An event-related brain potential (ERP) study on cross-modal action/verb and grammatical number matching in French: Adult control data for a follow-up study on developmental language impairment (DLI)

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Abstract

The present event-related brain potentials (ERP) study investigates questions concerning the neurocognitive mechanisms underlying the processing of semantic and morphosyntactic information in French sentence comprehension. Using an audio/visual sentence-picture matching paradigm, we investigate two types of anomalies: (i) lexico-conceptual semantic mismatches between visually presented actions and spoken verbs, and (ii) morphosyntactic number mismatches between the visually presented image and the spoken sentence. We varied the type and amount of number cues available in each sentence by adding two manipulations: (1) verb type, whereby each sentence contained either a verb whose number cue was only audible at the junction between the verb and the preceding subject pronoun by a liaison (Type-2), or a verb whose number cue was only audible on the verb ending (Type-3), (2) a context manipulation, whereby each sentence was preceded by either a neutral context phrase or a subject noun phrase (NP), the former providing no additional cue as to number and the latter containing a sentence-initial determiner as a cue. To our knowledge, we are the first to investigate the contribution of different number cues in such a systematic fashion.

This study was designed as part of a larger research project aiming to provide a better understanding of French language acquisition and comprehension abilities in children with developmental language impairment (DLI). ERP studies investigating DLI are scarce, and hardly any of these investigate French. In order to meaningfully interpret the child data that will be collected later on, we tested a control group of 16 neurotypical adult French native speakers to establish the prototypical ERP correlates for the anomalies included in the experimental paradigm. By comparing adult data to the data obtained later from children, we will be able to determine whether children with DLI demonstrate relative strengths/weaknesses in different linguistic areas (i.e., semantics, morphosyntax) and whether they exhibit immature or atypical processing strategies.

For Type-2 verbs, adult participants reliably exhibited distinct ERP components for auditory-visual verb-action mismatches (N400) and auditory-visual morphosyntactic number mismatches (LAN/P600), extending research conducted in the visual domain (i.e., reading studies) to include our cross-modal design and French stimuli. Our context manipulation demonstrated that if multiple cues are available to identify the subject number (and therefore also to detect number match or mismatches with the image), adult participants use the first available cue in the sentence to detect the mismatch, and do not show an additional mismatch effect at the position of the second cue.

Future steps involve investigating the sociolinguistic and phonological factors that may have affected interpretation of a subset of sentences, and completing data analysis so we can begin our studies on children with DLI.

Résumé

La présente étude utilise les potentiels évoqués (PÉs) afin d'étudier les mécanismes neurocognitifs sous-tendant le traitement de l'information sémantique et morphosyntaxique lors de la compréhension de phrases en français. Utilisant un paradigme d'appariement d'images et de phrases présentées en modalité auditive, deux types d'incongruences ont été étudiées : (i) des incongruences relevant de la sémantique lexico-conceptuelle entre l'action présentée visuellement et le verbe présenté oralement, (ii) des incongruences morphosyntaxiques concernant l'accord en nombre entre l'image présentée visuellement et la phrase présentée oralement. Deux manipulations permettaient de varier le type ainsi que la quantité d'indices relatifs au nombre disponibles dans chaque phrase. Premièrement, le type de verbe utilisé plaçait l'indice de nombre à différentes positions dans la phrase : soit au niveau de la liaison entre le verbe et le pronom sujet qui le précédait (verbes de Type-2), soit au niveau de la terminaison du verbe (verbes de Type-3). Deuxièmement, le syntagme précédant chaque phrase permettait de manipuler le contexte : un syntagme contextuellement neutre ne fournissait pas d'indice de nombre supplémentaire, tandis qu'un syntagme nominal sujet incluait dès le début un déterminant comme indice de nombre. À notre connaissance, notre étude est la première à examiner de manière aussi systématique la contribution de différents indices de nombre dans la compréhension de la phrase.

Cette étude fait partie d'un projet de recherche visant à mieux comprendre l'acquisition du français ainsi que les habiletés de compréhension du langage des enfants avec un trouble développemental du langage (TDL). Les études en PÉs étudiant le TDL sont rares et presque qu'aucune d'entre-elles ne s'intéresse au français. Un groupe contrôle composé de 16 adultes neurotypiques ayant le français comme langue maternelle a été testé afin d'identifier les PÉs prototypiques correspondant aux différentes anomalies de notre paradigme expérimental. Ces résultats permettront ainsi d'interpréter adéquatement les données qui seront ultérieurement recueillies chez les enfants. En effet, en comparant les données des enfants à celles des adultes, il sera possible de déterminer si les enfants ayant un TDL démontrent certaines forces ou des faiblesses dans différents domaines linguistiques (ici sémantique et morphosyntaxe) et s'ils présentent des stratégies de traitement immatures ou atypiques.

Pour les verbes de Type-2, les participants adultes ont systématiquement démontré des composants PÉs distincts entre les incongruences auditives-visuelles relevant de la sémantique lexico-conceptuelle (N400), et les incongruences auditives-visuelles morphosyntaxiques au niveau de l'accord en nombre (LAN/P600). Ces données résultant de notre design intermodal et de nos stimuli en langue française viennent enrichir la recherche conduite en modalité visuelle (p.e. les études portant sur la lecture). La manipulation du contexte à l'aide de différents syntagmes a démontré que les adultes utilisent le premier indice disponible dans la phrase pour détecter l'incongruence, et ne démontrent pas d'effet additionnel si un deuxième indice est présent par la suite.

Les étapes suivantes porteront, d'une part, sur l'étude des facteurs sociolinguistiques et phonologiques pouvant influencer l'interprétation d'un sous-ensemble de nos phrases, et d'autre part sur la finalisation de nos analyses afin de pouvoir débuter nos études s'intéressant aux enfants ayant un TDL.

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Acknowledgments and Contributions

Throughout my thesis project, I have been responsible (a) for assisting in the design of our study, (b) for developing part of the stimulus materials, including editing the speech files and setting trigger codes for the ERP analysis, (c) for testing the neurotypical adult control group (all data involving children will be collected and analyzed at the University of Montreal in future studies), (d) for preprocessing and analyzing a subset of the behavioural and ERP data, including statistical analyses, and (e) writing my thesis paper, which was done completely independently (although I received feedback from my supervisors and committee member).

I would like to express my deepest appreciation and gratitude to my research supervisors, Dr. Karsten Steinhauer and Dr. Phaedra Royle, for providing me with the opportunity to develop my research skills and for their willingness to share their knowledge and provide feedback on the first draft of the thesis.

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1. Introduction

1.1 Background and research objectives

The present paper reports on two sub-experiments probing questions concerning the neurocognitive mechanisms underlying the online processing of different types of linguistic information during real-time auditory sentence comprehension in French. These sub-experiments were the initial steps taken as part of a larger research project aiming to provide a better understanding of French language acquisition and comprehension abilities in children with developmental language impairment (DLI). To this end, four populations will ultimately be tested: (i) children with SLI, (ii) chronologically age-matched neurotypical children, (iii) developmentally age-matched neurotypical children, and (iv) neurotypical adults. As my thesis project consisted of preparing the stimuli and testing the neurotypical adult control group, I will provide background on the project as a whole but later report only on the sub-experiments involving neurotypical adult control subjects. Further, as most of my work, especially in terms of data analysis, focused on the second sub-experiment (Sub-experiment 2), I will discuss this study in much greater detail.

Although DLI is one of the most common childhood learning disabilities (Bishop, 2009), its underlying deficits and developmental trajectories are still poorly understood. Both language production and comprehension show some level of impairment in affected individuals, but studies on DLI often focus on aspects of language production (Leonard & Owen, 2000), possibly because production difficulties are more salient. Studies investigating linguistic comprehension in DLI are mainly based on behavioural experimental paradigms, which cannot directly measure underlying language competence, as children tend to be much less reliable than adults when asked to perform behavioural tasks such as grammaticality or acceptability judgments. A related issue is that different domains of linguistic competence do not appear to be equally impaired in children with DLI, who have demonstrated relative strengths in lexical-semantics (word meaning) but difficulties with aspects of morphosyntax (grammar). Also, it is unclear whether children with DLI show immature or atypical language processing strategies. Moreover, because studies on DLI are almost absent in French, we do not know whether highlighted strengths (e.g., lexical semantics) and weaknesses (e.g., morphosyntax) are the result of language-specific properties or general properties of DLI.

In light of the rapidity with which the human brain integrates different types of linguistic information during online language processing, the event-related potentials (ERP) technique, which renders millisecond-to-millisecond temporal resolution, offers the possibility of investigating how and when these processes unfold in real time (Rugg, 1995). This technique therefore profitably affords investigation into the neurocognitive processes underlying language comprehension. Few ERP studies have investigated language comprehension in children with DLI, and most do not use adult control subjects for comparison. This renders the task of meaningfully interpreting child data quite challenging; other available data from adults cannot be used as a comparison, because any observed group differences may be due to differences in tasks or modality, rather than processing differences between the two groups. The best methodological approach, therefore, is to test adult controls with the exact same stimulus materials and presentation paradigm designed for the child population to be tested.

Considering these apparent shortcomings, we developed an ERP study comprised of two sub-experiments, where we implement an auditory/visual sentence-picture matching paradigm to investigate questions concerning the processing of lexico-semantic, morphosyntactic, and syntactic information. Importantly, this paradigm obviates reading processes that may not be robust in children, while maintaining their interest and attention. Sub-experiment 1 investigates the processing of: (i) lexical-semantic mismatches between visual objects and spoken nouns, (ii) noun-adjective gender agreement (morphosyntax), and (iii) adjective placement relative to the noun (noun-phrase syntax). Sub-experiment 2 investigates the processing of: (i) lexical-semantic mismatches between visually presented actions and spoken verbs, and (ii) auditory-visual subject number mismatches (morphosyntax), where we also vary the types of number cues available for disambiguation.

Our adult controls were tested with the exact same stimulus materials and presentation paradigm that will be used for the child groups, as this is the best methodological approach for meaningfully interpreting the child data that will be collected in future studies. The goal of the present study is therefore to establish prototypical ERP correlates in young, neurotypical adults for the various linguistic anomalies in the experimental paradigm as a baseline for future studies on children. Our research objectives for this control group consist of determining: (i) whether neurotypical adult French native speakers will elicit distinct ERP components for auditory-visual lexico-conceptual semantic mismatches involving actions/verbs, and for auditory-visual morphosyntactic number mismatches, and (ii) whether these adults, when presented with multiple cues for the disambiguation of number mismatches, rely solely on the first available cue.

The remainder of this Introduction begins with a brief background on DLI and theoretical accounts for it. This is followed by an introduction to the ERP technique and components of interest, as well as a brief summary on adult processing of agreement violations, and language processing in neurotypical children and those with DLI. Finally, the Introduction concludes with an account of the experimental manipulations and predictions generated for the present study.

