative frequency to measure the predictability of an inflection based on a pronoun prime, by measuring their co-occurrence in the corpus. Prediction is now widely accepted to be a mechanism that intervenes in language comprehension (Kuperberg & Jaeger, 2016; Van Petten & Luka, 2012). It was therefore we expect to observe the associative frequency effect over brain areas related to phonological processing. As we have seen in previous EEG studies, we expect to observe associative frequency effect in verb processing in area related to spoken language comprehension.

Concerning associative representations, we found stronger activation for low associative frequency over the PAC. This result confirmed our previous result from EEG experiment where we found N100, in which there was stronger amplitude for low associative frequency than high associative frequency. This result indicates that predictive mechanisms are used in the PAC, and that they involve top-down processing from associative representations constraining the phonological processing of the verb. In general, top-down processing during spoken language processing is not surprising, as argued by Samuel (1981, 1997), who investigated phoneme restoration: lexical representations helped the recognition of phonemes that were replaced by another sound during spoken word processing. As word recognition is guided by lexical knowledge, the recognition of a verb inflection during subject-verb agreement is constrained by the associative information between subject and verb inflection that is obtained after hearing the subject pronoun. However, unlike the initial prediction, our results for the left PAC showed weaker neural activation for high associative frequency in the early time window, and this associative frequency effect was absent at the offset of the verb. Perhaps this absent was because PAC area was more sensitive to prediction and around the offset, the system does not need to generate expectation because it already received the verbal input. Nonetheless, associative frequency effect around the offset was found in TTG.

The fROI analysis in TTG did not reveal any significant cluster in the early time window. Yet, the whole-brain analysis showed two significant clusters in BA 42 which was around the onset and the offset of the verb. BA 42 is part of the transverse temporal gyrus. In the early time window we observed low associative frequency increased the neural activation, while at the offset we observed a reverse pattern wherein high associative frequency increased the neural pattern. Similar pattern for the late time window was also observed in fROI analysis over TTG. The result around the onset seemed to confirmed the results from EEG experiments, in the sense there was pre-activation of verbal inflection based on associative frequency information. On the other hand, the result around the offset might reflect the result of morphosyntactic error detection because around this time window, the system could verify the shared features between subject and verb. Thus, the activity around offset might also reflect a repairing analysis and perhaps associative frequency constrain this process. However, no firm conclusions about this can be drawn since there was no grammaticality effect in the left TTG. Additionally, this pattern was different from Ettinger et al. (2014) perhaps this is due to the fact that they investigated phoneme prediction within a word, while our study focused on the morphosyntactic information that binds a subject pronoun to a verb agreement.

Another temporal lobe area where we found an associative frequency effect was the left BA 38, which is part of the STG. We found that low associative frequency enhanced neural activation around the onset of inflection. The STG is also related to phonological processing (Hickok & Poeppel, 2007; Liebenthal et al., 2005; Poeppel & Hickok, 2004; Wessinger et al., 2001). Top-down processing in the STG was observed in a study by Dehaene-Lambertz et al. (2005), where participants were asked to perform a discrimination task on syntactic sine-wave analogs of speech: the acoustic stimuli could be perceived as either speech or non-speech, depending on the frequency of the sine-wave. Their results suggested that when the sine-wave was recognized as speech, there was a top-down effect of phonological representations on the left hemisphere. STG was activated by phonetic changes in speech mode stimuli. Furthermore, other studies in spoken word prediction (Ettinger et al., 2014; Gagnepain et al., 2012; Gaston & Marantz, 2017) also found activation over this area. Our findings thus extend the area where top-down processing could occur during the processing of grammatical agreement in spoken language. An associative frequency effect was also found in Wernicke's area around the onset of the inflection, with low associative frequency enhancing neural activation. Regarding the time window during which this occurs, it was around the onset of the inflection and it might indicate that the system has more commitment in generating expectation of verbal inflection for low associative frequency condition thus it increased the neural activation. Wernicke's area is initially one of the areas where one may expect to observe grammaticality effect in addition to the IFG, but the grammaticality effect was absent in both areas. Yet, in IFG we still observed the associative representations effect, thus in the following sub section we discuss how associative representations could affect syntactic processing in IFG.

In addition to left hemisphere, we also found activation over the right hemisphere, specifically over BA 42, where we observed an opposite pattern. However, it matched our expectation that high associative frequency would enhance neural activation in the early time window and reduce it around the offset of the verb. There might have been a stronger excitation of prediction from associative representations in the right hemisphere compared to the left hemisphere. This excitation resulted in higher neural activation from associative representations and higher commitment in prediction compared to low associative frequency, as in Ettinger et al. (2014). When perceiving the input stimuli, the system was guided by associative frequency information to activate the possible verbal inflection. High associative frequency thus caused the system to work more. Around the offset of the inflection, the system found more possible verbal inflection as it had more information about the input. It thus generated more possible verbal inflection for low associative frequency, which was reflected through a reduced activation of high associative frequency around word offset. Furthermore, previous studies have shown that the temporal lobes are related to language prediction, which we discuss in the following sub-section.

9.5.3 IFG and syntactic processing

The IFG is an area related to syntactic processing (Ben-Shachar et al., 2003; Embick et al., 2000; Friederici et al., 2003; Friederici, Fiebach, et al., 2006; Grodzinsky, 2000; Grodzinsky & Friederici, 2006; Matchin & Hickok, 2020) . We thus expected to observe a grammaticality effect around the second time window, when the onset of the inflection was detected. However, we only observed an associative frequency effect, with high associative frequency increasing neural activation in the early time window and decreasing it around the offset of the verb. This activation pattern was similar to the pattern found by Ettinger et al. (2014), although they did not investigate the IFG because they focused on an area related to spoken word recognition. This effect may have been observed because the IFG is sensitive to prediction at syntactic levels (Dikker & Pylkkänen, 2013; Obleser & Kotz, 2010; Rothermich & Kotz, 2013; Strijkers et al., 2019; Willems et al., 2016). Indeed, a study by Dikker and Pylkkänen (2013) using visual paradigms found an increase in neural activity in the left IFG for pictures that were predictive of specific words. In relation to our result here, the system might therefore have been working at generating prediction for a verb preceded by a subject prime that had high associative frequency, which resulted in stronger neural activity. We observed that high associative frequency reduced neural activity at offset perhaps because the system did not need to generate predictions anymore and because the system recognized that the input matched the expectation. Furthermore, in relation to syntactic processing, we suggested that associative representations might constraint the grammatical processing, since it informs the system about the possible verb inflections. This information might then have been used to guide the syntactic feature checking between subject and verb inflection. However, we could not make a strong affirmation about this because we had an absence of grammaticality effect.

9.5.4 Motor area and anterior cingulate cortex

Initially, we did not expect to see activation over motor area in our experiment. However, we found a significant cluster with a main effect of associative frequency over motor area (e.g., BA 6) when we performed the whole-brain analysis. It seemed high associative frequency decreased the neural activation around the onset of the verb which suggest that this area might be related to prediction. The idea of motor area involved in prediction is not new, in fact this result seemed to support the idea of prediction by production (Martin et al., 2018; Pickering & Gambi, 2018; Pickering & Garrod, 2013) . According to Pickering & Gambi (2018), there are three stages in prediction by production: 1) covert imitation: activation of the same representations in both the production and comprehension systems, as the production system would covertly imitate an input and this would facilitate the generation of a prediction by the comprehension system towards the upcoming input; 2) deriving the intention, which comes from a shared background knowledge: the comprehender needs sufficient background information to predict the utterance of the speaker; this information can be obtained through linguistic and nonlinguistic context; 3) running the intention in the production system: this is when the shared representation in the production system is activated and prediction is generated.

Martin et al. (2018) tested the notion that prediction uses a production system. In their EEG experiment, they asked participants to read highly constraining Spanish sentences which had expected and unexpected noun-phrases (i.e., article and noun). The participants were divided into three groups where they were asked to perform secondary tasks, depending on the group. The three groups were: 1) the syllable production (SP) group, where participants were asked to pronounce a syllable /ta/ on every word display; 2) the tongue tapping (TT) group, where participants were asked to tap the tongue loudly once on every word; 3) the syllable listening (SL) group, where participants were asked to listen to their own voice pronouncing the syllable /ta/ on every word.

N400 elicited by the article was reduced for the expected noun-phrase in the SP group compared to the other two groups. The authors argued that the production task in the SP group prevented the prediction mechanism. Therefore, their results support the idea of prediction by production, as they argued that the production system was useful to select the probable words.

Another cluster activation we did not expect when we did the whole-brain analysis was in the ACC of the right hemisphere. The activation of this area might be triggered by the task demand, as previous studies suggested that this area is related to conflict monitoring and response monitoring (Stroop task: Bench et al., 1993; Bush et al., 1998; Carter et al., 1995; Peterson et al., 1999; No-go task: Casey et al., 1995; Paus et al., 1993; Talati & Hirsch, 2005). Conflict-monitoring in language processing (for review see Meerendonk et al., 2009) is a process to detect whether the input is expected or not, and it is believed to be part of integration mechanism. Study in subject-verb agreement by Mancini et al. (2017) seemed to support this notion, as they found activation in this area was related to processing morphosyntactic violation. Therefore, it was not surprising to observe the involvement of the ACC since we used an experimental task where participants had to actively discriminate between words and non-words. The significant cluster with main effect of associative frequency was found around the onset of the inflection, in which increased of neural activation was elicited by low associative frequency. Perhaps similar to Mancini et al. (2017) this effect is related to integration because it occurs around the inflection time window thus the system could process the morphosyntactic information in the sense that the system combined information from both abstract and associative representation to check the shared feature between subject and prime. An alternative interpretation for this associative frequency effect was that low associative frequency required more attention than high associative frequency; because conflict monitoring was related to attention control. Note that grammaticality effect was not observed here, thus to verify the claim regarding integration, further studies are needed.

9.6 Conclusions

The MEG results showed that associative representations were accessed during prediction in subject-verb agreement. We found activation in the brain areas related to phonological processing, such as the PAC, which confirmed the findings of Experiments 1 and 2 that associative representations constrain the verb's phonological processing in a top-down manner. The present results also showed that associative representations are used to constrain verb processing not just at the early stage but also until the offset of the verb inflection. Interestingly, activation related to associative representations was also observed around the motor area, which supports the idea that language prediction and production are interlinked. It seems there is a lack of data regarding abstract representations. Grammaticality effect were not observed, except in the right-hemisphere PAC. This result was clearly not expected, as the PAC is more related to phonological processing than grammatical processing.

Chapter 10

General discussion

The aim of this thesis was to investigate the mental representations and processes involved in the processing of subject-verb agreement in spoken language. All studies were conducted in French, which is a morphologically rich language, and brain activity was measured with EEG and MEG. First, we examined how abstract and associative representations were accessed during the processing of subject-verb agreement. This issue was addressed in Experiment 1 (see Chapter 7). Second, we investigated whether there was flexibility in accessing abstract and associative representations. To this aim, we manipulated task demands and our results were reported and discussed in Chapter 8 (Experiments 1 & 2). Third, we wanted to know whether prediction intervened during subject-verb agreement processing and to identify the brain areas related to it. Previous studies (e.g., DeLong et al., 2005; Van Berkum et al., 2005) have shown that higher-level representations, such as syntactic and semantic representations, can affect the processing of the upcoming input via top-down processing, as these representations can pre-activate representations about the upcoming input at a lower level. To address this issue, we performed an MEG study in Experiment 3 (see Chapter 9). In the following sections, we summarize the findings from all three experiments and discuss their implications in the light of prior literature on grammatical agreement, flexibility and prediction.

10.1 Summary of results

The ERP components reported in previous studies investigating the processing of grammatical agreement, such as LAN and P600, were reproduced here. Our first study not only replicated these components but also showed evidence of the access to abstract representations. Indeed, we observed anterior negativity differences in an early time window (between 300 and 600 ms) between the effects of double and single violations during the processing of verb targets: double violations elicited stronger negativity than single violations; although condition with single violations were not stronger than congruent condition. In a later time window, positivity amplitude was increased by all types of morphosyntactic violations, in contrast with the congruent condition. Furthermore, our results demonstrated that associative representations also influenced the processing of subject-verb agreement. The effect of associative representations was captured at the early stage of verb processing, around 100 ms after verb onset. Associative representations were accessed after the recognition of a subject prime, based on the associative frequency between this subject and its verbal inflections. As this information affected phonological processing at a lower level, it suggested a top-down effect of associative representations between subject and verbal inflection on the phonological processing of the upcoming word. The system therefore uses the associative frequency between the subject and its verbal inflections to predict the upcoming verbal inflection, thus constraining the phonological processing of the verb.