1.2 Developmental language impairment

DLI is often described as a neurodevelopmental impairment linked to persistent difficulties in the linguistic domain, affecting different modalities (i.e., oral and written) and both language comprehension and production. The prevalence of DLI in children aged 5 years is 9.4%, and of this number, 72% have persistent language difficulties at age 12 (OOAQ, 2014). Affecting approximately 7% of the total population, DLI is one of the most common developmental disorders. Although commonly referred to as "Specific Language Impairment" (SLI), here we follow a recent suggestion to use the term DLI that was introduced both (1) in order to emphasize the developmental context, and (2) because the 'language specificity' of the disorder is controversial (Bishop, Snowling, Thompson, & Greenhalgh, 2017), as will be discussed briefly below.

DLI can affect all areas of language, however cross-linguistic investigations have demonstrated that aspects of grammar (i.e., morphology and syntax) and phonology (i.e., phonological working memory) tend to be more strongly affected than other cognitive domains (Leonard, 2014b). Several theoretical models of DLI have accounted for these difficulties by postulating that certain linguistic areas are 'deficient' in DLI. For example, Leonard (2014a) reports explanatory theories that converge towards a deficit in syntactic mechanisms, which would account for the observed weaknesses in this area relative to other aspects of language. Similarly, the *Procedural Deficit Hypothesis* put forth by Ullman and Pierpont (2005) highlights that children with DLI show strengths in semantics, relative to their difficulties in the areas of (morpho)syntax and phonological working memory, skills which the authors argue rely on the procedural memory. They therefore explain difficulties in (morpho)syntax in terms of deficits in procedural memory, concerned with aspects of grammar, as opposed to declarative (lexical) memory circuits being relatively spared. This model therefore clarifies the relative strengths seen in children with DLI, while accounting for non-linguistic deficits, such as various difficulties with motor skills, that have been seen to coexist with DLI (Bishop et al., 2017; Hill, 2001; Leonard, 2014a).

Recently, van der Lely and Pinker (2014) have put forth an explanatory model of DLI that focuses on the neurological bases of language, in which the linguistic domains of syntax, morphosyntax, and phonology are divided into two levels of complexity and are associated to two processing streams which differ in their processing requirements and rely on distinct brain networks: the *basic* level and the *extended* level. *Basic* representations refer to the processing of canonical word order, holistic elements such as irregular word forms, and aspects related to semantics, and are associated to the ventral processing stream. *Extended* representations refer to the processing of abstract categories defined by their grammatical properties, complex sentences involving hierarchical syntactic structure, as well as morphological rules, and are associated to the dorsal stream. The authors postulate that atypical development of the dorsal stream is responsible for both linguistic and non-linguistic deficits seen in individuals with *Grammatical-Specific Language Impairment* (G-SLI), a proposed subgroup of DLI (Bishop, Bright, James, Bishop & van der Lely, 2000; van der Lely & Stollwerck, 1996). Associated with G-SLI are persistent difficulties in verb production, and comprehension difficulties related to complex syntactic structures (i.e., passive forms), verbal inflection, and words with complex morphological structures.

In sum, morphological and syntactic abilities seem to be more impaired in DLI in comparison to semantic capabilities. However, there is little direct comparison of the relative strengths and weaknesses of children with DLI in the experimental literature. We therefore know little about the neurocognitive mechanisms underlying real-time language processing in DLI, which allow affected individuals to attain functional comprehension despite apparent difficulties. Importantly, our project will provide some necessary elucidation in this area by using ERPs to directly compare abilities in the areas of lexical-semantics, morphosyntax, and syntax.

1.3 Event-related brain potentials and components of interest

Event-related brain potentials (ERPs) are characteristic patterns of voltage change that are extracted from scalp-recorded electrical brain activity (i.e., EEG signals) time-locked to the presentation of stimuli (Luck, 2014). In the study of language processing, ERPs are elicited by performing linguistic manipulations on auditory or visual stimuli, and systematic differences between ERPs are then used to tease apart the action of systems in the brain involved in different aspects of language processing. The virtually unlimited temporal resolution offered by the ERP technique, and its ability to isolate neurocognitive processes, make ERPs an increasingly valuable source of empirical evidence for efforts to chart out the functional organization and temporal dynamics of language processing. ERP research on language processing has outlined several 'neural signatures', referred to as 'components', associated with the processing of different types of linguistic information in the adult native speaker. These components are discussed in terms of polarity (negative vs. positive), latency (onset timing), duration, distribution (scalp topography), and amplitude (strength). ERP components of interest to this project will be discussed below in relation to semantic and morphosyntactic agreement processing in neurotypical adults. A brief summary of experimental data on agreement processing will then be provided.

1.3.1 Semantic processing in adults

One component of interest, first described in Kutas and Hillyard (1980), is called the N400. This negative-going brain wave, which can be elicited by lexical and semantic expectancy violations is often observed between 300 and 500 ms after stimulus presentation, and tends to have a centro-parietal scalp distribution (Kutas & Federmeier, 2000; Steinhauer & Connolly, 2008). For example, when reading a sentence such as *John ate *democracy*, an enhanced negativity (the N400 effect) would be observed in centro-parietal regions 300-500 ms after presentation of the anomalous word (**democracy*), when compared to a semantically congruent sentence such as *John ate broccoli*. The functional interpretation of this component has been under debate. While some studies using word-priming paradigms present the N400 as reflecting costs of integrating a word in a semantic context (Brown and Hagoort, 1993; Holcomb, 1993), another line of research focusing on sentence-level 'expectancy' processes discuss this component as a reflection of the amount of cognitive resources invested in retrieving and recognizing a word (Federmeier, 2007; Kutas & Federmeier, 2000; Lau, Phillips, & Poeppel, 2008). However, the N400 is generally considered a reliable ERP correlate of increased semantic processing, that is often unaffected by task (i.e., the absence versus presence of a task such as acceptability judgments) (e.g., Fischler, Childers, Achariyapaopan & Perry, 1985; Balconi & Pozzoli, 2005; Royle, Drury, & Steinhauer, 2013), unless attention is drawn away from word meaning (Chwilla, Brown & Hagoort, 1995). Although most evidence of N400s has come from reading studies, this component has also been observed more recently in bimodal (auditory-visual or visual-visual) lexical semantic violations where an incongruous or unexpected image is presented concurrently with a written or auditory utterance (see e.g., Friedrich & Friederici, 2004; Willems, Özyürek & Hagoort, 2008; Royle et al., 2013).

1.3.2 Morphosyntactic agreement processing in adults

The *Left anterior negativity* (LAN) is an ERP component that has been reported for a range of morphosyntactic violations, such as verb agreement violations (e.g., *As a turtle grows, its shell *grow too*) (Friederici, 2002). The LAN has been reported both in languages with relatively free word order and rich morphological agreement marking (Italian: Angrilli et al., 2002; Spanish: Barber and Carreiras, 2005), as well as in languages with residual agreement patterns (Dutch: Hagoort and Brown, 2000; English: Osterhout and Mobley, 1995). In response to agreement violations, this component typically emerges between 300 and 500 ms after stimulus presentation. Most agreement studies eliciting LANs have been conducted in the written modality, but a number of auditory studies have reported negativities that occur slightly earlier and that are more frontal and sustained (e.g., Friederici, Pfeifer, & Hahne, 1993; Balconi & Pozzoli, 2005; Rossi, Gugler, Friederici, & Hahne, 2006; Hasting & Kotz, 2008; Morgan-Short, Sanz, Steinhauer, & Ullman, 2010). Interestingly, some authors have also reported LAN effects during the reading of grammatical sentences that required working memory resources in order to be comprehended, such as filler-gap dependencies (Kluender & Kutas, 1993; Streb, Rosler, & Henninghausen, 1999). This has led to a distinction between two types of LANs: (1) the 'morphosyntactic' LAN, which has been termed *focal* LAN because its onset is around 300 ms and it returns to baseline around 450 ms, and (2) the 'working memory' *sustained* LAN, a component that is similar in topography and latency, but which does not come back to baseline (Fiebach, Schlesewsky, & Friederici, 2002). The morphosyntactic LAN in particular is usually followed by a late parietal positive-going component, the P600 between 500 and 1000 ms. In fact, several reading studies do not report LANs for agreement violations (Osterhout & Mobley, 1995; Tokowitz & MacWhinney, 2005; Lau, Stroud, Plesch, & Phillips, 2006; Foucart & Frenck-

Mestre, 2010, 2012), and instead report only P600s (described in more detail below). Whether or not LANs are reliable reflections of morphosyntactic processes, and what their functional significance may be, is therefore still under debate.

In contrast to the LAN, the parietal P600 component is widely viewed as the most consistent ERP signature for a large range of grammatical anomalies. The P600 typically emerges between 500 and 1000 ms after visual stimulus presentation (Osterhout & Holcomb, 1993), and between 300 and 1500 ms in the auditory domain (e.g., Hahne & Friederici, 1999; Osterhout & Holcomb, 1993; Steinhauer, Alter, & Friederici, 1999). This component has been observed for gender-agreement and verb agreement violations (French: Frenck-Mestre, Osterhout, McLaughlin, & Foucart, 2008; Foucart, Foucart & Frenck-Mestre, 2010, 2012; see reviews in Molinaro, Barber, & Carreiras, 2011a; Royle et al., 2013), syntax violations (Friederici, 2002), syntactic garden path sentences (Osterhout & Holcomb, 1992, 1993), and has also been elicited by semantic anomalies in conjunction with N400s (Hagoort, 2003; Royle et al., 2013; Steinhauer, Drury, Walenski, Portner, & Ullman, 2010). Due to the heterogeneous conditions that elicit the P600, some have proposed that this component is a reflection of the processing load related to controlled language monitoring and reanalysis, and that it is not specific to grammatical syntactic processing (Kolk, Chwilla, van Herten, & Oor, 2003; Steinhauer & Connolly, 2008; van de Meerendonk, Kolk, Vissers, & Chwilla, 2010). While most authors agree that the P600 is the best candidate for a brain response related to sentence reanalysis and repair (i.e., controlled processing) (Hahne & Friederici, 1999), some argue that the P600 is an ERP correlate of implicit syntactic processing (Tokowitz & MacWhinney, 2005) due to the reliability of this component in comparison to the LAN.

1.3.3 Experimental data on agreement

Experimental studies have revealed differences between various types of agreement in terms of brain activation patterns. A brief summary of experimental findings on number and gender agreement will be presented, with more focus on subject-verb agreement, as this pertains more closely to Sub-experiment 2. In the interest of brevity, only a subset of the studies are presented here in order to establish typical ERP patterns expected for agreement errors. As most studies on agreement are pursued in the visual modality, most of the studies discussed are reading studies using word-by-word presentation methods.

Molinaro and colleagues (2011a) present a review of number and gender agreement processing in various languages (e.g., Italian, Spanish, German, English). In terms of subject-verb number agreement, of the 17 studies reviewed, all of them showed P600s and 13 showed LANs in response to subject-verb agreement violations. The authors correlate the LAN with the detection of morphosyntactic processing difficulties and explain the absence of a LAN in certain studies in terms of the saliency of surface morphosyntactic properties of the trigger elements, such that when these are underspecified (i.e., not morphologically expressed) or are expressed in a different clause, a LAN may not be triggered. For example, in Molinaro, Vespigiani, Zamparelli, and Job's (2011b) study, Italian speakers showed LANs on the verb in response to subject-verb agreement violations such as **I ragazzi corre…* 'The boys run.3rd p.sg.', but not in response violations such as **Il ragazzo e la ragazza corre…* 'The boy and the girl run.3rd p.sg.'. Note that, in the latter example, the conjoined noun phrase (NP) does not contain any overt plural marking. The authors thus propose that the LAN dissociation is related to the availability of relevant inflectional morphology in the triggering subject. However, Frenck-Mestre et al. (2008) do not observe any negativities resembling a LAN in French native speakers in response to subject-verb agreement violations such as **Le matin je mangez* ‘In the morning I eat.3rd p.pl.’ (but showed a P600). The authors suggest that the absence of a LAN may be indicative of a lack of an early syntactic processing mechanism (cf. Friederici, 2002). Their data run counter to Molinaro et al.’s (2011a) interpretation of the LAN, as this component was absent even though the number properties of the subject were clearly expressed by the singular pronoun *je* ‘I’.

In terms of gender agreement, Molinaro et al. (2011a) reveal that most studies involving determiner-noun and noun-adjective agreement also report the biphasic LAN/P600 complex in response to violations, with a small number of studies reporting negativities similar to the N400 instead of the LAN. The authors attribute the LAN/N400 differences in ERP patterns to presentation context, with isolated noun-adjective pairs eliciting the N400/P600 complex and the same elements presented in a sentence resulting in a LAN/P600 (see e.g., Barber & Carreiras, 2003, 2005). However, Foucart and Frenck-Mestre (2010; 2012) show late positivities (P600) in response to gender agreement errors but inconsistent, non-significant, early negativities in native speakers, despite these being presented in a sentence context.

In sum, while P600s seem to be rather stable responses to agreement errors, the appearance of LAN type negativities in different agreement conditions is more complex, as it is still unclear whether these are modulated by the languages, structures, or contexts used to elicit them. As such, in addition to serving as controls for child studies to be conducted later on (as adult data are essential to the interpretation of child ERP patterns), data collected from our adult subjects will help shed some light on these questions. By investigating different grammatical structures/violations and by using a cross-modal (auditory-visual) design, we will be able to contribute to the controversy surrounding the LAN component while adding to our knowledge about the generalizability of ERP profiles across structures, languages and modalities.

1.4 ERPs and developmental tendencies

To date, there are few ERP studies that have investigated the acquisition of semantic and (morpho)syntactic processing in first language acquisition, even fewer of which have included adult controls. Those that have included adults as a point of comparison have typically observed differences in ERP latency, distribution and amplitude between neurotypical children and adults. As will be outlined briefly below, these patterns are influenced by both the linguistic domains studied (i.e., semantics, morphosyntax) and by age. This section begins with a brief overview of ERP data on neurotypical language development, as this is an essential point of comparison if we want to understand language abilities in individuals with DLI. To conclude, a brief summary on language processing in DLI will be presented.

1.4.1 Lexical semantic processing in neurotypical children

Auditory ERP studies have demonstrated that, early on, children and adults show similar ERP components (i.e., N400 effects) for semantic processing in single-word and simple sentence paradigms. For example, in Friedrich and Friederci's (2004) bimodal (auditory-visual) study, 19-month-old children elicited a negativity similar to the N400 observed in adult controls, albeit starting somewhat earlier (300 ms) and showing a slightly broader scalp distribution, in response to incongruous noun-picture pairs (where the auditory name of the object did not match the image, e.g. you hear *chair* but see a ball). Beginning at 7 years of age, children elicited N400s similar to adults (in terms of latency and distribution) when presented with the same bimodal stimuli (Cummings & Čeponienė, 2010). Courteau, Royle, Gascon, Marquis, Drury, and Steinhauer (2013) used sentence-visual presentation with a mismatch in the auditory noun (i.e., you hear *Je vois un* ***train*** *brun sur la table* and see: a brown **shoe** on the table) and found that French-speaking children aged 4 to 8 years also elicited N400s similar to their adult controls

(Royle et al., 2013) in response to violations. In general, it appears that the lexical-semantic N400 for auditory sentence processing appears at early ages in life. However, it has been shown that these negativities appear to be larger in amplitude in younger children (Juottonen, Revonsuo & Lang 1996; Holcomb, Coffey, & Neville, 1992), can be delayed (Juottonen et al., 1996), longer lasting, and can have a more broad or different scalp distribution compared to adults (e.g. Hahne, Eckstein, & Friederici, 2004).

1.4.2 Morphosyntactic processing in neurotypical children

Some studies have observed late positivities homologous to P600s in children aged 3 and older when presented with morphosyntactic violations, but early negativities (i.e., LANs) take longer to emerge. For example, positivities have been observed in response to sentences in which there was a clash between the auxiliary and the verb in English-speaking children aged 3 and 4 (e.g. *My uncle will *watching the movie*) (Silva-Pereyra, Rivera-Gaxiola, & Kuhl, 2005), with the 'later' part of the positivity being more focal to the central region of the scalp in 4-year-olds. Biphasic wave patterns somewhat similar to LAN/P600s have also been observed in 3-, 4-, and 6-year-old children in response to morphosyntactic violations in German (i.e., sentences with double nominatives instead of a nominative subject and an accusative object) (Schipke, Friederici, & Oberecker, 2011), with the negativity showing longer latencies (i.e., 300 to 700 ms) and a broader distribution (i.e., broad frontal) in comparison to adults. Courteau et al. (2013) presented French-speaking children aged 4 to 8 with sentences containing determiner-noun (e.g. *Je vois *la soulier vert)* and noun-adjective (*Je vois le soulier *verte)* violations concurrently with images depicting the sentence. These violations elicited positive going waves in left-frontal as well as posterior sites (although data for determiner-noun agreement did not reach significance), which can be viewed as homologous to the adult LAN/P600 pattern, with frontal positivities being viewed as immature reflexes of the adult LAN (i.e., due to strong left-laterality). However, Clahsen, Lück and Hahne (2007) observe an N400-like negativity in 6- to 7-year-olds in response to noun inflection errors (plural overregularization) in German. By 8 years, children show an anterior negativity, which becomes more left-lateralized by the ages of 11 and 12, followed by late posterior positivities.

Based on this brief review, it appears that although children and adults show similar ERP components for semantic processing at young ages, the picture is less clear in the case of morphosyntax. Tasks on different grammatical components show different developmental patterns for morphosyntactic ERPs. It is unclear which morphosyntactic abilities mature earlier than others as tasks involving different grammatical domains (i.e., verb agreement, gender agreement, etc.) have been investigated in different languages. In general, however, the aforementioned studies seem to indicate a developmental pattern whereby a decrease in component latency and increased focalization occur as the child matures.

1.4.3 Language processing in DLI

The section above shows that ERPs can reflect lexical-semantic and grammatical abilities in children, and that they are sensitive to developmental changes in the neurocognitive mechanisms underlying these processes. We can therefore extend the study of language processing using ERPs to children with DLI, while using neurotypical children as comparison groups, to understand the first group's language difficulties and how such difficulties may change over time.

There is hardly any available ERP data on language development in children with DLI, as most studies conducted involve neurotypical children. The few ERP studies that have focused on children with DLI have observed the presence of N400s in response to semantic violations, with activation patterns resembling those of younger neurotypical children (i.e., longer latencies and greater amplitudes). For example, Cummings and Čeponienė (2010) observed that, in comparison to neurotypical controls, children with DLI aged 7 to 15 years showed longer N400 latencies in response to auditory-visual lexical congruencies. Fonteneau and van der Lely (2008) studied lexical-semantic processing in teenagers and adults aged 10 to 21 years with G-SLI. Sentences containing anomalous nouns (e.g., *Barbie bakes the !people/bread in the kitchen*) resulted in similar N400 patterns in both DLI and neurotypical groups, with slightly different scalp distributions in younger language-matched controls. Weber-Fox, Leonard, Wray, and Tomblin (2010) found no group differences on the N400 elicited by lexical-semantic sentences containing anomalous verbs (e.g., *Every day, the children !rust/pretend to be super-heroes*). Studies on morphosyntactic and syntactic processing in children with DLI are even more scarce, and have obtained heterogeneous and contradictory results which can be explained, in part, by methodological issues, leaving us with few interpretable data sets (for a review see Royle & Courteau, 2013).

Therefore, while it seems that children with DLI tend to show immature/delayed (i.e., similar to younger neurotypical children) semantic processing that appears to normalize with age (at least in part), the question remains whether morphosyntactic and syntactic processing are immature or atypical (i.e., distinct from neurotypical children). It is also unclear how these ERP components would mature over time. For example, at present we do not know whether children with DLI will follow a similar developmental trajectory whereby ERP components show decreased latency and increased focalization throughout development. The paucity of DLI studies in the ERP literature highlights the importance of our project, which will provide much needed elucidation about language processing abilities and developmental tendencies in French-speaking children with DLI. At the same time, we will contribute to the literature on first language acquisition in neurotypical children by providing high-quality cross-linguistic data.

1.5 Experimental manipulations and predictions for the sub-experiments

Our experimental paradigm, introduced in more detail below, aims to elucidate the neurocognitive mechanisms underlying the processing of lexico-conceptual semantics, morphosyntax, and syntax, in French children with DLI. To this end, we created two ERP sub-experiments that both implement a combined auditory/visual sentence-picture matching paradigm, specifically designed to elicit N400, LAN, and P600 effects. Predictions for each sub-experiment will be discussed below.

1.5.1 ERP Sub-experiment 1

Sub-experiment 1 investigates the processing of lexico-conceptual semantics, noun-adjective gender agreement (morphosyntax), and pre- and post-nominal adjective placement (noun-phrase syntax). Sub-conditions and sample auditory stimuli, as well as expected outcomes for the adult control group, are depicted in Table 1.1. An example visual stimulus to be presented concurrently with auditory stimuli is presented in Figure 1.1. Based on our adult data for similar stimuli, semantic errors were expected to elicit N400 components followed by P600s (Royle et al., 2013), while morphosyntactic gender agreement errors, as well as adjective placement syntactic errors, were expected to elicit the complex LAN/P600 profile (Royle et al., 2013; Steinhauer, 2014).

Table 1.1. Experimental conditions, including French auditory experimental stimuli, and ERP predictions for the adult control group. Critical words are underlined.