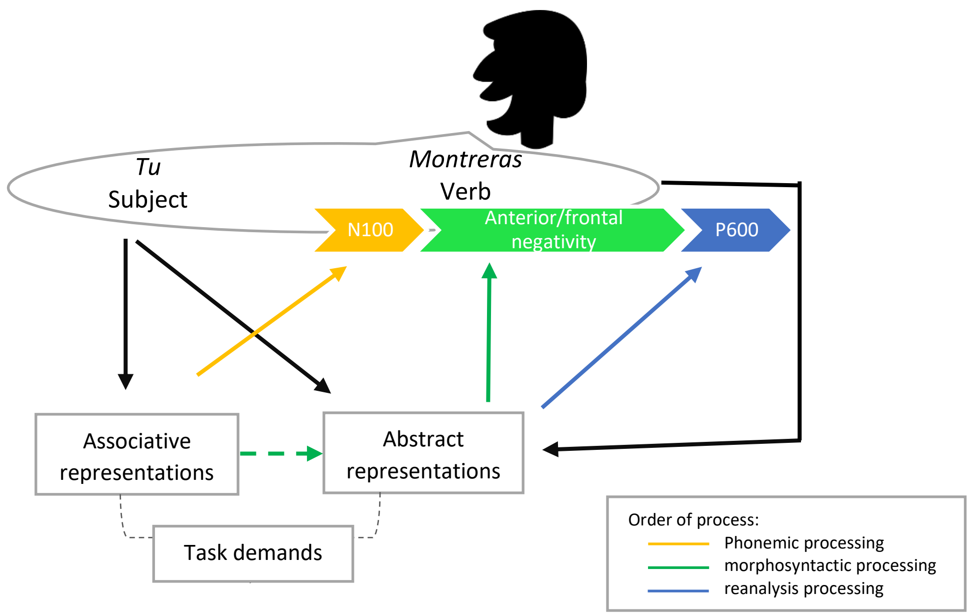
In the second study, we compared two experiments that had different task demands but used the same stimuli. In Experiment 1, participants performed a no-go lexical decision task, where they had to respond to nonword targets; in Experiment 2, they performed a noun categorization task, where they had to respond to the target if they recognized a noun. The results suggested that the accessing of associative representations between subject and verbal inflection was automatic, as it occurred in both experimental tasks. However, it also proved to be flexible, since the influence of associative representations depended on the task demand. The LDT seemed to enhance lexical processing and it caused the system to rely on the associative representations, as reflected by the N100 amplitude. On the other hand, the noun categorization task prompted access to grammatical information. Yet, the results showed that associative representations were also accessed, which we believe was due to automaticity. Automaticity in accessing associative representations between subject and verb inflection is unsurprising, as behavioral studies have suggested that these representations could be encoded and employed implicitly (Turk-Browne et al., 2005). In terms of flexibility in accessing the abstract representations, we observed that it was affected by the experimental task, such as noun categorization task decreased the elicitation of the N400 wave because the sensitivity towards the morphosyntactic violations was lowered. Note that the stimuli in both experiments were the same: nouns were always preceded by articles, which might have affected the attention level towards the critical stimuli in an experiment with a noun categorization task. As a result, during the computation of subject-verb agreement the system did not seem to rely heavily on abstract representations, as indicated by a lower negative amplitude. On the other hand, it used a different strategy when performing a LDT: it verified the agreement relationship between the subject prime and the verb target; when morphosyntactic violation was detected, it enhanced negative amplitude.

The third study showed that the primary auditory cortex (PAC) is involved in prediction during the processing of subject-verb agreement. The MEG results seemed to confirm the top-down effect during phonological processing observed in the EEG results of Experiments 1 and 2 concerning the use of associative representations. These representations were used in an area related to auditory processing to constrain the phonological level at the early stage of verb processing. Due to this constrain, the system was able to predict, i.e., pre-activate, the possible upcoming verb input. In the MEG study, we thus observed that the activation of the auditory primary cortex was affected by the degree of associative frequency between the subject and its verbal inflections. The activation of this area was stronger with low associative frequency than with high associative frequency, in an early time window around 150 ms after verb onset. This is related to the idea of prediction through production: prediction in language comprehension also activates the brain motor area, as the system uses the production pathway for covert imitation to generate word prediction. The MEG results indicated activation over the motor area, where high associative frequency decreased neuronal activation.

In Figure 30, we tried to summarize these results to demonstrate how the system uses the representations to process subject-verb agreement. After perceiving the subject prime, the system extracts the associative frequency information between a subject and its inflection, as depicted by the black arrow from subject to associative representations. Apart from that, subject input also activated the abstract representations, indicated by the black solid arrow in the figure. Then, the system applies top-down processing by using the associative frequency information to constrain the phonological verb input, which is reflected by N100 amplitude. This constraint is a manifestation of inflection prediction, since phonological pre-activation is limited to the phonological information of an inflection related to its subject. Note that verb also activated the abstract representations, indicate by the black solid arrow in the figure. Around the onset of the inflection, abstract representations are accessed to process the morphosyntactic agreement, meaning that the system combine the morphosyntactic information from the verb with the information from the subject. Morphosyntactic error detection is thus also involved in this process. Interestingly, our result showed that at this stage the system also used associative representations to constraint abstract representation. This is why we have dashed arrow from associative to abstract representations. The way abstract representations are used depends on the top-down processing from the associative frequency information, as high associative frequency decreases the grammaticality effect during morphosyntactic error detection. This process was reflected in anterior and frontal negativity in the EEG studies. Around the inflection offset, a reanalysis process occurs, during which abstract representations are accessed, as reflected by late P600. Importantly, our findings showed that there is flexibility in accessing the representations because the way the representations used were influenced by the task demands.

Figure 30

Illustration of how the representations are used during agreement processing



10.2 Representations in agreement processing

Our results do not seem to support the idea of a hierarchy of representational organization between abstract morphosyntactic features as we did not observe differences between the type of feature violation (person vs. number) such as in Mancini et al. (2011a). However, our results indeed suggest that abstract representations are accessed during the processing of subject-verb agreement as we observed differences between number of feature violation (single vs. double) as in Silva-Pereyra & Carreiras (2007) and Zawiszewski (2016). This difference between single and double feature seemed to indicated that they are represented separately. In Experiment 1, this difference was reflected through anterior negativity and late P600, while in Experiment 2, it was evidenced by N400, after detecting the syntactic errors.

Concerning the associative representations, we observed that these representations, which concern about the co-occurrence between a subject and its inflection, are also used during the processing of subject-verb agreement. That being said, our results indicate that abstract representations are not the only representations used. This finding confirms that statistical information (i.e., associative representations) indeed play a role in the processing of subject-verb agreement in spoken language. Furthermore, our results suggest that associative representations constrain the early stage of the verb's phonological processing, as reflected by N100. In the following sub-section, we describe the accessed representations in more detail.

10.2.1 Abstract representations

Our study is one of the first to show that abstract representations are accessed during agreement processing, particularly in subject-verb agreement processing in spoken language. As seen in Chapter 2, language processing uses abstract representations, which consist of morphological, syntactic and phonological information used to comprehend a word. Consequently, to process the verb agreement, the system performs a morphological decomposition (Estivalet & Meunier, 2016; Meunier & Marslen-Wilson, 2004): the system checks the verb's phonological input and its morphosyntactic information, such as word root and inflection, and agreement feature then verify it with the subject's syntactic information.

Our results suggest that when the system encounters morphosyntactic violation, the system verifies the agreement features by taking into account the number of feature violations that were involved in the verb. Hence, when the system encounters violation we observed differences between double and single violation. Among all morphosyntactic violations, double violations, such as in '*nous*$_{\text{1st person-plural}}$ *montreras*$_{\text{s2person-singular}}$' – 'we watches', are easier to detect, since the subject and the verb do not share any similar feature, as reflected by greater negativity. In contrast, in sentences with single violations, such as '*je*$_{\text{1st person-singular}}$ *montreras*$_{\text{s2person-singular}}$' – 'I watches', the subject and the verb share a similar number feature, which might make the violation less easy to detect. This is why a single violation requires more effort from the system to perform the reanalysis process as reflected by stronger positivity in our study. In line with our results, Lambert and Kail (2001) also showed that morphosyntactic cues were affected by the number of feature violations. They found that double violations in subject-verb agreement reduced the reaction time in a grammatical judgment task, where participants had to determine whether a sentence was grammatically correct or not.

The effect of the syntactic feature checking between a subject and a verb was also observed in the way the system responded to subject manipulation, in a sense using either first or second or third person as subject. Furthermore, the processing of subject was affected as well by the number of features violation (Lambert & Kail, 2001). In a sentence in which the subject was a singular third person (such as a person's name), the response time was faster than in a sentence with a longer subject clause that consisted of an article, a noun and an adjective. Moreover, when a double violation was introduced to the former, the reaction time was even reduced. This result suggests that the number of feature violations affects the morphosyntactic processing. However, keep in mind that the double violation effect might differ depending on the agreement features and language. For example, Lambert and Kail (2001) found a different pattern for the double violation effect in gender agreement. Concerning other languages, Lukatela et al. (1987), who conducted grammatical agreement studies in Serbo-Croatian, did not find any differences between the number of feature violations. In languages where double violation effect was not observed, it does not mean there are no abstract representations. As another study about subject-verb agreement by Mancini et al. (2011) showed topographical differences in the processing of syntactic features which implied that the abstract representations were accessed. These differences between the number of feature violations, such as single and double violations, or type of feature violations, such as number feature and person feature violation, suggest a separate processing of abstract representations in subject-verb agreement. Furthermore, our results suggest that abstract representations were not the sole representations that the system employs, it also uses associative representations in subject-verb agreement processing.

10.2.2 Associative representations and top-down processing

As mentioned before, the notion of top-down processing in spoken word recognition during early phonemic processing has been suggested in many studies (Baart & Samuel, 2015; Getz & Toscano, 2019; Noe & Fischer-Baum, 2020; Sivonen et al., 2006). For instance, the

Ganong study (Ganong, 1980) revealed a top-down effect where lexical representations constrained phonemic processing. In our studies, we also observed top-down processing, with high associative frequency decreasing N100 amplitude. During this top-down processing, the system prepares itself to receive the inflection by placing a constraint on the verb's phonological input. These findings are in line with previous studies showing top-down processing in sentences where higher-level representations, such as lexical or semantic information, constrain the processing of the word input, as reflected by N100 (Brunellière & Soto-faraco, 2015; Getz & Toscano, 2019; Noe & Fischer-Baum, 2020).

Our results are among the first to show the importance of the statistical properties of language during the processing of subject-verb agreement in spoken language. Importantly, other studies in language production have investigated the statistical properties involved in grammatical agreement (Haskell et al., 2010) followed by prepositional phrases. Their study showed that the use of collective nouns (such as "the government") together with plural verbs increased the possibility of generating erroneous agreement in production, as the system tends to generate plural verbs. In gender agreement, researchers in language production have shown that there was competition related to determiners. This competition was affected by the frequency of exposure (Spalek & Schriefers, 2005), which emphasized the importance of statistical information in language production.

How does agreement production relate to our findings? Some studies have suggested that production seems to be involved in language processing (MacDonald, 2013; Pickering & Gambi, 2018; Pickering & Garrod, 2013; Thornton & MacDonald, 2003). If statistical language information is used in prediction and agreement production, then it is very likely to be used during agreement processing as well. Regarding prediction by production, a recent study by Martin et al. (2018), which used Spanish sentences, supports the notion that the production system plays a role in prediction during comprehension. Likewise, our MEG results seem to support the idea of prediction by production, by showing activation related to associative frequency over the motor brain area, which is related to production. It seems the motor area was also involved in prediction during subject-verb comprehension. According to Levelt (1993), there are four steps in language production. The first step is conceptual preparation, where the system prepares to select the appropriate word from a candidate list that is generated by the speaker's intention. The second step is grammatical encoding where the intended message generates the activation of the syntactic structure. The third step is phonological encoding; this is when the system selects the word's phonemes; the serial structure of the word's phonology functions as a pronunciation guide for the speaker. The fourth step is word articulation which is executed by the motor system. Interestingly, studies in language production indicated that the system does not only rely on grammatical representations, but it also considers the statistical information of the word (Haskell et al., 2010; Thornton & MacDonald, 2003). In our study, we argued that associative representations guided covert production were associative representations, which then modulated the activation of the motor area. This activation suggests that the production system is used in language processing, particularly in subject-verb agreement.

10.2.2.1 Motor area and prediction

Here, we would like to discuss briefly about motor production because in the MEG study, we found activation over this area, which we did not expected before, around the onset of the verb which suggested this area is related to prediction. Even so, this is not surprising because it has been suggested that production is related to prediction (Pickering & Gambi, 2018). Motor areas are related to word articulation and there have been studies showing motor area related to prediction in speech processing (Morillon & Baillet, 2017; Morillon & Schroeder, 2015; Park et al., 2020). To be more precise, they investigated temporal prediction in speech processing using oscillatory entrainment (i.e., aligning the neuronal rhythmic pattern with the stimuli). Temporal prediction is the ability that allows the system to predict when the upcoming input is going to come, so that prediction is more precise. These studies showed that this top-down processing in the motor area was reflected by delta oscillation (1-4 Hz). Although we did not perform a frequency analysis because we interpreted prediction by the associative frequency effect in which low associative frequency increased neural activity around the onset of the verb and decreased it around the verb offset. Our result seems to corroborate those studies that motor area is related to prediction; this implies that prediction also employs language production system.