Conditions	Sample auditory stimuli	Predictions
(1) Semantic	Je vois la !fourchette verte sur la table	N400, P600
(2) Morphosyntactic	Je vois la chaise *vert sur la table	LAN, P600
(3) Syntactic	Je vois la verte **chaise sur la table	LAN, P600
(4) Congruent/grammatical	Je vois la chaise verte sur la table	-

Note: ! = semantic error; * = morphosyntactic error; ** = syntactic error

Figure 1.1. Sample visual stimulus to be presented concurrently with auditory stimuli for congruent condition (4) and incongruent conditions (1-3).

1.5.2 ERP Sub-experiment 2

1.5.2.1 Lexico-conceptual semantics

The semantic condition was designed to investigate whether children with DLI would elicit an N400 component in response to cross-modal (audio-visual) mismatches involving visually presented actions and spoken verbs. To our knowledge, this is the first ERP study that uses complex action/verb mismatches that require participants to analyze the entire picture, instead of object/noun mismatches (as done in previous studies, such as in Sub-experiment 1). Verb-action matching is arguably more complex than the noun-object matching, as the former involves analysing the entire sentence/image while the latter simply involves analysing the noun/object. Although we can expect that a competent, adult native speaker is capable of performing such analyses, the question remains whether children with (and without) DLI can perform the complex task of cross-modal mismatch resolution involving actions based on analysis of the entire sentence/image.

Table 1.2. Experimental subconditions and predictions for the semantic condition, including French auditory experimental stimuli. Critical words are underlined.

Condition	Context	Sample auditory stimuli		Prediction
Semantic Congruent	Neutral	(1a)	Chaque semaine, elle chante dans une salle de concert	-
	Subj NP	(1b)	La vedette, elle chante dans une salle de concert	-
Semantic Violation	Neutral	(1c)	Chaque semaine, elle !nage dans la piscine publique	N400, P600?
	Subj NP	(1d)	La vedette, elle !nage dans la piscine publique	N400, P600?

Note: Subj NP = subject NP; ! = semantic error

Figure 1.2. Sample visual stimulus to be presented concurrently with auditory stimuli for congruent conditions (1a-b) and incongruent conditions (1c-d).

Main conditions and sample auditory stimuli, as well as expected outcomes for the adult control group, are depicted in Table 1.2. An example visual stimulus to be presented concurrently with auditory stimuli is presented in Figure 1.2. Following previous studies that have investigated semantic processing in bimodal modalities (auditory-visual or visual-visual) (see e.g., Friedrich & Friederici, 2004; Willems et al., 2008; Royle et al., 2013), we expect lexico-conceptual semantic mismatches to elicit negativities consistent with the N400 when compared to correct controls in our adult subjects. A number of studies have also found that P600-like positivities follow the N400 in response to semantic phenomena (e.g., Hagoort, 2003; Royle et al., 2013; Steinhauer et al., 2010), and it is therefore entirely possible that our subjects also elicit a P600, especially in the presence of an acceptability judgment task (e.g., Royle et al., 2013). Of interest to us is whether or not the semantic violations elicit both an N400 and a P600 in neurotypical adults, as this will allow us to make precise predictions about child ERPs later on.

1.5.2.2 Morphosyntax

The morphosyntax condition was designed to investigate whether children with DLI would elicit the complex LAN/P600 profile, as seen in adults, in response to cross-modal (auditory-visual) subject number mismatch errors. A second question addressed by our morphosyntactic condition is whether children with DLI are sensitive to the different phonological cues provided for the disambiguation of number mismatches in French. To this end, we varied both the number and types of cues available for subject number disambiguation by varying between two types of verbs in main sentences, and two type of context phrases preceding the main sentence. A subset of conditions and sample auditory stimuli, as well as expected outcomes for the adult control group, are depicted in Table 1.3. Example visual stimuli to be presented concurrently with auditory stimuli is presented in Figures 1.3 and 1.4. Whereas in examples (2a-d), verb cues for number are audible at the junction between the pronoun and the vowel-initial verb by the presence/absence of a liaison (e.g., elle‿aime [ɛlɛm] vs. elles‿aiment [ɛlzɛm]; henceforth referred to as 'Type-2' verbs), in examples (3a-d) number cues are contained in phonologically different conjugational endings on the verb (e.g., il rugit [ilʁyʒi] vs. ils rugissent [ilʁyʒis]; henceforth referred to as 'Type-3' verbs.). In addition to cues involving the verb, a context phrase with a sentence-initial determiner/noun combination preceded half of the sentences, with the sentence-initial determiner serving as an additional number cue, as in examples (2-3b) and (2-3d) (henceforth referred to as 'subject NP' context). The other half were preceded by context phrases containing locative or temporal information, with no additional cues for number, as in examples (2-3a) and (2-3c) (henceforth referred to as 'neutral' context).

Table 1.3. Experimental conditions and predictions for morphosyntax, including French auditory experimental stimuli. Critical words are underlined.

Cond	Verb	Context	Sample auditory stimuli		Determiner	Verb
Morph Con	Liais	Neutral	(2a)	Au dessert, elle aime la mousse au chocolat	-	-
		SubjNP	(2b)	La fille, elle aime la mousse au chocolat	-	-
	Infl	Neutral	(3a)	En soirée, il rugit dans la savane	-	-
		SubjNP	(3b)	Le lion, il rugit dans la savane	-	-
Morph Incon	Liais	Neutral	(2c)	Au dessert, elle *aime la mousse au chocolat	-	LAN/P600
		SubjNP	(2d)	*La fille, elle *aime la mousse au chocolat	LAN/P600	None
	Infl	Neutral	(3c)	En soirée, il *rugit dans la savane	-	LAN/P600
		SubjNP	(3d)	*Le lion, il *rugit dans la savane	LAN/P600	None

Note: Morph = Morphosyntax; Con = Congruent; Incon = Incongruent; Liais = Liaison; Infl = Inflection; SubjNP = Subject NP; * = morphosyntactic error

Figure 1.3. Sample visual stimulus for congruent conditions (2a-b).

Figure 1.4. Sample visual stimulus for incongruent conditions (2c-d).

To our knowledge, this is the first ERP study investigating the contribution of different cues for number in such a systematic manner. Our manipulations will allow us to determine whether the first available sentence cue is sufficient to detect the number mismatch, and whether the liaison information carried at the junction between the pronoun and the verb is an equally informative cue as information carried on the verb ending. Following previous studies that have investigated morphosyntactic (dis)agreement (e.g., Balconi & Pozzoli, 2005; Foucart & Frenck-Mestre, 2010, 2012; Royle et al., 2013), we expect the number mismatches to elicit P600 components in comparison to correct controls, potentially preceded by a LAN, in our adult control group. We would also expect that neurotypical adults are efficient in extracting the relevant number information from the speech signal, such that they only show mismatch effects (i.e., a P600/LAN complex) on the first available cue, and that liaison and verb ending cues are equally informative, such that both will elicit mismatch effects on the verb (when these are the first available number cues). Two interesting questions regarding children with DLI are (i) whether they will be equally efficient in extracting the relevant information from the speech signal (such that only the first available number cue is necessary for disambiguation) and (ii) whether liaison information can be used as an informative cue, an important question given the difficulties often demonstrated by children with DLI with the production and comprehension of verbal inflection (e.g., Leonard, 2000; Pourquié et al., 2016).

2. Materials and Methods

2.1 Participants

Sixteen (13 female) neurotypical adults aged 18 to 40 years participated in the experiment, after receiving Ethics approval by McGill's Institutional Review Board (IRB) and the University of Montreal's *Comité d'éthique à la recherche en Santé* (refer to Appendix A for a copy of the preliminary approval letter from McGill's IRB). All were right-handed as assessed by the Edinburgh Handedness Inventory (Oldfield, 1970) and had normal or corrected-to-normal vision. All had French as their mother tongue and their everyday language, and were not exposed to any other language before the age of 5. None had a history of learning disabilities, neurological damage, or hearing loss. Participants were recruited from the university student populations of Montreal, Quebec via advertisements made on the University of Montreal campus and on social media (e.g. Experimental Science Billboard Montreal's Facebook page). Written consent was obtained prior to participation in the experiment (see Appendix B for a copy of the consent form). Participants were compensated $45 for their time. Following data inspection, 14 (12 female) participants were retained for the study. The eliminated data sets presented high levels of artifacts (i.e., blinking or body movements) or electrode reading problems that contaminated the ERP signal.

2.2 Materials and design

2.2.1 Questionnaires and evaluative tasks

Before being recruited for the study, potential participants who expressed interest in participating filled out a questionnaire to ensure their eligibility. Included were questions about age, handedness, developmental, linguistic and neurological history, as well as visual and hearing abilities. Once deemed admissible, participants were scheduled for a testing session.

During the experimental session, participants completed a French version of the Edinburgh Handedness Inventory (Oldfield, 1970). The questionnaire was adapted to French in Dr. Royle's lab. Participants also completed a language background questionnaire, which probed more specific questions related to participants' exposure to and daily use of language(s) for different activities (i.e., reading, watching television, listening to the radio) and in different environments (i.e., home, school, work). The handedness and language background questionnaires are included in Appendices C and D respectively. Lastly, participants' working memory (WM) capacity was measured using the *Répetition de nombres (ordre direct* and *ordre inverse*) subtests of *the Évaluation clinique des notions langagières fondamentales—version pour francophones du Canada* (CELF cnd-F) (Secord, Wiig, Bouilianne, Semel and Labelle, 2009). The WM test was administered orally by a researcher or research assistant at the end of the EEG session. Although not included in the present analyses due to time constraints and sample size, this measure may later be used in analyses to investigate the extent to which WM constraints and inter-individual differences in WM capacity interact with and modulate ERP effects.

2.2.2 Experimental Design

ERP Studies 1 and 2 both implement a combined auditory/visual (i.e., cross-modal) sentence-picture matching paradigm, whereby auditory stimuli were presented with either concordant or discordant images. Sub-experiment 1 is modeled closely after Courteau et al. (2013), Royle et al. (2013), and Steinhauer (2014) with some conservative design modifications, such as combining various conditions into one study and adapting materials for French. Stimuli in Sub-experiment 2 were inspired by the fLEX evaluation tool (Pourquié et al., 2016), with modifications, such as the creation of several new stimulus materials and experimental manipulations. The design of Sub-experiment 1 is presented briefly below, while Sub-experiment 2 is discussed in greater detail.

2.2.2.1 ERP Sub-experiment 1

Table 2.1 provides examples of auditory stimuli for each experimental condition, as well as the accompanying visual stimulus which, in combination with auditory stimuli, creates either congruent (as in (4)) or incongruent (as in (1) - (3)) conditions. In this first ERP study, conceptual semantic processing was investigated by creating semantic violations where the image does not correspond to the noun presented in the auditory stimulus (e.g., the sound file describes 'a green fork on the table' and the image is of a green CHAIR on the table, example (1)). Morphosyntactic processing was targeted by creating gender mismatches between the noun and adjective in the auditory stimulus (e.g., la chaise *vert/verte sur la table, 'a chair green masc./fem. on the table'), such that a feminine adjective is heard with a masculine noun, or vice versa (example (2)). Lastly, syntactic processing was investigated by creating adjective placement violations (e.g., la *verte chaise, ‘the green chair’), such that prenominal (i.e., occurring before the noun) adjectives occurred in postnominal positions, and vice versa (example (3)).