10.3 Flexibility in accessing the representations

Here, flexibility was related to the ability to process subject-verb agreement despite the task demand, as observed in Study 2 where abstract and associative representations were accessed flexibly. Flexibility in accessing abstract representations was reflected by N400, with the lexical decision task relying more on abstract representations than the noun categorization task. In addition to flexibility, we also observed automaticity in accessing associative representations. Attention was still required, however, since behavioral results in both experiments showed a high level of accuracy. Helie et al. (2010) suggested that automacity is related to frequency of exposure, in a sense that a shift to automaticity occurred due to the frequency of exposure. Their study looking at the automaticity of rule-based categorization. In their fMRI experiment, they found that rule-based categorization elicit activation over the prefrontal cortex, and the pre-motor cortex was related to automaticity. As mentioned earlier, the transfer from rule based learning to automaticity was due to frequency of exposure. In language processing, Information from that was due to language exposure is related to statistical information. In our case, this is related to associative frequency information. That said, the automaticity that we observed in accessing the associative representations seemed to be natural.

10.4 Future directions

We acknowledge the limitations in this work, such as lack of participants. Perhaps for future study we can try to replicate the associative frequency because there are not many studies investigating how associative representations played role in agreement processing. In our experiments, in each associative frequency condition, we had the same type of comparison, in the sense each associative frequency condition composed of four grammatical conditions (i.e., congruent, number violation, person violation, number and person violation). Consequently, the result concerning associative frequency information combine the results from the four grammatical conditions. Perhaps, in the future study we could have equal number of congruent and incongruent condition so that we can see if there are differences between the associative frequency conditions when they are used to process congruent and incongruent conditions. Indeed, we could see this in our present design, however in some incongruent conditions, the associative frequency condition derived from different subject. For instance, in congruent condition, the associative frequency information was derived from *'tu'* and *'nous'* while in incongruent conditions, e.g., person violation, the associative frequency was derived from *'je'* and *'vous'*; it might be good to control the subject prime so that we have more homogenous stimuli. So that if we see associative frequency effect around the inflection offset, it would be easier to interpret the result. At the moment if we want to isolate the associative frequency effect for congruent condition only, the result might not be stable because we have small number of participants.

Perhaps for the future study we could also control the verb phoneme. We considered that inflection prediction based on the associative frequency information constrains phonological processing of the verb. Thus, if we control the verb phoneme, we might observe a clearer prediction effect. For instance, if we manipulate the second phoneme of the verb, by matching it with the expected inflection (e.g., /a/). Hypothetically, if associative frequency information affect verb phonological processing, this manipulation might decrease N100 if the system detects a phoneme that is related to the associative frequency information. The second phoneme is chosen because using a vowel for the first phoneme would change the pronunciation of the subject and the verb.

Furthermore, it might be interesting to see if the same representations are used in longer or complex sentences, such as embedded sentence. In the present experiments, we used short sentences that consist of subject and verb to keep the local distance. For future studies, we would like to know which representations that the system would rely on if it encounters longer sentence where sentential context can be detected. Previous studies normally suggested that sentential constraint affect word prediction.

Moreover, in a recent study by Ito et al., (2020) in which they investigated syntactic and phonological prediction in Italian written sentences that were highly predictable. They found that the system tends to generate prediction related to syntactic information, such as gender than phonological information of words. Thus, we would like to know if in a highly constraining sentence, the associative representations still be used to predict the verbal inflection, or will the system prefers abstract representation.

Concerning prediction and brain lateralization, we found activation over the right hemisphere, as confirmed by other studies showing that the right hemisphere is involved in language processing (Federmeier et al., 2008; Gazzaniga & Hillyard, 1971; St George et al., 1999). Hence, it would be interesting to know to what extent the right hemisphere plays a role in grammatical agreement. Federmeier (2007) suggested that the right hemisphere is more related to integration, so it might be more sensitive to abstract representations than associative representations, since the latter are known to be related to prediction.

10.5 Conclusions

Our principal finding is that abstract and associative representations are both accessed during subject-verb agreement processing in spoken language. However, our experiments revealed more information about these representations. Concerning associative representations, our results highlight the importance of statistical information in agreement processing. To our knowledge, our study is among the first to examine the role of associative frequency between a subject and its inflection in subject-verb agreement. The cognitive system uses associative representations to actively generate a morphosyntactic prediction, thus affecting verbal processing at lower levels (i.e. phonological level). Our findings highlight the importance of such statistical information in prediction, which also occurs in subject-verb agreement processing. They also provide new insights regarding flexibility in accessing the representations involved in subject-verb agreement processing.

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Appendix A

List of the stimuli

Training session

Critical verbs	Fillers		
	Verb	Noun	Pseudoword
casserons	composent	beurrier	biélance
citeras	consentiez	cervelles	ficrasse
craqueras	décorais	cotation	prézet
rejoindrons	repartaient	flacons	traimas
retiendrons		mission	vébandes
séduiras		potier	baconges
serons		retards	biruaient
voudras		sévice	feinsarons
		symphonie	rypessais

Main Trials

Critical verbs

volerons	vêtirons	tomberons	vengerons	vieillirons	traînerons
baveras	berneras	battras	blesseras	Coudras	conviendras
copieras	boiteras	boufferas	chanteras	Cuirass	couperas
cueilleras	brancheras	commettras	crèveras	Frapperas	ficheras
décevras	choqueras	couleras	descendras	Jeûneras	guériras
douteras	détiendras	duperas	fermeras	Noteras	nageras
garderas	masseras	flatteras	monteras	Pèseras	renieras
nettoieras	murmuras	grilleras	piqueras	Pleureras	saigneras
prétendras	pêcheras	jureras	préviendras	promettras	saisiras
régneras	raseras	liras	prouveras	Reliras	supplieras
rempliras	suivras	soigneras	reprendras	Sonneras	tueras
tireras	tarderas	tourneras	toucheras	Tiendras	vendras
calmerons	bénirons	combattrons	conterons	bouclerons	briserons
causerons	chérirons	déploierons	débattrons	Brûlerons	construirons
connaîtrons	croiserons	dirons	déferons	comprendrons	créerons
détruirons	dînerons	léguerons	festoierons	foncerons	mangerons
mettrons	doublerons	planterons	grefferons	fournirons	prêterons
mourrons	fixerons	posterons	rallierons	goûterons	rangerons
répondrons	grimperons	relouerons	siégerons	longerons	recevrons

resterons	passerons	renaîtrons	souperons	Plierons	rentrerons
revendrons	plongerons	songerons	tâcherons	Poserons	traquerons
sortirons	romprons	tremblerons	triompherons	Saurons	veillerons
tromperons	signerons	verserons	viendrons	vaincrons	vivrons
balaieras	brosseras	bosseras	baisseras	Cocheras	boiras
broieras	contreras	décriras	crieras	Colleras	caleras
coifferas	coucheras	fuiras	dormiras	Croiras	flotteras
creuseras	guideras	jetteras	fouilleras	Loueras	pinceras
faucheras	laveras	marcheras	nommeras	marqueras	porteras
miseras	marieras	mentiras	périras	plaqueras	prieras
penseras	montreras	rouleras	ramperas	pousseras	râperas
pointeras	parviendras	sentiras	recoudras	racleras	sabreras
surferas	rayeras	siffleras	sauveras	rameras	sculpteras
trancheras	reverras	tordras	surprendras	referas	transmettras
vénéras	tresseras	trahiras	vexeras	rejoueras	videras
bâtirons	chargerons	fêterons	conquerrons	bougerons	brillerons
camperons	choisirons	nierons	courrons	cesserons	danserons
devrons	convaincrons	nourrirons	lutterons	conduirons	formerons
franchirons	défendrons	perdrons	parlerons	couvrirons	fumerons
gravirons	finirons	placerons	plaiderons	deviendrons	jouerons
guetterons	gagnerons	produirons	publierons	grandirons	livrerons
logerons	jugerons	reviendrons	punirons	lancerons	renverrons
maudirons	poursuivrons	rirons	revivrons	mènerons	sauterons
pillerons	sourirons	saluerons	testerons	rendrons	servirons
trinquerons	survivrons	sèmerons	tisserons	serrerons	souffrirons

Fillers

<u>Nouns</u>

baraque	maréchal	profil	déficit	lentille	pendaison
candidat	médecin	saphir	demi-frère	levier	présence
carabine	microscope	sardine	désordre	maman	progression
caravane	paragraphe	séance	dicton	marchepied	prophétie
citation	pétrin	silence	docteur	marqueur	provenance
comptine	salami	sponsor	fiasco	mauviette	prudence
déesse	baiser	termite	forgeron	melon	qualité
détresse	ballerine	toxine	fournisseur	morille	révision
dynastie	boyau	trouvaille	légume	munition	barbier
fondation	bureau	videur	maçon	piment	baron
lagune	cerise	virage	magot	polar	campement
licence	charlatan	wagon-lit	martini	prénom	castor
lingerie	charrette	belle-fille	motard	prêtre	chemin
marmite	cheville	biographie	moucheron	racontar	cimetière

parabole	coffret	braguette	navire	rempart	couvre-feu
patrie	colline	cafetière	patio	ressort	cricket
phobie	compagnon	coiffeur	prototype	sage-femme	dilemme
poésie	continent	colère	purgatoire	salade	dimanche
pression	convention	concession	régal	saucisse	doyen
province	coquille	direction	seigneur	scooter	fléau
psychiatrie	coureur	falaise	baïonnette	sottise	gazon
réaction	domino	fanfare	bestiole	surface	genou
réunion	douleur	ferveur	brassière	templier	gorille
richesse	friandise	frontière	carapace	tirage	gouverneur
risée	gravure	guitare	citerne	traqueur	magnum
barreau	guichet	légion	cocon	vieillerie	maquillage
bateau	joyau	limonade	conclusion	boucherie	moustique
blaireau	jumeau	matière	confession	caissier	mouvement
brevet	lambeau	mélasse	contact	caméra	procureur
calvaire	lavabo	morsure	copeau	casserole	remède
capitole	madame	passion	corvée	citoyen	réveil
caprice	ministère	perfusion	courrier	clairière	salon
charabia	moissonneur	pharmacie	couvent	clientèle	bactérie
ciné	nana	pizza	croquette	confidence	baril
container	patate	politesse	dollar	confusion	barrière
courtier	permission	propagande	fantaisie	conséquence	beaux-parents
crumble	pilule	prostate	flamant	faculté	braquage
dossier	piscine	bandeau	fondement	faiblesse	brassard
frérot	plafond	bouclier	fréquence	jouissance	budget
fumeur	poignard	caillot	fusible	misère	calamar
jardin	praline	caniveau	fusillade	montagne	camisole
kimono	prétention	carreau	guérisseur	notion	capsule
loup-garou	prière	consul	lanterne	partition	carence
servant	charogne	fossette	projecteur	contusion	tisane
silhouette	château	grumeau	ricochet	coton-tige	tonneau
situation	cheveu	jeudi	seringue	couleuvre	tribune
sondage	chichi	mallette	piano	destin	tromperie
sortilège	comics	nettoyeur	poison	figurant	
soucoupe	condiment	pastèque	potence	formation	
prévision	problème	procession	vitamine	vanité	

Verbs

discernait	tutoyais	martyrise	percevons	démontrait	sifflotais
forçait	distançons	stylise	planquions	justifiait	grimacions
réprimait	feignons	tarabuste	présidons	noyait	limions
retraitait	flanquons	dédommagent	ravalons	soumettait	militons
chevauchent	frôlions	démêlent	reprochions	dénigrent	profitions

dénaturent	gisions	démontent	trafiquions	déversent	prônons
diffament	stoppions	cuisinait	conjugues	picorent	resserrons
mordillent	traçons	déconnait	dopais	rebâtissent	séjournions
certifie	ciblais	gelait	durcissais	cohabite	cédais
densifie	concèdes	complotaient	paraphes	pétarade	consoles
résilie	demeurais	repoussaient	poireautais	réforme	déclares
théorise	lambines	sursautaient	prononces	surpaye	dramatises
fermentaient	piochais	cultivais	rappelles	captivaient	lésais
furetaient	pollues	diverge	tablais	drainaient	pistais
malaxaient	rattrapes	maniais	censuriez	glorifiaient	recréais
supposaient	baillez	réaffirme	commerciez	respiraient	chauffiez
concluais	bavassiez	rétrograde	défiliez	comparais	conserviez
confectionne	changiez	rigolais	détestiez	concerte	dépensiez
croquais	cumulez	traînassais	faussez	cotise	détourniez
farfouille	dénommez	vocalise	prolongez	dévalise	picolez
perfuse	dictiez	cirions	taxez	relâchais	résidez
sanctionne	stagnez	louchons	valsez	relançais	trimbalez