Table 2.1. Experimental subconditions, including French auditory experimental stimuli and corresponding visual stimulus for relevant conditions. Critical words are underlined.

Conditions	Sample auditory stimuli	Sample visual stimulus
(1) Semantic	Je vois la !fourchette verte sur la table	
(2) Morphosyntactic	Je vois la chaise *vert sur la table	
(3) Syntactic	Je vois la verte **chaise sur la table	
(4) Correct/grammatical	Je vois la chaise verte sur la table	

Note: ! = semantic error; * = morphosyntactic error; ** = syntactic error

2.2.2.2 Experimental Design – Sub-experiment 2

Semantics. Lexico-conceptual semantic processing was investigated by creating violations where the verb depicted in the image does not correspond to the verb presented in the auditory stimulus (e.g., the sound file describes ‘she swims…’ and the image depicts ‘she sings…’). Table 2.2 provides an example of how we cross-spliced sentences to create various experimental conditions, which were created as follows. Items for the congruent condition were created in three steps. First, a native French Canadian actor was recorded while she spoke each congruent item, consisting of a context plus sentence combination. This resulted in 60 sentence pairs (60 with subject NP context and 60 with neutral contexts), for a total of 120 spoken items. For each item pair, we selected one sentence version and cross-spliced it with both a neutral context and subject NP context, as depicted in examples (1a) - (1b), and (1c) - (1d). Each item pair was associated with one image depicting the action described in the audio files (refer to Table 2.3 for an example image). Items for the incongruent condition were then created by cross-splicing the contexts from one item pair with the sentences from another, as depicted in examples (1e) - (1f) and (1g) - (1h), resulting in 60 more item pairs (120 items total). In the end, 60 item quadruplets were created (30 belonging to the congruent condition and 30 corresponding items belonging to the incongruent condition), for a total of 240 items (120 congruent and 120 incongruent). In order to create semantic mismatches, each item quadruplet was associated to the same image, such that both incongruent and congruent item versions were displayed with the same image. Table 2.3 provides an example of one item quadruplet, showing example auditory stimuli for each subcondition as well as the corresponding image.

Table 2.2. Sample stimuli for the semantic condition with an example of cross-splicing demonstrated. Critical words are underlined.

		Context	Sentence		
Condition	Item	S NP / Neutral	S Pro	Verb	Complement
Semantic Congruent	1a	La vedette	elle	chante	dans une salle de concert
	1b (1b – 1a)	Chaque semaine	elle	chante	dans une salle de concert
	1c	La grand-mère	elle	nage	dans la piscine publique
	1d (1d – 1c)	Aujourd'hui	elle	nage	dans la piscine publique
Semantic Incongruent	1e (1a – 1c)	La vedette	elle	!nage	dans la piscine publique
	1f (1b – 1c)	Chaque semaine	elle	!nage	dans la piscine publique
	1g (1c – 1a)	La grand-mère	elle	!chante	dans une salle de concert
	1h (1d – 1a)	Aujourd'hui	elle	!chante	dans une salle de concert

Note: S NP = subject noun phrase; S Pro = subject pronouns; ! = semantic error; the dashed vertical line represents the splicing point. Refer to Table 2.2 for visual stimulus example.

Table 2.3. Experimental subconditions for the semantic condition, including French auditory experimental stimuli and corresponding visual stimulus. Critical words are underlined.

Condition	Context	Sample auditory stimuli		Sample illustration
Sem Con	Neutral	(1a)	Chaque semaine, elle chante dans une salle de concert	
	Subj NP	(1b)	La vedette, elle chante dans une salle de concert	
Sem Incon	Neutral	(1c)	Chaque semaine, elle !nage dans la piscine publique	
	Subj NP	(1d)	La vedette, elle !nage dans la piscine publique	

Note: Sem Con = Semantic Congruent; Sem Incon = Semantic Incongruent; Subj NP = Subject NP; ! = semantic error.

Morphosyntax. Morphosyntactic agreement processing was studied by creating number mismatches between the subject depicted in the image and the subject presented in the auditory stimulus (e.g., the sound file describes 'she likes…' and the image depicts 'they like…'). Table 2.4 provides an example of how we cross-spliced to create various experimental conditions, which were created as follows. Items for the congruent condition were created in three steps. First, we recorded a subset of congruent items, namely a singular subject NP context and singular sentence combination (as in item 2a), a neutral context and singular sentence combination (as in item 2b), and a plural subject NP context and plural sentence combination (as in item 2c). This resulted in 120 sentence triplets (120 with singular subject NP context and singular sentence, 120 with plural subject NP context and plural sentence, and 120 with neutral context and singular sentence), for a total of 360 spoken items. We then cross-spliced as in the example provided in Table 2.4: each singular sentence was spliced with both a singular subject NP and neutral context (as in 2a and 2b), and each plural sentence was spliced with a plural subject NP context and the same neutral context that was used for the singular (as in 2c and 2d). This created item quadruplets, whereby the two singular versions differed in context but used the same singular sentence, the two plural versions also differed in context while using the same plural sentence, and the same neutral context was paired with both singular and plural sentences.

This resulted in 120 item quadruplets, or 480 items. Each singular and plural item pair was associated with a corresponding image (i.e., singular items were paired with an image depicting one agent, and plural items were paired with an image depicting two or more agents). With regards to the incongruent conditions, morphosyntactic number mismatches were created by presenting the same audio files, but swapping the images, such that audio files describing singular subjects were presented with images depicting plural subjects, and vice versa. In total, 960 audio file and image combinations were created (480 congruent and 480 incongruent). Table 2.5 provides an example of congruent and incongruent item quadruplets with corresponding image for Type-2 verbs, and Table 2.6 provides an example of congruent and incongruent item quadruplets with corresponding image for Type-3 verbs.

Table 2.4. Sample stimuli for the morphosyntactic condition with an example of cross-splicing for Type-2 verbs demonstrated. Critical words are underlined.

		Context	Sentence		
Condition	Item	S NP / Neutral	S Pro	Verb	Complement
Morphosyntax Congruent	2a	La fille	elle	aime	la mousse au chocolat
	2b (2b – 2a)	Au dessert	elle	aime	la mousse au chocolat
	2c	Les filles	elles	aiment	la mousse au chocolat
	2d (2b – 2c)	Au dessert	elles	aiment	la mousse au chocolat
Morphosyntax Incongruent	2e (2a)	*La fille	elle	*aime	la mousse au chocolat
	2f (2b)	Au dessert	elle	*aime	la mousse au chocolat
	2g (2c)	*Les filles	elles	*aiment	la mousse au chocolat
	2h (2d)	Au dessert	elles	*aiment	la mousse au chocolat

Note: S NP = subject noun phrase; S Pro = subject pronouns; * = semantic error; the dashed vertical line represents the splicing point. Refer to Tables 2.4 and 2.5 for examples of visual stimuli.

Table 2.5. Experimental subconditions involving Type-2 (liaison) verbs, including French auditory experimental stimuli. Critical words are underlined.

Cond	Subject Number	Context	Sample auditory stimuli	
Morphosyntax Congruent	Singular	Neutral	(2a)	Au dessert, elle aime la mousse au chocolat
		Subject NP	(2b)	La fille, elle aime la mousse au chocolat
	Plural	Neutral	(2c)	Au dessert, elles aiment la mousse au chocolat
		Subject NP	(2d)	Les filles, elle aiment la mousse au chocolat
Morphosyntax Incongruent	Singular	Neutral	(2e)	Au dessert, elle *aime la mousse au chocolat
		Subject NP	(2f)	*La fille, elle *aime la mousse au chocolat
	Plural	Neutral	(2g)	Au dessert, elles *aiment la mousse au chocolat
		Subject NP	(2h)	*Les filles, elle *aiment la mousse au chocolat

Note: * = morphosyntactic error

Figure 2.1. Sample visual stimulus for congruent conditions (2a-b) and incongruent conditions (2g-h).

Figure 2.2 Sample visual stimulus for congruent conditions (2c-d) and incongruent conditions (2e-f)

Table 2.6. Experimental subconditions involving Type-3 (final consonant) verbs, including French auditory experimental stimuli. Critical words are underlined.

Cond	Subject Number	Context	Sample auditory stimuli	
Morphosyntax Congruent	Singular	Neutral	(3a)	En soirée, il rugit dans la savane
		Subject NP	(3b)	Le lion, il rugit dans la savane
	Plural	Neutral	(3c)	En soirée, ils rugissent dans la savane
		Subject NP	(3d)	Les lions, il rugissent dans la savane
Morphosyntax Incongruent	Singular	Neutral	(3e)	En soirée, il *rugit dans la savane
		Subject NP	(3f)	*Le lion, il *rugit dans la savane
	Plural	Neutral	(3g)	En soirée, ils *rugissent dans la savane
		Subject NP	(3h)	*Les lions, il *rugissent dans la savane

Note: * = morphosyntactic error

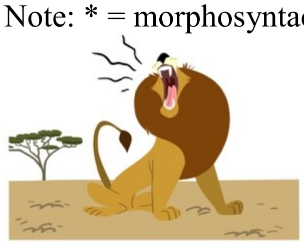

Figure 2.3. Sample visual stimulus for congruent conditions (3a-b) and incongruent conditions (3g-h).

Figure 2.4 Sample visual stimulus for congruent conditions (3c-d) and incongruent conditions (3e-f)

With regards to verb types, half of our sentences contained Type-1 verbs (480 items; 240 correct & 240 incorrect) and half contained Type-2 verbs (480 items; 240 correct & 240 incorrect). Type-2 verbs consisted of regular verbs, such as *aimer* 'to-like', which, in French, provide no audible cues for disambiguation between singular plural forms. All verbs selected for this category had vowel onsets. This allowed us to ensure, as mentioned above, that the only cue for disambiguation between singular and plural forms is located at the junction between the subject pronoun and the verb by the presence/absence of liaison (e.g., *il aime* [ilɛm] 'he likes' vs. *ils aiment* [il**z**ɛm] 'they like'). Type-3 verbs consisted of those belonging to the 2nd and 3rd French conjugation classes, such as *rugir* 'to-roar', where the distinction in number between singular and plural forms is audible on the verb ending due to the implementation distinct morphophonological realisations (e.g., *il rug**it*** [ilʁyʒ**i**] 'he roars' vs. *ils rug**issent*** [ilʁyʒ**is**] 'they roar'). All verbs selected for this category contained consonantal onsets in order to prevent liaison between the subject pronoun and the following verb, as this would provide an additional phonological cue for number.