Pseudowords

blévapie	tunaux	clitusions	grembonne	lantrite	recléait
chefassion	détondelle	cociondre	sulmite	péfuille	regnèlait
davoche	rejoute	cucarie	sumplitue	pricette	résimiait
gristilly	rétunère	gragéition	vebenge	recolde	benontaient
mocu	sactienne	loissaint	cedolent	réfontion	mémisent
pecrarie	sécolle	marulle	contulent	rôcarie	pifrétaient
peudrade	bistrotaient	nédriégie	dacassent	sevogue	princitaient
plavine	briplaient	nionture	situlent	siveusse	recerbaient
pournaise	chastalaient	petose	sussègent	sounarde	relefaient
precetion	décarsaient	pugrerie	dacaibait	vuviale	claignoute
rivetion	désenpaient	tadiche	fipaillait	chioge	clature
vépente	claintrait	vulorne	nenvolait	ciguet	démaduse
vetière	dévontait	brollon	palquait	coumon	désalie
brampon	titturait	cigron	provolhuait	cunom	movice
cacodron	tointait	dépenroi	braffaient	drigot	sputafie
chublon	triolait	fourdiau	cataient	fesontier	besannent
coldage	claidissent	grimpin	décannaient	londeur	complitent
consmoir	forgopent	kespourou	déproyaient	pâtarin	dacolent
flaget	lacudent	liasel	sacussaient	repeuil	dégravent
jeticier	souveillent	piaffin	clagoûle	riffret	sablissent
magon	vélient	plegin	claifroue	sencantif	tersulaient
mazut	concéinais	soffème	décresais	siurme	clétissais
puinfait	copame	vajel	diérrais	cappreurs	déciltais
rouron	décurtais	veudon	méfisente	chévaitions	déviubre

sauder	dénète	beviges	polaie	choufions	féresse
vrosade	rembactais	brimbeurs	vambengiais	crenstés	pladuais
becignes	ruvoie	cerateurs	basorlons	jédoces	renlie
blasseurs	schivène	clampeurs	derastons	mendirs	vourcendais
brineges	cessanrions	clergines	grosquons	necailles	cavutions
câssues	dégelpions	clovisions	plauvanions	népeunes	gacouions
cavous	dévortons	dysardies	plovrions	nionences	mingions
ceflouelles	lârons	fotats	recantrions	nonges	plinduons
cormostions	pevutions	jovisées	rochions	paifrasses	rècissions
cossormes	pritivons	mapeders	rullons	prégnons	refalons
dimporsions	comdèrais	mardas	bouconnais	redopes	sanlourons
drandeges	conchubles	médionnons	chérantes	reveciers	bafrisses
duscrines	débiètes	meloines	dacosses	roinons	divais
masaliers	décènes	nacunnes	dommersais	rolons	fadessais
mocêtes	moupiais	pefrices	mitais	ronteurs	mucipiais
moniers	reverlais	pissages	pabiais	saveches	précugnes
nammarons	sénasais	prigments	paveges	semdères	resutes
poubous	tatumes	repicts	cailirez	sevènes	dacutez
pudges	cèflétez	rétriques	décupiez	tembouzes	fémériez
sareles	clepolez	teulages	dipangez	tonéats	fetupiez
sévéplies	compimiez	tieilleges	pacipez	ventiones	gurez
sévetes	convostiez	tuniloirs	padripiez	vobits	préresez
ssterneurs	démingez	vations	rembastiez	vrocartes	tarmiez
tampeurs	fervinez	vautuères	répuriez	convognait	
tômeries	pecotiez	vicures	dairade	fongait	
tremoichées	racassiez	bicinque	failorde	recarmait	

Appendix B

Statistical table

Table 8

Statistical results from ERP analysis over the four time windows of experiment 1

	Time window between 100 and 160 ms	Time window between 300 and 600 ms
Associative frequency	$F(1,22)=0.003$, $p>.2$	$F(1,22)=1.42$, $p>.2$
Grammaticality	$F(3,66)=0.05$, $p>.2$	$F(3,66)=5.06$, $p<.01$
Topographical sites	$F(6,132)=6.83$, $p<.001$	$F(6,132)=2.41$, $p=.06$
Associative frequency x Grammaticality	$F(3,66) = 1.35$, $p>.2$	$F(3,66) = 0.83$, $p>.2$
Associative frequency x Topographical sites	$F(6,132)=2.80$, $p<.05$	$F(6,132)=0.29$, $p>.2$
Grammaticality x Topographical sites	$F(18,396) = 1.33$, $p>.2$	$F(18,396) = 1.52$, $p=.17$
Associative frequency x Grammaticality x Topographical sites	$F(18,396)=0.90$, $p>.2$	$F(18,396)=0.57$, $p>.2$
	Time window between 650 and 850 ms	**Time window between 920 and 1120 ms**
Associative frequency	$F(1,22)=0.14$, $p>.2$	$F(1,22)=2.35$, $p=.14$
Grammaticality	$F(3,66)=6.24$, $p<.01$	$F(3,66)=0.44$, $p>.2$
Topographical sites	$F(6,132)=28.07$, $p<.001$	$F(6,132)=25.26$, $p<.001$
Associative frequency x Grammaticality	$F(3,66) = 2.17$, $p=0.1$	$F(3,66) = 2.20$, $p=.11$
Associative frequency x Topographical sites	$F(6,132)=0.91$, $p>.2$	$F(6,132)=1.44$, $p>.2$
Grammaticality x Topographical sites	$F(18,396) = 1.51$, $p=.17$	$F(18,396) = 2.52$, $p<.05$
Associative frequency x Grammaticality x Topographical sites	$F(18,396)=1.98$, $p=.07$	$F(18,396)=0.94$, $p>.2$

Note. Results of Experiment 1 in Study 2 (Chapter 8) when baseline correction is not applied.

Appendix C
Submitted paper

Title: Associative and abstract feature representations are accessed during the processing of subject-verb agreement in short spoken sentences: evidence from ERPs

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Abstract:

While the computation of abstract feature representations is largely documented in literature of subject-verb agreement, the impact of associative representations between a subject and its verbal inflections is unclear. The aim of the present study is to explore access to abstract and associative representations underlying subject-verb agreement processing. Event-related potentials (ERP) were recorded from French participants listening to verbs preceded by pronominal subjects. The amplitude of auditory N100 response after the onset of verbs was affected by associative representations. Then, an anterior negativity showed sensitivity to both abstract features and associative representations, while a P600 was enhanced to a morphosyntactic violation between the subject and the verb, irrespective of the number or the type of features involved. The study showed that both abstract and associative representations are used in the computation of subject-verb agreement and it sheds light immediate predictions triggered from the subject based on associative representations.

Count: 148 words, limit: 150 words

Keywords: subject-verb agreement, associative representations, feature representations, prediction, event-related potentials.

Introduction

Learning the structure of language involves the accumulation of information about statistical and probabilistic aspects of language (Seidenberg, & MacDonald, 1999). Children and adults use statistical properties of language to acquire a new language (Aslin & Newport, 2008; Ellis, 2002; Lew-Williams, Pelucchi, & Saffran, 2011; Perruchet, & Pacton, 2006; Saffran, Aslin, & Newport, 1996; Wells, Christiansen, Race, Acheson, & McDonald, 2009). Although acquisition processes and learning are assumed to shape the nature of the expert system, a major debate concerns which mental representations underlie language use and how mental representations are organized in experts. A distinction between statistically-based and abstract representations has been formulated in agreement processing (Carminati, 2005; Chomsky, 1959; Harley and Ritter, 2002; Truswell & Tanenhaus, 1994; Seidenberg & MacDonald, 1999). However, few studies thus far have investigated how statistical-based and abstract representations are accessed in agreement processing. In the present study, we seek to gain a better understanding concerning the debate about which and how representations underlie language use in the case of subject-verb agreement processing by using event-related potentials (ERP) giving fine temporal information about neurocognitive operations.

Agreement can be defined as a morphological co-variance between words signaling that words share common grammatical relations. According to a probabilistic constraint-based view, the associative lexical representations code the probability between words (Truswell & Tanenhaus, 1994; Seidenberg & MacDonald, 1999). By accessing associative representations, we can recognize whether or not a sentence is correct through the statistical regularity between words and between morphological elements, such that the dependencies between a subject and a verb can be extracted. For instance, pronominal pronouns co-occur more or less frequently with particular verbal inflections in morphologically rich languages (e.g., the subject pronoun *'nous'* is always associated with the *'ons'* verbal inflection in subject-verb dependencies of French language use, except for two rarely used tenses). Based on a probabilistic constraint-based view, it is expected that the strength of activation for associative representations between words and morphological elements might depend on their co-occurrence frequencies in language use (e.g., the co-occurrence frequency between pronominal pronouns and their verbal inflections). In line with this assumption, subject-verb agreement has been described as being processed, at the neuronal level, by sequence detectors linking the representations of morphemes which are likely to occur in succession and the activation of neuronal populations underlying the processing of subject–verb agreement would be modulated by the frequencies of co-occurrence between morphemic units (Pulvermüller, 2002).

Contrary to statistical and probabilistic aspects of language, the abstraction involves having dimensions in mind (i.e., features) from which words can be distinguished in terms of grammatical properties in agreement and from which they will be considered identical. According to one view formulated in the context of generative syntax (Carminati, 2005; Chomsky, 1959; Harley and Ritter, 2002), abstract morphosyntactic features, such as gender, number and person, are represented separately and are computed by the agreement mechanism. This contrasting view holds that computational operations during subject-verb agreement processing consist in checking the feature consistency between the subject and the verb. Moreover, a hierarchy of representational organization between abstract features is assumed to exist (Bianchi, 2006; Carminati, 2005; Harley and Ritter, 2002; Sigurdsson, 2004) within which the person feature is expressed at a higher position than number in the syntactic tree.

Theories in favor of the representation of abstract morphosyntactic features make at least two particular predictions about the ERP responses elicited after agreement violations: (i) each feature violation should lead to a distinct ERP response; and (ii) a double violation involving two morphosyntactic features should elicit larger ERP responses than a violation of a single feature. To date, three ERP studies in subject-verb agreement (Mancini, Molinaro, Rizzi, & Carreiras, 2011; Nevins, Dillon, Malhotra, & Phillips, 2007; Silva-Pereyra, & Carreiras, 2007) have focused on the representations of abstract features in Spanish and Hindi. Two ERP correlates usually found after agreement violations in subject-verb dependencies (for a review Molinaro, Barber, & Carreiras, 2011) include: (i) a left-anteriorly distributed negativity in the 300–500 ms interval (Left Anterior Negativity, LAN); and (ii) a positive deflection, arising about 600 ms poststimulus (P600) over posterior sites. While the LAN reflects the early detection of agreement violations, the P600 is linked to the reanalysis process to repair the anomalous structure. In written Hindi sentences, Nevins, Dillon, Malhotra, & Phillips (2007) observed a larger P600 for the double violation person/gender in comparison to the simple violations involving either the gender feature or the number feature and to the double violation number/gender. The person feature seemed to be stored in memory separately from the gender feature, contrary to the number and gender features which are not differently represented between them. A Spanish ERP study investigating number and person agreement (Silva-Pereyra and Carreiras, 2007) showed a greater response during the first phase of the P600 for a double person/number violation in comparison to the simple violations of person or of number, claiming for a distinctive representation of person and number features. Mancini, Molinaro, Rizzi, & Carreiras (2011) again showed a greater response on the P600 for a double person/number violation in comparison to the simple violations involving either the person feature or the number feature during the reading of Spanish sentences. In addition, there were earlier differences in the topographical distribution of the left anterior negativity (LAN) between person violation and number violation. The number violation elicited a negativity with a more frontal topography with respect to the person violation, suggesting that the two morphosyntactic anomalies were processed differently. Although the time course of ERP effects between feature representations differ between the previous studies – a fact which can be explained by differences based on the properties of stimuli – these ERP studies in reading are in favor of the representation of abstract morphosyntactic features in subject-verb agreement (Mancini, Molinaro, Rizzi, & Carreiras, 2011; Nevins, Dillon, Malhotra, & Phillips, 2007; Silva-Pereyra, & Carreiras, 2007), such that number and person features are processed separately.

Some authors (Carminati, 2005; Faussart, Jakubowicz, & Costes, 1999) have gone beyond investigating the mere processing of morphosyntactic features separately and proposed a temporal dissociation in the processing of feature consistency. While Carminati (2005) suggested that access to features representations arises during the initial stages of processing, Faussart, Jakubowicz, & Costes (1999) proposed that the repair processes are the sole moment during which access to feature representations can be highlighted. In line with the latter suggestion, the amplitude of P600 appears to be more sensitive to the abstract morphosyntactic features during the processing of the dependencies of subject-verb agreement (Mancini, Molinaro, Rizzi, & Carreiras, 2011; Nevins, Dillon, Malhotra, & Phillips, 2007; Silva-Pereyra, & Carreiras, 2007). Moreover, Molinaro, Barber, & Carreiras (2011) suggested that the LAN is an electrophysiological correlate of an active predictive process on syntactic information, such that the LAN reflects a violation of expectancy. Consistent with this view, Brunellière (2011) showed that this anterior response was larger after the recognition point of verbal inflection for the incongruent predictive condition with respect to the congruent predictive and non-predictive conditions in French subject-verb agreement.