List presentation. The 1200 different sentence-picture combinations (240 for conceptual semantics and 960 for morphosyntax) were evenly distributed across four lists. 300 stimuli sentences with accompanying images were presented to participants in each list (60 for conceptual semantics and 240 for morphosyntax). Item versions for each condition were distributed across lists as follows. For semantics, one version of a given item quadruplet was included in each list, such that a participant heard one audio file and saw one image (either congruent or incongruent) for each quadruplet. In morphosyntax, for each verb type (Type-2 and Type-3), two versions of a given item quadruplet was included in each list. The two items presented were maximally distinct, in order to minimize strategic processing effects, such that they differed in: (1) number (one contained a singular subject and one contained a plural subject), (2) context type (one contained a neutral context and one contained a subject NP context), and (3) congruency (one belonged to the congruent condition while one belonged to the incongruent condition). This entailed that each subject be presented the same image twice (one congruent and one incongruent), but two completely different audio files. Versions were presented in different halves of the experiment.

In each list, stimuli were evenly distributed across 15 blocks of 20 items each. The following constraints were met: (1) each block contained two items in each of the eight morphosyntactic subconditions as well as one sentence in each of the four semantic subconditions; (2) there was no consecutive repetition of the same subcondition; (4) match and mismatch conditions were evenly distributed across each block; (5) in order to minimize strategic processing effects, pseudorandomization within blocks also prevented (a) consecutive presentation of items with the same agent, (b) consecutive presentation of more than three items from congruent or incongruent conditions, (c) consecutive presentation of more than three singular or plural items, (d) clusters of particularly long or short sentences. In order to further rule out any sequence effects, four additional "mirror" versions of each list were created by reversing both the block order and the sentence order within each block. Thus, a total of eight experimental lists were created and evenly assigned across male and female participants.

2.2.3 Stimuli creation

Stimuli selection was constrained by age of acquisition norms, as we developed the stimuli to be used on younger populations after running it on adults. 180 French verbs acquired before the age of 8 years were selected from the Manulex database (Lété, Sprenger-Charolles, & Colé, 2004). Both Manulex (Lété, Sprenger-Charolles, & Colé, 2004) and Lexique (New, Pallier, Ferrand, &

Matos, 2001) were consulted to provide oral language frequency norms for selected items. All verbs were selected with their imageability in mind, and were matched on lemma frequency, age of emergence, and length (syllables and phonemes) across the three verb categories described above (invariable, liaison, and inflection verbs).

Verbs were inserted into sentences containing a singular or plural third person subject pronoun, and a sentence continuation phrase consisting of a direct object NP, or a prepositional phrase, to avoid wrap-up effects in the ERPs (Hagoort, 2003). Context phrases (neutral or subject NP) preceded all sentences. We ensured that there were no additional instances of liaison in sentences or context phrases, such that only sentences in the Type-2 verb subcondition contained them. We also ensured that all nouns, adverbs, prepositions and adjectives included in sentences and carrying phrases were age appropriate, as per Manulex (Lété et al., 2004). Further, subject gender (feminine or masculine), as well as syllable length of context phrases and of sentences were balanced across verb category.

A visual stimulus was created for each sentence. A professional artist created drawings emphasizing the relevant properties of interest, namely the action being described in the sentence and the agent(s) carrying out the action. The drawings maintained a constant level of visual complexity, avoiding superfluous or distracting details. Sentences and images were presented in the context of an 'Alien learning paradigm', similar to Labelle and Valois (2003), where an alien visited Quebec and was learning French. A story containing filler sentences, images and animations was also created, and interspersed throughout the experiment to maintain interest and attention.

Auditory stimuli were recorded in a sound booth using a Sony DAT recorder (PCM-M1 recorder, 1997). All sentences were spoken by a native French Canadian actor who was trained to pronounce words with clear but natural articulation, while maintaining constant and natural prosody and intonation. Sentences were spoken with natural within- and between-word coarticulation, however this was avoided between words at splicing points (i.e., between the last word in context phrases and the first word in sentences). The actor was also instructed to maintain a constant vocal intensity, intonation, and speech rate, throughout sentences as much as possible. Further, all conditions within a given block of stimuli were recorded together. All of this allowed us to create very natural-sounding auditory stimuli, while reducing post-recording manipulations.

Before cross-splicing took place, context phrase and sentence files were processed and normalised in five steps using Audacity® (Audacity Team, 2018) and Praat (Boersma & Weenik, 2018) software: (1) we reduced noise, such as microphone feedback and other extraneous sounds that were present in the recordings, by applying Audacity's built-in Noise Reduction function to all files. During this process, care was taken to use the lowest level of manipulations possible in an effort to reduce distortion to the resulting audio. For example, the sensitivity (which controls how much of the audio is considered noise) and frequency smoothing (which spreads the noise reduction process to the specified number of neighbouring frequency bands) options were always maintained at lowest possible levels; (2) as noise reduction created new instances of 'silence' at the start and end of audio files, such silences were trimmed using the Audacity Trim Silence plug-in (Daulton, 2011). A threshold of -35 dB was selected, as this level was deemed most appropriate in removing silent portions, while sparing phonemes with lower amplitudes such as voiceless stops, during tests performed on a subset of files; (3) using a Praat script (created in-house by the present author), sentence onsets and offsets were then trimmed at zero-crossings – the point where the waveform crosses the zero-level axis–, in order to avoid discontinuities in the sound wave that can be perceived as clicks or pops; (4) we listened to each file to assess the naturalness of speech rate. In cases where speech rate was perceived to be too fast/slow in comparison to the majority of audio files, or where there was a discontinuity between context phrases and associated sentences, speech rate was adjusted by using Audacity's built-in *Change Tempo* function. The lowest level of manipulation necessary to create natural sounding and consistent speech was used (maximum 15% slower/faster); (5) lastly, we added silent portions to the onsets and offsets of all audio files, such that all final audio files (once context phrases and sentences were cross-spliced) contained 0.035 seconds of onset silence, 0.05 seconds of offset silence, and 0.1 seconds of silence between the context phrase and the rest of the sentence (these values were perceived to be most natural-sounding when tests were performed on a subset of audio files). Audacity's *Trim/Extend* plugin (Daulton, 2011) was used to process all files in this manner. Once context phrase and sentence processing was complete, they were cross-spliced to create audio files for different experimental conditions, as outlined above. Cross-splicing was carried out in Praat by means of a script (created in-house by the present author) which concatenated all context-phrase and sentence files based on conditions outlined above. Lastly, the amplitude of the resulting audio files was normalised to a level of 70 dB SPL using Praat.

2.3 Procedure

Experimental sessions took place in a quiet room at the University of Montreal's School of Speech-Language Pathology and Audiology. Upon arrival, participants read and signed the consent form, after which they completed the Edinburgh Handedness Inventory (Oldfield, 1970) and a language background questionnaire. They were then fitted with an EEG cap, and completed both studies 1 and 2 consecutively in one single EEG session. After the session, the WM span test was administered, and participants could then wash their hair before departing.

Total session duration was approximately 3.5 hours, including the completion of the consent form and other questionnaires, administration of the WM test, preparation, and clean up.

Participants were seated in a comfortable chair at a distance of ~ 1 m from a computer monitor throughout the EEG session. Examples presented at the beginning of Sub-experiment 2 explained that Eusabie the Alien was learning French, and was describing images in her book during class, but could make mistakes. Participants listened to spoken sentences presented binaurally via insert headphones, while images were presented on computer monitor. A pause was programmed after every three experimental blocks, after 60 stimuli were presented. Pauses were preceded and followed by animations, included to maintain attention and motivation of children tested in future studies.

Participants were instructed to listen to each sentence, while attending to all aspects of language (i.e., grammar and meaning), and judge its acceptability in relation to the simultaneously presented image, by pressing one of two keys on a response pad ('acceptable' or 'not acceptable'). In order to avoid potential laterality effects, the 'acceptable' button was programmed on the right side of the response pad, with the 'unacceptable' button on the left, for half of the participants, while the inverse ('acceptable' on the left and 'unacceptable' on the right) was programmed for the other half. Participants were instructed to minimize movement and to keep their eyes open during stimuli presentation. In order to allow the participants to familiarize themselves with the task, procedures, and acceptability judgments, the first 6 –non-experimental– trials were excluded from all subsequent analyses. There was always at least one researcher or research assistant present throughout the session. EEG recording was monitored throughout the entire session and participants were given feedback about eye blinks and other body movements during pauses whenever necessary in order to reduce movement artefacts.

Trial structure was as follows: (1) each trial began when a fixation cross appeared in the center of the screen 1000 ms before sentence/image presentation, (2) auditory (sentence) and visual (image) stimuli were presented simultaneously, with the visual stimulus being presented in the center of the computer monitor until the end of the auditory stimulus, (3) a response prompt (???) appeared on the screen until a button was pressed on the response pad, (4) a blank screen appeared for 1000 ms, indicating the interval during which the subjects were instructed to blink their eyes before the next trial began.

2.4 Analysis time-locking

In reading studies using word-by-word presentation method, the entire word information becomes available at once and ERPs can simply be analyzed relative to word onset time. Also, because each word is presented for a pre-determined duration, word onset can be determined based on simple computation. The situation is more complex for auditory studies, where each item consists of a variable speech signal. As spoken words unfold over time, different types of information (i.e., carried by different morphemes) may be available at different points in time. For example, depending on whether morphosyntactic information is encoded in prefixes or suffixes, semantic information carried by the stem morpheme may either become available prior to or following the morphosyntactic information. In order to quantify the specific time course of effects, analyses made for auditory ERP studies should time-lock analyses to the relevant morphemes. Due to the variability of each speech signal, time-locking necessarily involves manually placing 'triggers' in each audio file to take into account the timing of each piece of relevant information in each speech signal.

The issue of time-locking of ERP effects to the relevant information has been overlooked in the analysis and interpretation of ERPs in several auditory studies (as brought up by Hasting &

Kotz, 2008; Royle et al., 2013; Steinhauer, 2003; Steinhauer & Drury, 2012; van den Brink & Hagoort, 2004). However, we have ensured to take into account all relevant information by placing several relevant triggers in our audio files. Figure 2.1 depicts an example waveform for the sentence *Le lion, il rugit dans la savane* as well as the various trigger points measured. Of importance for the analyses presented in this paper are Triggers 1, 4 and 5. Trigger 1 marks the onset of the sentence. Recall that for our morphosyntactic condition, we made predictions involving the sentence-initial determiner, as this was included as the initial number cue for sentences with subject NPs. This trigger was used to time-lock our ERP analyses to the critical determiner, therefore allowing us to look for mismatch ERP effects (and to confirm the absence of mismatch effects for sentences with neutral contexts). Trigger 4 marks on the onset of the verb. Recall that for our subcondition involving Type-2 verbs, we predicted to see mismatch effects on the verb when the immediately-preceding liaison was the first number cue, as was the case for sentences with neutral contexts (and predicted we would see no such effects for sentences with subject NP contexts). Further, recall that we also expected to see mismatch effects on the verb for the lexico-conceptual semantics condition, as violations involved verbs/actions. This trigger was therefore used to time-lock ERP analyses to the critical verb to look for ERP mismatch effects in the Type-2 and semantic conditions. Trigger 5 marked the onset of the verb-final consonant marking number agreement, and was therefore only included for Type-3 verbs (as Type-2 verbs contain no audible number cues on the verb). Here, we placed the trigger at the onset of the difference between the singular and plural verb endings (e.g. *rug|it / rug|issent*), as we would expect mismatch effects to occur only once the number difference becomes audible. As with Type-2 verbs, we expected to find mismatch effects on verb endings only when this was the initial number cue (i.e., for sentences with neutral contexts). As trigger placement is a very time consuming process, analyses for Type-3 verbs are still underway, as we are still in the process of placing triggers on verb endings. As such, I only report results for semantic and Type-2 conditions.