The role of prediction in language comprehension has recently drawn researchers' attention (for reviews, see Huettig, 2015; Kuperberg & Jaeger, 2016). It thus appears that the brain is not passive. Rather, it is actively making predictions about the upcoming input (Bar, 2007). According to a predictive view of language processing, higher linguistic levels are supposed to constrain the activation of lower linguistic levels in advance of the incoming input (for a review, Kuperberg & Jaeger, 2016). For instance, there is experimental evidence for a lexical pre-activation triggered by sentential context (e.g., in reading, DeLong, Urbach, & Kutas, 2005, Van Berkum, Brown, Zwitserlood, Kooijman, & Hagoort, 2005; in spoken language, Foucart, Ruiz-Tada & Costa, 2015; Wicha, Bates, Moreno, & Kutas, 2003). Moreover, other neuroimaging studies in written and spoken language comprehension have even shown that predictability effects can affect the early sensory responses, such as the visual cortex (Kim & Lai, 2012; Dikker & Pylkkänen, 2011; Dikker, Rabagliati, & Pylkkänen, 2009) or the responses at low levels of processing, such as the left inferior temporal cortex associated with the processing of phonological word form level (Willems, Frank, Nijhof, Hagoort, & van den Bosch, 2015). In the context of spoken word recognition, Gagnepain, Henson, & Davis (2012) also found that superior temporal gyrus (STG) neurons response to the difference between predicted and heard speech sounds. In accordance with a predictive coding theory, these findings suggest that predictions are derived from information going from hierarchically higher to lower areas via a top-down processing (Bar, 2009; Friston, 2005; Rao and Ballard, 1999). Even though it is known that predictive syntactic contexts affect the recognition of grammatical class (Strijkers et al, 2019), neurocognitive operations underlying the top-down predictions during the subject-verb agreement are still elusive.

Interestingly, top-down predictions are considered to be probabilistic systems mirroring the statistics of the linguistic environment (Kuperberg, & Jaeger, 2016; Levy, 2008). Associative representations between the subject and the associated verbal inflections thus can play a crucial role in top-down predictions during the subject-verb agreement. In other words, the subject would trigger the pre-activation of verbal inflections based on associative representations and thereafter the strength of this pre-activation should constrain the processing of a new incoming input at sensory levels. As noted above, the LAN component reflects a violation of expectancy after the recognition of verbal inflection, whereas the strength of associative representations involved in the processing of subject-verb agreement could affect immediately the processing of new incoming input prior to the verbal inflection.

The present study thus explores access to abstract and associative representations in subject-verb agreement processing and their associated processing routines by using event-related potentials (ERP). To the best of our knowledge, no study has yet looked at the importance of associative representations in subject-verb agreement. Agreement processing in spoken language (Brunellière, 2011; Isel, & Kail, 2018; Dube, Kung, Peter, Brock, & Demuth, 2016; Hanulíková & Carreiras, 2015; Hasting, Kotz, & Friederici, 2007; Rossi, Gugler, Hahne, & Friederici, 2005) has been the object of less investigation than in the reading of written language (for a review, Molinaro, Barber, & Carreiras, 2011). Moreover, the complexity of spoken language and its fleeting nature could render the role of associative representations in subject-verb agreement particularly apparent. To achieve the aim of this study, we focused on the ERP components elicited by the processing of spoken verbs in short French sentences when they were preceded by spoken pronominal subjects either sharing or not sharing the same grammatical properties. Studying subject-verb agreement in short sentences offers the possibility to track at the dynamics of computation processes during the comprehension of subject-verb agreement without being affected by other variables, such as sentential structural constraints, semantic complexity and semantic relationship between words.

To probe the access to abstract representations, we manipulated the nature of agreement violations in terms of abstract features (single violation of person feature, single violation of number feature, and double violation of person and number features, see Table 1). Moreover, access to associative representations is studied by contrasting pronouns which had either a high co-occurrence frequency with one verbal inflection in French language use (high associative frequency) or a low co-occurrence frequency (low associative frequency). As described in previous studies (Brunellière, 2011; Brunellière, & Frauenfelder, 2014), French offers an interesting case of strong predictive context between the subject and the expected morpheme within the French pronominal subject-verb agreement relation. More precisely, the first and second person plural pronouns are more frequently associated with the same verbal inflections than the other pronominal subjects (see Table 1). During this experiment, participants heard pairs of stimuli, 40% of which were short pronoun-verb sentences, which created the possibility that participants did not develop a strategy specifically to process subject-verb agreement. A no-go lexical decision task (Gómez, Ratcliff, & Perea, 2007) was performed on the second stimulus within pairs of stimulus such that participants were asked to make a response when the second stimulus was a nonword. This enabled us to avoid any motor responses during the processing of verb targets while keeping the attention of the participants on the stimuli.

< Insert Table 1 here >

As associative representations are surface elements based on the statistical regularity between morphological elements, we questioned when associative representations are accessed during the computation of subject-verb agreement, whether their activation would occur earlier than the activation of abstract representations based on the grammatical features and, finally, whether associative representations are involved in the top-down predictions during the computation of subject-verb agreement. According to an active predictive view of language processing, the pronominal subject should cause pre-activation of upcoming verbal inflections and thereby it would affect the processing of the auditory input at lower levels. Since the N100 wave is known to be an index of perceptual processing of auditory input and phonological processing (Krumbholz, Patterson, Seither-Preisler, Lammertmann, & Lütkenhöner, 2003; Näätänen, 2001; Obleser, Scott, & Eulitz, 2006); one can expect to observe an influence of associative frequency between the pronoun and the verbal inflection over the N100. Moreover, the prediction based on associative representations between subject-verb dependencies should persist upon arrival of verbal inflection, such that one might expect to observe an influence of associative frequency between the pronoun and the inflection over the LAN component from which the verbal inflection can be recognized. As in the prior literature, the amplitude of the LAN should be larger after morphosyntactic violations. Regarding the use of abstract features in subject-verb agreement, one might expect to replicate findings from the previous studies in reading, such that the amplitude of P600 would be higher for a double violation of person and number than simple violations (involving person or number feature).

Methods

Participants

Twenty-three native speakers of French (eighteen females) were recruited for this study. Their range of age was 18-30 (mean = 21.6, SD=3.03) years old. All were right-handed as assessed by the Edinburgh handedness inventory (Oldfield, 1971). They had normal or corrected-to-normal vision. All declared no hearing, language or neurological impairments as per self-report. Participants received monetary compensation for participation (15€) or credits for courses. Prior to the experiment, they gave their written informed consent. This study has been approved by the ethics committee of University of Lille.

Stimuli

The critical stimuli consisted of 264 pronoun primes and 264 verb targets. All were selected from the Lexique French database (New et al., 2004). The verbs were composed of either two or three syllables and were ended by either the –/a/ or –/õ/ suffixes. The verbal forms were in the future tense, where the inflection expressing variations in terms of person and number properties is the final single phoneme. The –/a/ verbal ending in future form corresponds to the second- and the third-person singular, whereas the –/õ/ verbal ending in future form corresponds to the first- and the third-person plural. Therefore, the syntactic and phonological complexity of morphological marks did not vary as a function of experimental conditions, since each verbal ending was associated with two sub-categories of person feature and corresponded to a single phoneme. The verbal forms ending with –/a/ or –/õ/ suffixes were matched for all psycholinguistic properties (lexical frequency, lemma frequency, number of phonemes, phonological neighbors and phonological uniqueness). The two groups of verbal forms ensured the presentation of different word stems and reduced the need for experimental lists to 4.

The verbal forms were preceded by four different pronominal subjects: *'tu', 'vous', 'nous'*, and *'je'*, leading up a set of eight experimental conditions (33 trials per condition). More precisely, two factors, grammaticality and associative frequency, were manipulated in the present study (see Table 1). In the congruent condition, the pronominal subject shares the same grammatical properties with the verbal form. In the person violation condition, the grammatical properties of pronominal subjects mismatched only in terms of person features with those of verbal forms. For instance, the *je* pronoun refers to the first-person singular, whereas the –/a/ verbal ending expresses to the second- and the third-person singular. In the number violation condition, the grammatical properties of pronominal subjects mismatched in terms of number features with those of the verbal forms. For instance, the *je* pronoun refers to the first-person singular, whereas the –/õ/ verbal ending in future form refers to the first- or the third-person plural. Therefore, in this condition, a violation involving the number feature is obvious and the detection of violation based on the person feature is not necessarily relevant, since the verbal ending may refer to the same person properties. In the person and number violation condition, the grammatical properties of pronominal subjects differed from those of verbal forms in terms of both number and person features. For example, the *tu* pronoun refers to the second-person singular, whereas the –/õ/ verbal ending in future form refers to the first- and the third-person plural.

Regarding the other critical factor of this study, called associative frequency, we collected the co-occurrence frequency between pronominal subjects (*'tu', 'vous', 'nous'*, and *'je'*) and their associated verbal inflection from large language corpora of film subtitles (New et al., 2007), accessible on the Lexique website (www.lexique.org). We used the following formula from Van Petten (2014) to obtain the value of the associative frequency (for similar approach with behavioural measures in semantic priming, see Brunellière, Perre, Tran, & Bonnotte, 2017):

$$log_2\left(\frac{ct * corpus\ size}{c * t * span}\right)$$

c is the frequency of the pronoun meanwhile *t* is the frequency of the inflection; *corpus size* refers to the size of the corpus; *ct* is the frequency which with the pronoun and the inflection co-occur, and span is the distance between the pronoun and the inflection. It appears that the associative frequency between the *nous* pronoun or the *vous* pronoun and a particular verbal inflection is high (respectively, 7.8 and 5.6), whereas the associative frequency between the *je* pronoun or the *tu* pronoun and its particular verbal inflections is low (around 3). High associative frequency thus means that the pronoun has a high co-occurrence frequency with one verbal inflection in French language use (e.g., the *vous* pronoun and the –/e/ verbal inflection), even though the pronoun was necessarily not followed by this particular verbal inflection in the experimental design.

To avoid exposing participants to repeated presentations of the same verb targets, four different lists were created. Each verb target was presented in the four experimental conditions of the grammaticality factor (Congruent, Person violation, Number violation, Person and Number violation) across all participants by varying the pronoun prime. The psycholinguistic properties of verb targets were equivalent between experimental conditions in each list. In addition to the experimental stimuli, other stimuli consisted of article-nouns pairs (297) and pronoun-verbs pairs in the present and past forms (132), and word-pseudoword pairs (297) in each of these lists remained the same. These pairs were used as fillers to prevent strategies related to subject-verb dependencies and subject-verb violations. In total, 20% of all presented stimuli had a subject-verb violation. For the purpose of the task, pseudo-words were presented as targets. To make sure that participants paid attention, 30% of all presented targets were pseudowords. Pseudowords were constructed by replacing the first or second syllable from French verbs and nouns. Pseudowords were generated by the multilingual pseudoword generator Wuggy (Keuleers & Brysbaert, 2010), and it was checked that pseudowords followed the phonological rules of French.

All stimuli were produced several times by a female French native speaker in a soundproofed room, and the recordings were digitally sampled at 48 kHz with 16-bits. The speaker was asked to pronounce the stimuli with natural prosody at normal speaking rate. We selected the best pronunciation of each stimulus. Through the voice analysis software, Praat (Boersma, & Weenink 2011), we extracted the mean intensity, the mean fundamental frequency and the duration on the critical verb targets. The verbal forms ending with –/a/ or –/õ/ suffixes were equivalent for the mean intensity (mean for all verb targets ending with –/a/: 70.5 dB; –/õ/: 71.5 dB), for the mean fundamental frequency (mean for all verb targets ending with –/a/: 172 Hz; –/õ/: 174 Hz) and for the duration (mean for all verb targets ending with –/a/: 692 ms; –/õ/: 714 ms).

Procedure

Participants were seated in front of the computer in a sound attenuated and shielded chamber. Stimuli were delivered through psychotoolbox (Brainard, 1997) and the auditory stimuli were presented through a normal earphone binaurally at a comfortable sound level. Every trial began with a fixation cross for 300 ms in the center of the monitor followed by the presentation of the auditory prime. There was then an interval of fifty milliseconds between the auditory prime and the auditory target. The fixation cross remained on the screen during the presentation of primes and targets and persisted until 1500 ms after the offset of the target. To reduce motor artifacts, participants

were asked to avoid making any movements when the fixation cross appeared. After a 1000-ms intertrial interval, the next fixation cross was presented. In each trial, participants were asked to determine whether the target they heard was a word or non-word. They were asked to perform a no-go lexical decision task in which they pressed the space bar only when the target was a pseudoword. Participants first received a practice block of thirty-three trials comprising all the experimental conditions to familiarize them with the task. The experimental trials were then divided into three blocks, each block consisting of 330 pairs. Each block lasted around 20 minutes and was composed of stimuli from all experimental conditions and fillers randomly presented. Each block was followed by a break, and participants could take as much time as they wanted between blocks.