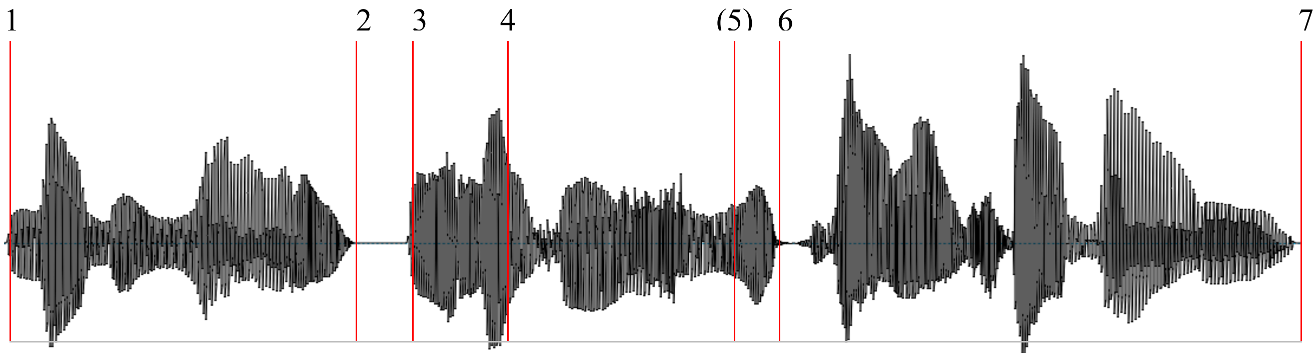

Figure 2.5. Example waveform of an auditory stimulus for the sentence *Le lion, il rugit dans la savane*. The red lines represent the various cue points, called 'triggers', measured in the audio file.
Notes: Trigger 1 = sentence onset, at 0.00 seconds; Trigger 2 = context phrase offset; Trigger 3 = verb phrase onset; Trigger 4 = verb onset; Trigger 5 = onset of verb-final consonant marking for number (only included for Type-3 verbs); Trigger 6 = verb offset; Trigger 7 = sentence offset, at 3.32 seconds.

2.5 EEG recording and data analysis

The EEG was recorded continuously with a 500 Hz sampling rate from 64 cap-mounted electrodes (WaveGuard caps, ANT; Enschede, NL) placed according to the extended International 10/20 System. The electrodes used for the recording covered frontal, central, parietal, temporal and occipital lobes (FP1, FP2, F3, F4, F7, F8, Fz, C3, C4, Cz, P3, P4, Pz, T3, T4, T5, T6, O1, O2, Oz; see Figure 2.6 for a representation of electrode sites included in analyses). All impedances were maintained below 5 kΩ and were verified approximately every 45 minutes throughout the experiment. The EEG was amplified using an ANT Neuro Eego™ sports amplifier referenced to the CPz electrode. All subsequent steps of EEG/ERP data processing and analysis were carried out using the EEProbe software package (ANT; Enschede, The Netherlands).

Offline, raw data were re-referenced to the linked mastoids and filtered using a bandpass of 0.3 to 40 Hz. Trials contaminated with eye blinks or other artefacts were rejected using a 30 μV criterion. All uncontaminated trials were entered into the final analysis. Using a 600 ms pre-stimulus baseline interval, single-subject EEG waveforms were averaged separately over a 3100 ms time epoch for each experimental condition (-600 to 2500 ms), time-locked to the onset of the relevant critical word (refer to the position of the underlined words in Tables 2.5 and 2.6 above), after which these data entered the grand average ERPs.

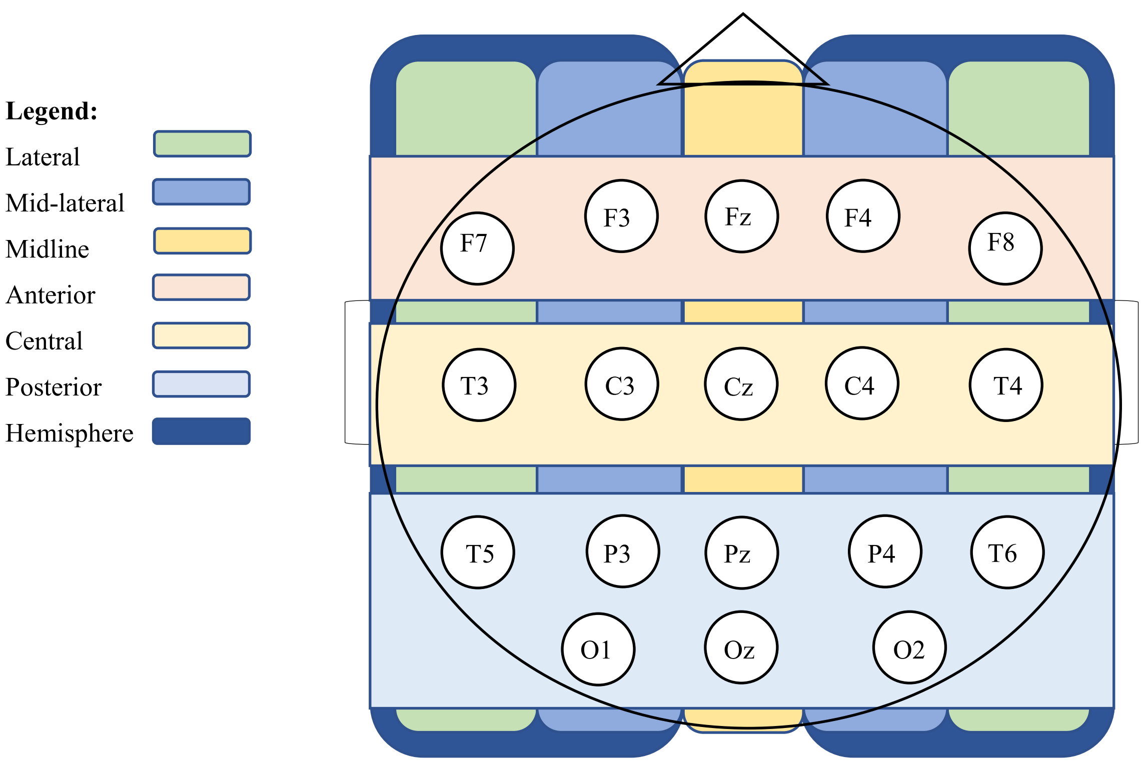

Figure 2.6. Head map depicting the organization of electrode sites included in analyses.

Following a visual inspection of each participant's ERP file, data sets that were considered to be too noisy or containing insufficient data points per condition were excluded (3 cases). In the remaining subjects, 2% of critical trials on average were rejected due to artefacts (eye movements or electrode drifts). An average of 23 trials for the semantic violations condition and 81 trials for the morphosyntax violation condition were analyzed. Based on visual inspection of the data, and on the basis of previous literature on N400 and P600 effects, we chose specific time-windows for statistical analyses of the grammatical and semantic errors, which were analyzed by means of repeated-measure ANOVAs. The N400 component was quantified as the mean voltage (μV) of the EEG signal between 300-500 ms post-onset of the critical word in the sentence, while the P600 was quantified between 500-1000 ms. Due to time constraints, statistical analyses for the LAN component are not yet complete, but are currently underway.

Violation conditions were compared to matched correct conditions. For each time-window, and for each condition, analyses for midline electrodes and lateral electrodes were performed separately. For lateral electrodes, the global ANOVA included four factors: CONDITION (2 levels: violation vs. control), HEMISPHERE (2 levels: right vs. left), ANT/POST (3 levels: anterior vs. central vs. posterior), and LATERALITY (2 levels: lateral vs. medial). For midline electrodes, global ANOVAs for the semantic condition included 2 factors: CONDITION (2 levels: violation vs. control), and electrode CHANNEL (4 levels: Fz, Cz, Pz, and Oz). For the morphosyntactic condition, two additional factors of CONTEXT (neutral vs. subject NP) and NUMBER (singular vs. plural) were included for both lateral and midline analyses. In future analyses, a between-subject factor of GROUP (2 levels: high vs. low WM span) may be included in both midline and lateral analyses in order to investigate the extent to which WM constraints and inter-individual differences in WM capacity interact with and modulate ERP effects. An alpha of $p < 0.05$ was used for all statistical analyses. The Greenhouse-Geisser correction was applied in order to address potential violations of sphericity. In these cases, the original degrees of freedom and corrected probability levels are reported.

In light of the specific aims of the study, a hierarchically-organized analysis of variance was pursued whereby only theoretically relevant interactions (i.e., CONDITION effects and their interactions with other scalp distribution effects) and attendant post-hoc analysis results are reported. In addition, given that ERP effects of interest in this type of experiment are observed close to the midline rather than at more lateral recording sites, as a general principle, statistics derived from analyses at lateral sites are reported only when these results elucidate effects of the experimental conditions beyond those derived from analyses at the midline alone.

Behavioural data were analyzed by means of repeated measures ANOVAs with response accuracy scores from the acceptability judgment task as the dependent measure, computed separately for semantic and morphosyntactic conditions. The global ANOVA included four factors: CORRECTNESS (2 levels: violation vs. control), CONTEXT (2 levels: subject NP vs. neutral), GENDER (2 levels: masculine vs. feminine), NUMBER (2 levels: singular vs. plural).

3. Results

3.1 Behavioural data

With respect to participants' ability to judge the acceptability of sentences within the semantic condition, response accuracy was nearly at ceiling for both correct and violation sentences (correct: $M = 93.1\%$, $SD = .07$; violation: $M = 92.5\%$, $SD = .08$). Global ANOVAs with response accuracy as the dependent measure indicated a significant GENDER×NUMBER interaction ($F(1,13) = 8.63$, $p < .05$). Refer to Table 3.1 for further details. Figure 3.1 depicts this interaction with mean target responses. Overall, the data suggest a relative difficulty with singular sentences containing feminine subjects. However, it should be noted that response accuracy was still high (i.e., at least at 91%) for each subcondition.