Electrophysiological recording and pre-processing

The EEG data was recorded with 128-channel BioSemi ActiveTwo AD-Box at the sampling rate of 1024 Hz. Four external electrodes were used; two were used to measure the ocular movements for blinking and eye movement rejection; the two others placed on the right and left the mastoid area were used as an external off-line reference. The offset values (i.e., the voltage difference between each electrode and the CMS-DRL reference) of all electrodes were kept lower than 20 mV during the recording. Independent component analysis (ICA) to reject artifacts (i.e., eye blinks and movements) was conducted off-line through the Brain Electrical Software Analysis (BESA). The other pre-processing steps were then performed using Cartool (Brunet et al., 2011). The EEG epochs started 50 ms before and lasted 1200 ms after the onset of verbs. Each epoch was filtered offline with a 0.1–30 Hz band-pass filter and corrected to a 50-ms baseline. Epochs were rejected under a rejection criterion of 100 µV for any channel. ERP waveforms were calculated for each participant, experimental condition and electrode. They included at least 22 trials for every participant and for one experimental condition. The total number of accepted epochs was equivalent across the experimental conditions (Low Associative Frequency-Congruent: 29.4; Low Associative Frequency-Person violation: 29.7; Low Associative Frequency-Number violation: 29.6; Low Associative Frequency-Number and Person violation: 29.7; High Associative Frequency-Congruent: 32; High Associative Frequency-Person violation: 32.1; High Associative Frequency-Number violation: 32.5; High Associative Frequency-Number and Person violation: 32.2). The EEG signal was re-referenced offline to an average mastoid reference (left and right).

ERP analyses

The analyses focused on three ERP components, one component commonly elicited by the auditory input (N100) and two ERP components known to be sensitive to the processing of subject-verb agreement (LAN and P600). Based on visual inspection of ERP waves, we extracted the mean amplitude of the N100 component over a time window (100-160 ms) centered on the maximum of the global field power. As in previous studies in agreement processing (Barber & Carreiras, 2005; Mancini, Molinaro, Rizzi, & Carreiras, 2011; Nevins, Dillon, Malhotra, & Phillips, 2007; Silva-Pereyra and Carreiras, 2007), we selected three consecutive time windows of interest to probe the ERP complex of LAN and P600 components. We extracted therefore the mean amplitude of the ERP data in four time windows (100-160 ms, 300-600 ms, 650-850 ms, 920-1120 ms). A three-way repeated analysis of variance (ANOVA) was conducted on the mean amplitude over each time window with independent variables: associative frequency (2: Low vs. High), grammaticality (4: Congruent, Person violation, Number violation, Number & Person violation) and topographical sites (7: Left Anterior: D3-D5, D10-D12, D19-D21; Right Anterior: B22-B24, B29-B31, C3-C5; Frontal: C12-C14, Afz-Fz, C25-C27; Central: Cz-CPz, B1, B2, C1, D1, D15, D16; Left mid-parietal: A6-A8, D17, D26-D30; Left mid-parietal: A6-A8, D17, D26-D30; Posterior: A5, A17-Poz, A30-A32). Each scalp site contained 9 channels, and the scalp sites were chosen to provide appropriate scalp topography for the components of interest. To adjust for violations of sphericity (Greenhouse & Geisser, 1959), the Greenhouse-Geisser correction was applied when there was more than one degree of freedom in the numerator. The corrected *p*-values are reported. When a significant interaction was found, post-hoc Tukey tests were performed to interpret the significance of the effects. Only the significant effects are reported in the text. The ANOVA results over each time window are presented in Table 2. The ANOVA over the baseline period revealed no significant difference between all experimental conditions.

< Insert Table 2 here >

Results

Behavioral results

Participants performed the no-go lexical decision task accurately, as assessed by the rate of correct responses (mean: 89%; range: 73.5-98.4%; median: 94.4%). The mean of hit rates was 0.93 and that of false alarm rates was 0.13. Therefore, participants paid close attention to the targets. The mean of reaction times was 1249 ms after the onset of pseudoword targets.

ERP results

Grand-average waveforms corresponding to the processing of verb targets across the four conditions related to grammaticality are shown for each level of associative frequency in Figures 1 and 2 (respectively, for high and low associative frequency). As seen in Figures 1 and 2, the verb targets elicited the typical auditory N100 response followed by a large anterior negativity and a late positivity in all experimental conditions. Based on visual inspection of ERP data, the number and person violation condition seemed to trigger a larger negative wave occurring between 300 and 850 ms than the congruent condition, whatever the level of associative frequency. Interestingly, the high associative frequency reduced the amplitude of the N100 response and that of the anterior negativity, and decreased the sensitivity to abstract features over a period between 650 and 850 ms. Moreover, the late positive shift from 920 ms was enhanced for both simple violations involving the number or person feature and a double violation with respect to the congruent condition.

< Insert Figures 1 and 2 here >

3.2.1 Time Window between 100-160 ms

In the N100 time window, the ANOVA revealed main effects of associative frequency, $F(1,22)=5.94$, $MSE=37.28$, $p<.05$ and of topographical sites, $F(6,132)=17.01$, $MSE=2.17$, $p<.001$. As seen in Figure 3, the N100 amplitude was stronger for the low associative frequency than for the high associative frequency. In accordance with the traditional topography of the N100, paired Tukey *t*-tests comparisons regarding the topography factor showed there were more negative values over the left and right anterior sites and the central sites relative to the right and left mid-parietal sites and posterior sites ($p<.001$). More negative values were also shown over the frontal sites than the right mid-parietal and posterior sites (respectively, $p<.001$, $p<.05$). As seen in Table 2, no other main effects were found, nor were there any significant interactions.

< Insert Figure 3 here >

3.2.2 Time Window between 300-600 ms

Similar to the N100 time window, the ANOVA revealed a main effect of associative frequency $F(1,22)=7.90$, $MSE=57.65$, $p<.05$, such that the amplitude of the anterior negativity was stronger for the low associative frequency than for the high associative frequency (see Figure 3). There was also a main effect of topographical sites, $F(6,132)=6.91$, $MSE=4.78$, $p<.001$, and contrary to the N100 time window, a main effect of grammaticality was found, $F(3,66)=5.65$, $MSE=31.67$, $p<.01$. Regarding the topographical sites, paired Tukey *t*-tests comparisons indicated that there were more negative values over the left and right anterior sites relative to the left mid-parietal and posterior sites ($p<.001$), showing the elicitation of an anterior negativity over this time window. The right anterior sites also showed more negative values than the right mid-parietal sites ($p<.05$) and the central sites had more negative values than the posterior sites ($p<.05$). The Tukey comparisons related to the grammaticality factor revealed that the amplitude of this anterior negativity was stronger for the number and person violation condition than the congruent condition ($p<.05$, see Figure 4) and than the two other simple violations (person violation, $p<.01$, number violation, $p<.05$, see Figure 3). This suggests that only the double violation was detected over this stage.

< Insert Figure 4 here >

3.2.3 Time Window between 650-850 ms

Similar to the previous time window, main effects of topographical sites, $F(6,132)=35.77$, $MSE=7.59$, $p<.001$, and of grammaticality, $F(3,66)=3.69$, $MSE=56.12$, $p<.05$, were shown. However, no associative frequency effect was found (see Table 2). Regarding the factor of topographical sites, paired Tukey *t*-tests comparisons indicated the right and left anterior sites and the frontal sites had more negative values than the central sites ($p<.001$), the right and left mid-parietal sites ($p<.001$) and the posterior sites ($p<.001$). In addition, both right and left mid-parietal sites revealed more negative values than the posterior sites ($p<.001$). There thus was a sustained frontal negativity over the time window between 650 and 850 ms after the onset of targets. As for grammaticality, the Tukey tests revealed that the amplitude of this frontal negativity was stronger for the double violation involving the number and person features than the congruent condition ($p<.05$). Interestingly, there was also a significant interaction between grammaticality and sites, $F(18,396)=3.06$, $MSE=0.78$, $p<.01$, and a significant interaction between grammaticality, sites and associative frequency, $F(18,396)=2.90$, $MSE=0.72$, $p<.05$. The increased amplitude of the negativity elicited by the number and person violation condition with respect to the congruent condition was observed over all sites ($p<.001$). Paired Tukey *t*-tests comparisons also revealed that the amplitude of the negativity elicited by the number and person violation condition was higher than that elicited either by the person violation condition or by the number violation condition over all sites ($p<.001$). Moreover, the amplitude of the negativity elicited by the two simple violations involving number or person feature was stronger than that of the congruent condition over the left and right anterior sites ($p<.05$) and the frontal sites ($p<.01$), suggesting that the detection of simple violations occurred at this stage contrary to the previous time window (see Figures 1 and 2).

The interactive effects between grammaticality and sites also depended on the associative frequency. As seen in Figures 1 and 2, it seems that the amplitude of the negativity was increased by the double violation condition compared to the other conditions over all sites ($p<.001$) but there was no difference between the simple violation conditions and the congruent condition if the associative frequency was high. In contrast, when the associative frequency was low, the negativity elicited by the simple violation condition involving the number feature differed from that for the congruent condition in terms of an increased amplitude over the frontal sites ($p<.001$) in addition to the increased negativity elicited by the double violation condition over all sites with respect to the congruent condition ($p<.001$). There was also a significant trend for the simple violation condition involving the person feature ($p=.07$). More precisely, the amplitude of the negativity elicited by the number and person violation condition was higher than that of simple violations involving person or number feature over the left anterior, central, right and left mid-parietal and posterior sites ($p<.001$) and was also stronger than that of person violation over the frontal sites ($p<.05$). When the associative frequency was high, this increased negativity elicited by the number and person violation condition was also higher than that elicited by simple violations involving person or number feature over all sites ($p<.05$).

To sum-up, when the associative frequency was either low or high, the increased amplitude of the negativity elicited by the number and person violation condition with respect to the congruent condition was observed over all sites ($p<.001$). Interestingly, when the associative frequency was low, there was a frontal negative shift associated by the processing of the simple violations , such that the amplitude of the negativity elicited by the number violation condition was higher for the low associative frequency than for the high associative frequency over the frontal sites ($p<.001$). A low associative frequency between the pronoun and the verbal inflection facilitated more the detection of simple violations than that of the double violation.

3.2.4 Time Window between 920-1120 ms

Over this late time window, there was no effects of associative frequency or grammaticality (see Table 2). However, the ANOVA analysis revealed a main effect of topographical sites, $F(6,132)=28.18$, $MSE=9.94$, $p<.001$, and a significant interaction between grammaticality and topographical sites, $F(18,396)=3.53$, $MSE=1$, $p<.01$. Regarding the topographical factor, the Tukey *t*-tests indicated that the posterior sites had more positive values than the other sites ($p<.05$). There were also more positive values over the right and left mid-parietal sites as well as the central sites than the right and left anterior sites and the frontal sites ($p<.001$). Similar to the P600 described in the prior literature, a clear positivity with a maximum amplitude over the most posterior part across the scalp was found over this time window. Moreover, the amplitude of this positivity was influenced by the grammaticality factor over particular sites. The paired Tukey *t*-test comparisons showed that the amplitude of the positivity was stronger for simple violations involving the number or person feature or for a double violation than for the congruent condition over the posterior sites (respectively, $p<.001$; $p<.001$, $p<.05$, see Figure 5). In addition, the late positivity was also enhanced in amplitude over the right mid-parietal sites after simple violations involving the number or person feature with respect to the congruent condition (p<.001) and over the left mid-parietal sites after the simple violation involving the number feature than the congruent condition (p<.05) and the double violation of number and person features (p<.05). The simple violations involving the number or person feature elicited a positive response which was more distributed across the posterior part of the scalp.

< Insert Figure 5 here >

Discussion

The purpose of this study is to shed light on the representations that are accessed and their associated processing routines during the computation of subject-verb agreement. Two types of representations stored in memory have been described by two opposing theoretical views. Although a probabilistic constraint-based view (Truswell & Tanenhaus, 1994; Seidenberg & MacDonald, 1999) proposes that the associative lexical representations code the probability between words, such as within a subject-verb relationship, a generative syntax view (Carminati, 2005; Chomsky, 1959; Harley and Ritter, 2002) assumes that abstract morphosyntactic features, such as gender, number and person, are represented separately and are computed via an agreement mechanism. It must be considered that both abstract features and associative representations can be used during the computation of subject-verb agreement and that their time courses of access during the computation of subject-verb agreement need to be known. To this end, we manipulated the nature of subject-verb agreement violations in term of abstract features (single violation of person feature, single violation of number feature, and double violation of person and number features) and the associative frequency related to pronouns which had either a high co-occurrence frequency with one verbal inflection in French (high associative frequency) or a low co-occurrence frequency (low associative frequency). To the best of our knowledge, no study has yet looked at the time course of the access to abstract and associative representations during the computation of subject-verb agreement in spoken language. The present study thus explores the access to abstract and associative representations in subject-verb agreement processing by using event-related potentials (ERP) when spoken verbs were preceded by spoken pronouns that either share or do not share the same grammatical properties.

As expected, we found the typical auditory N100 response followed by the ERP complex usually observed in the processing of subject-verb agreement, which is composed of an anterior negativity and a late positivity. Interestingly, the N100 response was influenced by the associative frequency, such that its amplitude was reduced when the associative frequency was high. The amplitude of anterior negativity occurring in a time window between 300 and 600 ms was affected separately by the associative frequency and the grammaticality between the subject and the verb. Similar to the N100, the amplitude of the anterior negativity was reduced when the associative frequency was high. In addition, this component was sensitive to the checking of abstract features in subject-verb dependencies, such that only the double violation involving both the number and person features elicited an increased negative amplitude with respect to the congruent condition. Later on, the associative frequency and the checking process on the abstract features affected interactively the amplitude of a sustained frontal negative wave. During this wave, the simple violations involving the number or person feature were detected. Thereafter, a parietal positivity wave similar to the P600 component, was enhanced by all types of agreement violations with respect to the congruent condition. The implications of these findings merit attention, and we discuss below them according to previous literature.

Early Stages of Word Processing: the N100

The N100 is indexing perceptual processing of auditory input and phonological processing (Krumbholz, Patterson, Seither-Preisler, Lammertmann, & Lütkenhöner, 2003; Näätänen, 2001; Obleser, Scott, & Eulitz, 2006). Even though the N100 reflects the initial stages of bottom-up processing at the acoustic and sub-lexical levels, this component is also sensitive to top-down information, such as lexical context (e.g., Getz & Toscano, 2019; Noe, & Fischer-Baum, 2020). According to a predictive coding theory (Bar, 2009; Friston, 2005; Rao and Ballard, 1999), predictions are derived from information going from hierarchically higher to lower areas via a top-down processing. This optimizes the processing of incoming information by reducing the processing demands over time and top-down predictions are computed based on prior knowledge and the statistical regularities of context. In line with this view, the perceptual processing of verbs was affected by the associative frequency after hearing pronouns in the present study. This finding showed for the first time that the processing of pronouns triggered top-down predictions based on associative representations, such that the strength of predictions between pronouns and verbal inflections constrained the processing of auditory levels according to their co-occurrence frequency in the language use. This finding claims in favor of the role of prediction in language comprehension (for reviews, see Huettig, 2015; Kuperberg & Jaeger, 2016; Pickering, & Gambi, 2018) and reinforces the idea that the brain actively and immediately makes predictions about the upcoming input (Bar, 2007). The demonstration of prediction occurs when a study indeed reveals activation of a linguistic representation before the comprehender encounters the predicted information, such that in previous ERP studies (e.g., Foucart, Ruiz-Tada & Costa, 2015; Van Berkum, Brown, Zwitserlood, Kooijman, & Hagoort, 2005; Wicha, Bates, Moreno, & Kutas, 2003), the processing of an adjective or an article was shaped by the prediction of the upcoming noun. Our findings in spoken language are therefore consistent with other electrophysiological studies pointing out that contextual predictability effects in written language comprehension can affect the early sensory responses, such as the visual cortex (Kim & Lai, 2012; Dikker & Pylkkänen, 2011; Dikker, Rabagliati, & Pylkkänen, 2009). This study thus provides a better understanding of computational operations in subject-verb agreement by showing that associative representations are involved in the top-down predictions during the computation of subject-verb agreement.

Different Stages of subject-agreement processing: From anterior negativity to P600

As usually found in prior literature (for a review, Molinaro, Barber, & Carreiras, 2011), the agreement mismatches evoked a biphasic electrophysiological pattern with an anterior negativity occurring in a time window from 300 ms after the word onset followed by a late posterior positivity. Regarding the brain’s reaction to morphosyntactic violations, only the double violation involving both the number and person features first elicited an enhanced amplitude of the bilateral anterior negative wave, then the simple violations were detected and the reaction to morphosyntactic violations depended on the associative frequency over a time window between 650 and 850 ms. The detection of morphosyntactic violations over a time window from 300 ms was consistent with the temporal properties of stimuli and the rapidity of processes involved in spoken word recognition (Marslen-Wilson, & Welsh, 1978). Moreover, the topography of negativity elicited by agreement violations in the present study was not left-lateralized but others electrophysiological studies (Hinojosa, Martin-Loeches, Casado, Munoz, & Rubia, 2003; Leinonen, Brattico, Jarvenpaa, & Krause, 2008) reported anterior bilateral negative effects for agreement mismatches without a clear left maximum. In the same vein, the two previous ERP studies exploring French subject-verb agreement relations in spoken language (Brunellière, 2011; Isel, & Kail, 2018) found an anterior negativity without a left predominance. Regarding the access of abstract features, there was an earliness to detect the double violation in comparison with simple violations. It also is interesting to observe that the topography of negative shifts elicited by the morphosyntactic violations was dependent on the nature of morphosyntactic violations. In line with a distinct storage of abstract morphosyntactic features (Carminati, 2005; Chomsky, 1959; Harley and Ritter, 2002), the negative shifts elicited by morphosyntactic violations appeared all over the scalp for the double violation, whereas the negative shift triggered by the simple violation was found only over the anterior and frontal sites. The primacy of brain responses elicited by the double violation in comparison with the simple violations and their particular topographical effects are in accordance with previous ERP studies in subject-verb agreement (Mancini, Molinaro, Rizzi, & Carreiras, 2011; Nevins, Dillon, Malhotra, & Phillips, 2007; Silva-Pereyra, & Carreiras, 2007) focusing on the representations of abstract features in Spanish and Hindi. It was indeed shown that abstract morphosyntactic features, such as number and person, are represented separately and are computed by the agreement mechanism. Moreover, it appeared that the access to feature representations arises during the initial stages of processing after the verbal recognition and persisted later during the repair processes. As previously described in the subject-verb agreement literature at late stages (for a review, Molinaro, Barber, & Carreiras, 2011), negative shifts elicited by morphosyntactic violations were followed by a late positive wave which took place 200 ms after the offset of word targets. While these negativities reflect the early detection of morphosyntactic violations after the verbal recognition, the P600 component is known to be associated with a reanalysis process between the morphological elements and the previous context. By showing that both negative and positive shifts triggered by morphosyntactic violations produced differential patterns between the double violation and the simple violations, this excluded the possibility that the repair processes might be the sole moment during which access to feature representations can be highlighted (Faussart, Jakubowicz, & Costes, 1999).

Remarkably, during the stage of verbal recognition, both abstract and associative representative are accessed during the computation of subject-verb agreement. This stage corresponds to the moment from which the top-down predictions based on associative representations between the pronoun and the verbal inflection meet the bottom-up processing on the incoming verbal inflection. The associative frequency between pronouns and verbal inflections affected the processing of verb targets in the same manner as semantic constraints provided within a sentence. As in previous electrophysiological studies in spoken language comprehension focusing on the influence of semantic constraints of sentence context (e.g., Brunellière & Soto-Faraco, 2015; Connolly et al., 1990, 1992), target words embedded in low constraining context elicited a response with greater negative amplitude in comparison to the same targets when embedded in high constraining context (hence, more predictable) in a time window from 300 ms after the word onset. It can be defined that the high associative frequency between a pronoun and a verbal inflection provides a high constraining context from hearing this pronoun which can cause a strong pre-activation of the associated verbal inflection. Another aspect comparable with the results found in the semantic constraints of sentence context is that the brain reaction to morphosyntactic violations was more sensitive to the access to abstract features stemming from the bottom-up processing in low-constraining pronoun context. For instance, some electrophysiological studies in sentence context (e.g., Brunellière & Soto-Faraco, 2015) already demonstrated that less predictable sentence contexts led to a finer sensitivity to bottom-up processing. The present findings are also suggestive of flexible processing routines that could be involved in the expectancy for the target functional morphology, since the top-down predictions based on associative frequency did not operate early in interaction with the access to abstract features. Later on, the top-down predictions based on associative frequency and the checking process on the abstract features interacted together when the verb is completely recognized and combined with the grammatical properties of the subject. Then, the repair processes are not sensitive to the top-down predictions based on associative representations between the pronoun and the verbal inflection.

Representations involved in the subject-verb agreement

The present study provides interesting contributions about the nature of the representations from which subject-verb agreement is computed by showing that both abstract and statistically-based representations (i.e., frequencies of occurrence) are stored in memory and used in the computation of subject-verb agreement. The present findings are in favor of the representation of abstract morphosyntactic features, since a double violation involving two morphosyntactic features elicited earlier and larger negative responses than a violation of a single feature. Similar to the semantic model proposed by Plaut and Booth (2000), it may be suggested that two separate networks are formed in memory about agreement processing: one purely lexical with connections built through repeated occurrences between words (e.g., pronouns and verbal inflections), and the other purely abstract including the morphosyntactic features. Accordingly, the more parts of words are unfolded, the more the two networks (lexical and abstract) are connected together after the recognition of verbal inflection. This was revealed by the later interactive effects between associative frequency and the access to abstract features over a time window comprising between 650 and 850 ms. Further neuroimaging and computational studies are needed to explore in more detail the two separate networks and their dynamics of activity. Up to now, prior studies focusing on the representations of abstract features involved in subject-verb agreement (Mancini, Molinaro, Rizzi, & Carreiras, 2011; Nevins, Dillon, Malhotra, & Phillips, 2007; Silva-Pereyra, & Carreiras, 2007) have never probed the access to associative representations and studied the subject-verb agreement only in visual modality. Moreover, the methodological advantage of the present study is that the presentation of short spoken sentences, composed of a pronoun and a verb, enables us to avoid the integration of discourse-level information within the computation of subject-verb agreement.

Conclusion

First, we have been able to replicate in spoken short sentences the traditional findings showing a sensitivity to morphosyntactic violations and abstract features, as reflected by the variations in the amplitude of anterior negativity and P600. Second, we have shown that associative representations are accessed during the processing of subject-verb agreement. Relating to the associative representations, this study has confirmed that statistical properties played a role in agreement processing. We therefore need to consider this factor for future studies in order to have better understanding of agreement processing. By using the associative representations after hearing the pronoun, the cognitive system actively makes a prediction about the morphosyntactic information, leading up to affect the verbal processing at low levels.

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Tables

Table 1. Examples of stimuli for all experimental conditions

Grammaticality	**Associative Frequency**	**Examples in written forms**
Congruent	Low	*Tu (2nd ps) marcheras (2nd & 3 rd ps)* You will walk
	High	*Nous (1^{rst} pp) sauterons (1^{rst}& 3 rd pp)* We will jump
Person violation	Low	*Je (1^{rst} ps) marcheras (2nd & 3 rd ps)* I will walk
	High	*Vous (2nd pp) sauterons (1^{rst}& 3 rd pp) You will jump*
Number violation	Low	*Je (1^{rst} ps) sauterons (1^{rst}& 3 rd pp)* *I will jump*
	High	*Vous (2nd pp) marcheras (2nd & 3 rd ps)* *You will walk*
Number & person violation	Low	*Tu (2nd ps) sauterons (1^{rst}& 3 rd pp)* *You will jump*
	High	*Nous (1^{rst} pp) marcheras (2nd & 3 rd ps)* *We will walk*

Grammatical properties provided by the phonological forms of verbal endings are displayed in parenthesis (pp: person plural; ps: person singular).

Table 2. Statistical results of ERP data across the four time windows (100-160 ms, 300-600 ms, 650-850 ms, 920-1120 ms)

	Time window between 100-160 ms	**Time window between 300-600 ms**
Associative frequency	$F(1,22)=5.94$, $p<.05$	$F(1,22)=7.90$, $p<.05$
Grammaticality	$F(3,66)=2.15$, $p=.11$	$F(3,66)=5.65$, $p<.01$
Sites	$F(6,132)= 17.01$, $p<.001$	$F(6,132)= 6.91$, $p<.001$
Associative frequency x Grammaticality	$F(3,66)=1.39$, $p>.2$	$F(3,66)=0.45$, $p>.2$
Associative frequency x Sites	$F(6,132)=2.78$, $p=.06$	$F(6,132)=0.75$, $p>.2$
Grammaticality x Sites	$F(18,396)=1.08$, $p>.2$	$F(18,396)=1.42$, $p>.2$
Associative frequency x Grammaticality x Sites	$F(18,396)=1.79$, $p=.10$	$F(18,396)=1.27$, $p>.2$
	Time window between 650-850 ms	**Time window between 920-1120 ms**
Associative frequency	$F(1,22)=3.87$, $p=.06$	$F(1,22)=1.67$, $p>.2$
Grammaticality	$F(3,66)=3.69$, $p<.05$	$F(3,66)=0.51$, $p>.2$
Sites	$F(6,132)= 35.77$, $p<.001$	$F(6,132)= 28.18$, $p<.001$
Associative frequency x Grammaticality	$F(3,66)=0.05$, $p>.2$	$F(3,66)=0.09$, $p>.2$
Associative frequency x Sites	$F(6,132)=1.36$, $p>.2$	$F(6,132)=1.85$, $p=.14$
Grammaticality x Sites	$F(18,396)=3.06$, $p<.01$	$F(18,396)=3.53$, $p<.01$
Associative frequency x Grammaticality x Sites	$F(18,396)=2.90$, $p<.05$	$F(18,396)=1.63$, $p=.12$

Figure Captions

Figure 1. Grand-average ERP waveforms time-locked to the auditory onset of target words embedded in a high associative frequency with the pronoun prime across the four experimental conditions of the grammaticality (Congruent, Person violation, Number & Person violation, Number violation).

Figure 2. Grand-average ERP waveforms time-locked to the auditory onset of target words embedded in a low associative frequency with the pronoun prime across the four experimental conditions of the grammaticality (congruent, number violation, person violation, number violation and number & person violation).

Figure 3. Mean and SEM bars of ERP amplitude in the 110-160 ms and 300-600 ms time windows across the two modalities of the associative frequency factor (High versus Low). *p<.05

Figure 4. Mean and SEM bars of ERP amplitude in the 300-600 ms time window across the four modalities of the grammaticality factor (in black, congruent condition, in green, number violation, in blue, person violation, and in red, number & person violation). *p<.05; **p<.01

Figure 5. Mean and SEM bars of ERP amplitude in the 920-1120 ms time window across the four modalities of the grammaticality factor (in black, congruent condition, in green, number violation, in blue, person violation, and in red, number & person violation). *p<.05; **p<.01; **p<.001

Figure 1

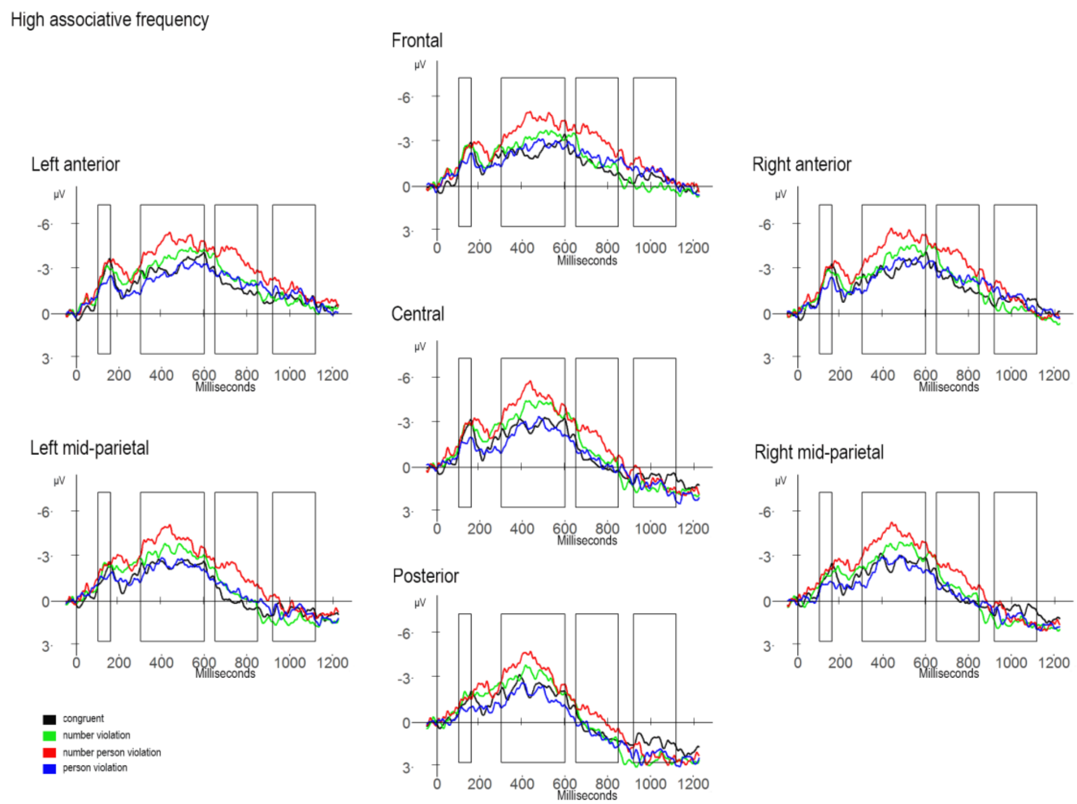
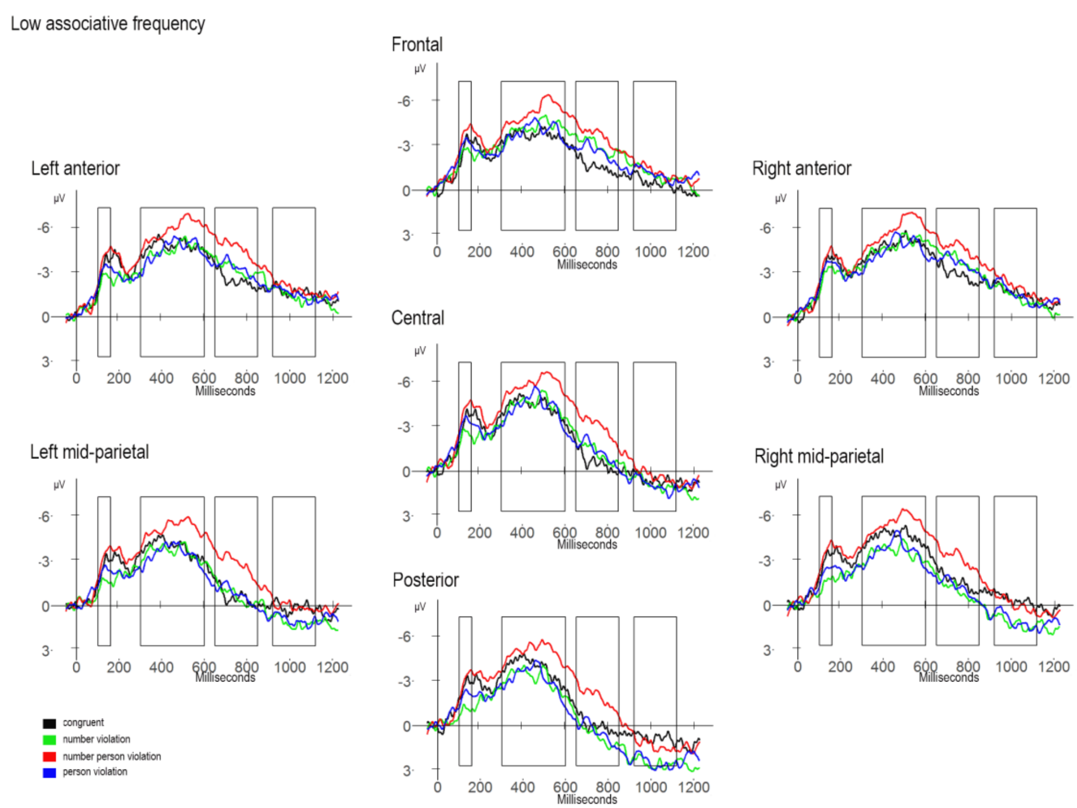
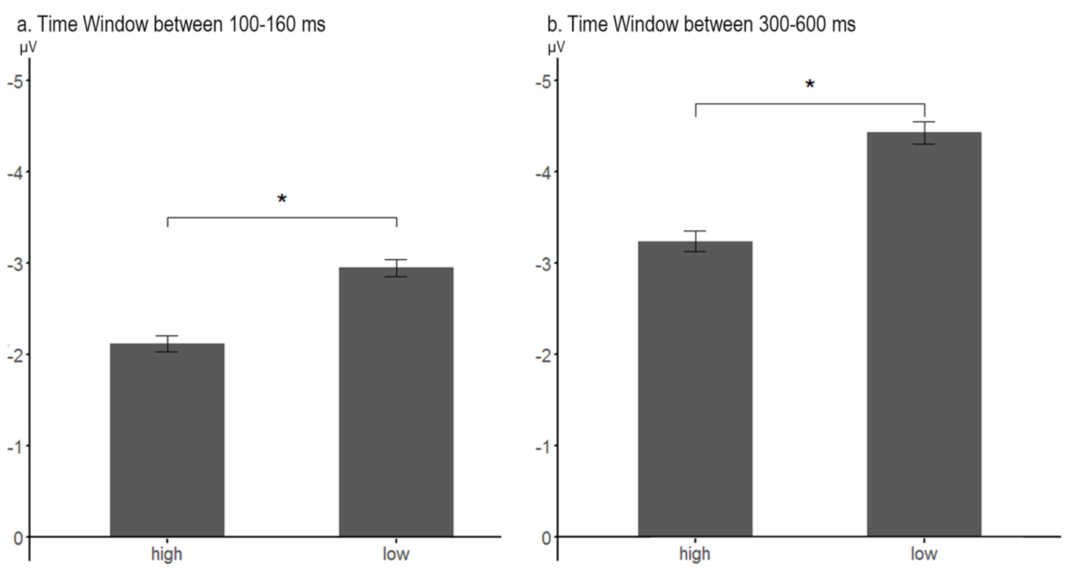

High associative frequency
Frontal
Left anterior
Right anterior
Central
Left mid-parietal
Right mid-parietal
Posterior
μV
-6
-3
0
3
0
200
400
600
800
1000
1200
Milliseconds
congruent
number violation
number person violation
person violation

Figure 2



Low associative frequency
Frontal
Central
Posterior
Left anterior
Left mid-parietal
Right anterior
Right mid-parietal
µV
Milliseconds
congruent
number violation
number person violation
person violation

Figure 3



a. Time Window between 100-160 ms
µV
-5
-4
-3
-2
-1
0
*
high
low
b. Time Window between 300-600 ms
µV
-5
-4
-3
-2
-1
0
*
high
low

Figure 4

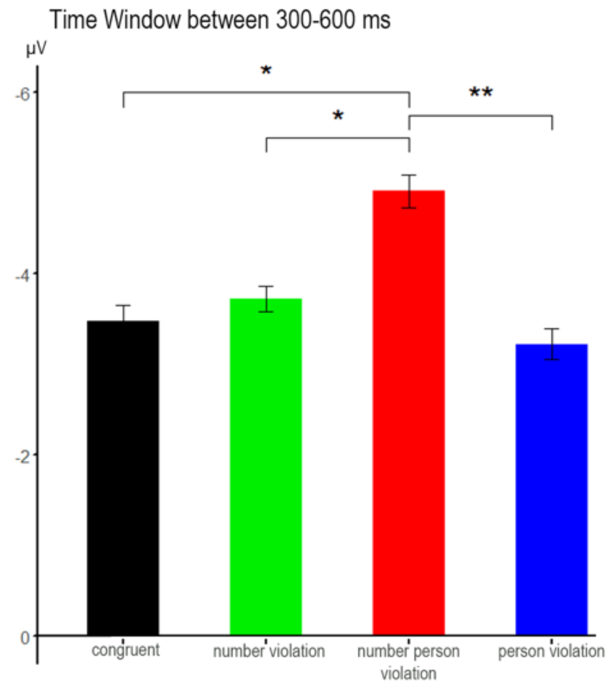
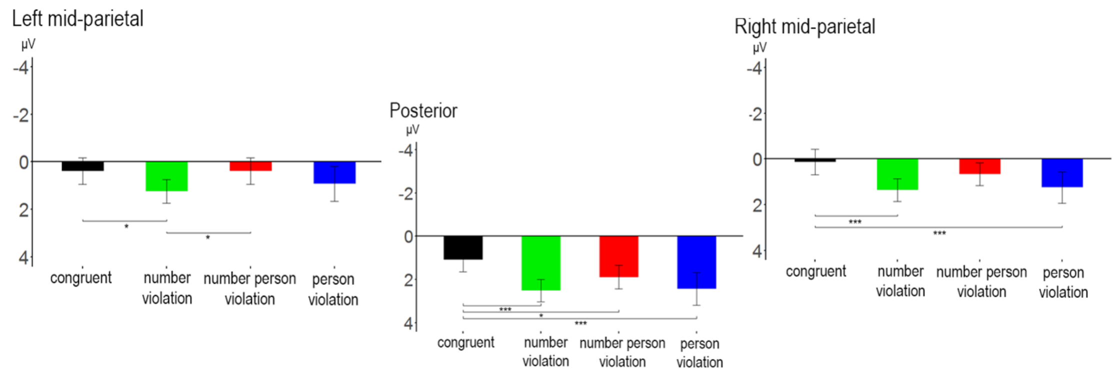

Time Window between 300-600 ms
μV
-6
-4
-2
0
*
*
**
congruent
number violation
number person violation
person violation

Figure 5



Left mid-parietal
µV
-4
-2
0
2
4
*
*
congruent
number violation
number person violation
person violation
Posterior
µV
-4
-2
0
2
4
***
*
***
congruent
number violation
number person violation
person violation
Right mid-parietal
µV
-4
-2
0
2
4
***
***
congruent
number violation
number person violation
person violation