Table 3.1. Global repeated measures ANOVA results for acceptability judgment response accuracy in the semantic condition

Global ANOVAs	***df***	***F***	***p***
Correctness	1, 13	.74	.40
Gender	1, 13	2.27	.16
Number	1, 13	.83	.38
Context	1, 13	.19	.67
Gender × Number	1, 13	8.63*	.01

Note: only main effects and significant interactions are shown; * = p ≤.05

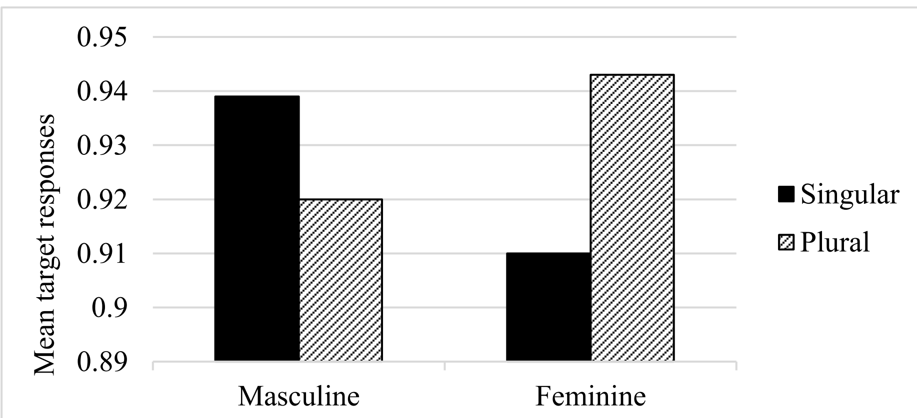

Figure 3.1. Mean target response accuracy across participants for singular and plural sentences with feminine and masculine subjects in the semantic condition.

Table 3.2. Global repeated measures ANOVA results for acceptability judgment response accuracy in the morphosyntactic verb Type-2 condition

Global ANOVAs	*df*	*F*	***p***
Correctness	1, 13	3.54†	.08
Gender	1, 13	3.09†	.10
Number	1, 13	7.56*	.02
Context	1, 13	.43	.52
Correctness × Context	1, 13	5.89*	.03
Correctness × Number	1, 13	6.61*	.02
Context × Number	1, 13	7.02*	.02

Note: only main effects and significant two-way interactions are shown; † = p ≤.10; * = p ≤.05; *** = p ≤.001

In terms of participants' response accuracy for sentences within the morphosyntactic condition, overall performance was also close to ceiling for both correct and violation sentences (correct: $M = 95.7\%$, $SD = .04$; violation: $M = 93.2\%$, $SD = .05$). Global ANOVAs with response accuracy as the dependent measure indicated significant CORRECTNESS×CONTEXT ($F(1,13) = 5.89$, $p < .05$), CORRECTNESS×NUMBER ($F(1,13) = 6.61$, $p < .05$), and CONTEXT×NUMBER ($F(1,13) = 7.02$, $p < .05$) interactions (note that we focus only on two-way interactions at this point in our analyses). See Table 3.2 for further details. Figures 3.1 – 3.3 depict these interactions respectively with mean target responses. Overall, the data suggest a relative difficulty rejecting singular mismatch sentences with neutral contexts. However, it should be noted that response accuracy was still high (i.e., at least at 90%) for each subcondition.

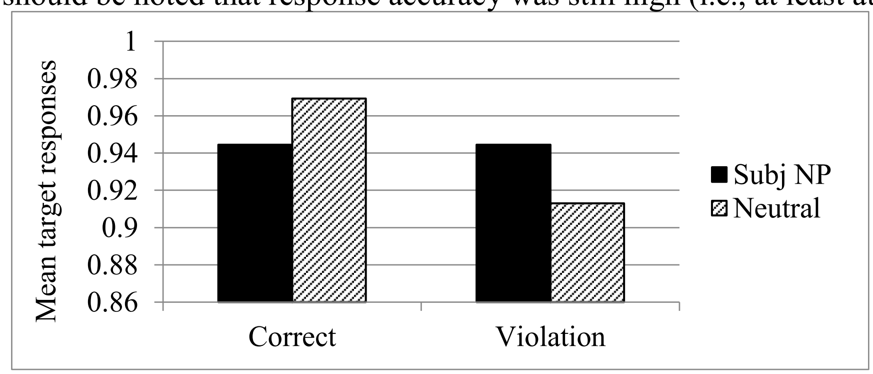

Figure 3.2. Mean target response accuracy across participants for correct and violation sentences with subject NP and neutral contexts in the morphosyntactic verb Type-2 condition.

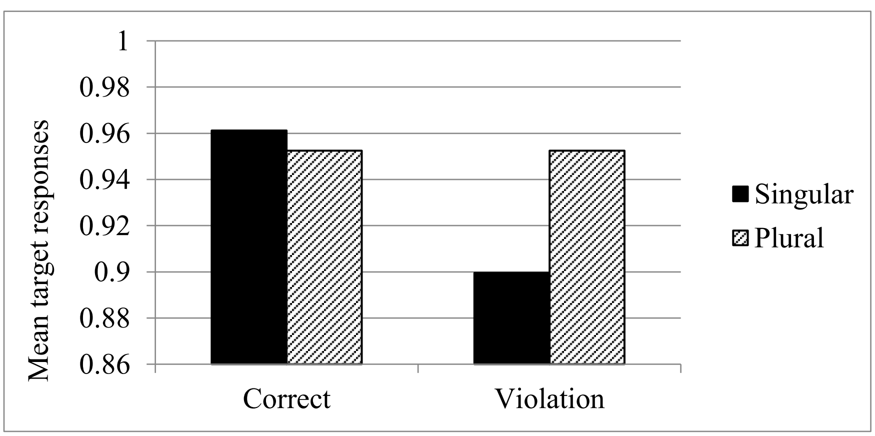

Figure 3.3. Mean target response accuracy across participants for singular and plural correct and violation sentences in the morphosyntactic verb Type-2 condition.

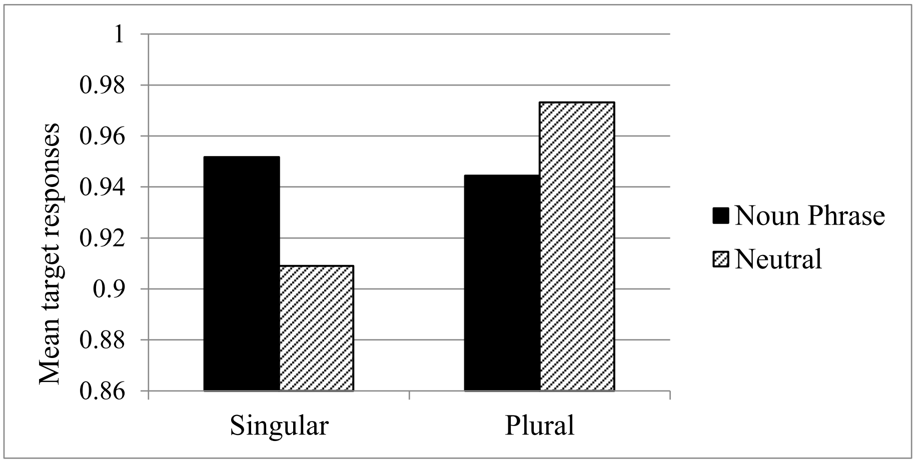

Figure 3.4. Mean target response accuracy across participants for singular and plural sentences with subject NP and neutral contexts in the morphosyntactic verb Type-2 condition.

3.2 Event-related potentials

3.2.1 Conceptual semantic violations

As depicted in Figure 3.5, compared with the correct control condition, the critical verb in the semantic violation condition elicited a posteriorly distributed negativity in the N400 time window, across the subconditions with subject NP and neutral contexts. These effects were even visible at the sentence level, before analyses were time-locked to the onset of the verb (depicted in Figure 3.6). Figure 3.5 also depicts a sustained negativity immediately following the N400, lasting until approximately 1500 ms (e.g., Pz electrode), as well as frontal negativities beginning at approximately 1000 ms (F3, Fz, F4 electrodes). Although these subsequent negativities are not yet substantiated statistically, the rather conservative '*running t-test*' implemented in EEProbe software suggests that these negativities are significant in the time windows mentioned.

The N400 observations were substantiated statistically: in the N400 (300-500 ms) time window, global ANOVAs yielded a significant CORRECTNESS×ANTERIORITY interaction at lateral electrode sites ($F(2,26) = 4.41$, $p = .05$), reflecting enhanced negativity in the violation relative to the control condition. Follow-up analyses of this interaction yielded a significant effect of CORRECTNESS at posterior electrode sites, indicating that this effect was most prominent at posterior relative to more central or frontal electrodes (Posterior: $F(1,13) = 6.18$, $p < .05$; Central: $F(1,13) = 2.76$, $p = .12$; Frontal: $F(1,13) = .28$, $p = .60$). Midline analyses did not yield significant effects, although trends for a main effect of CORRECTNESS ($F(1,13) = 4.33$, $p = .06$) and a CORRECTNESS×ELECTRODE interaction ($F(3,39) = 3.34$, $p = .07$) were found. These effects may thus possibly reach significance as the number of subjects included in subsequent analyses increases. Further, the lack of interactions with factor CONTEXT demonstrates that the size and distribution of the N400 effects were not affected by context (subject NP vs. neutral). Refer to Table 3.3 for further details).

Table 3.3. Global and post-hoc repeated measures ANOVA results for the semantic condition within a 300-500 ms time window

Global ANOVAs - midline	*df*	*F*	***p***
Correctness	1, 13	4.33†	.06
Correctness × Context	1, 13	0.54	.48
Correctness × Electrode	3, 39	3.34†	.07
Correctness × Context × Electrode	3, 39	0.51	.54
Global ANOVAs - lateral	*df*	*F*	*p*
Correctness	1, 13	2.95	.11
Correctness × Context	1, 13	.24	.64
Correctness × Laterality	1, 13	2.63	.13
Correctness × Anteriority	2, 26	4.41*	.05
Correctness × Hemisphere	1, 13	.82	.38
Correctness × Cont × Lat	1, 13	.99	.34
Correctness × Cont × Ant	2, 26	.03	.97
Correctness × Cont × Hemi	1, 13	.14	.71
Correctness × Lat × Ant	2, 26	.68	.51
Correctness × Lat × Hemi	1, 13	.41	.53
Correctness × Ant × Hemi	1,13	1.10	.35
Correctness × Cont × Lat × Ant	2, 26	.23	.80
Correctness × Cont × Ant × Hemi	2, 26	.99	.39
Correctness × Cont × Lat × Hemi	1, 13	.03	.87
Correctness × Lat × Ant × Hemi	2, 26	.10	.91
Correctness × Cont × Lat × Ant × Hemi	2, 26	1.52	.24
Post-hoc ANOVAs - lateral	*df*	*F*	*p*
Posterior: Correct vs. Violation	1, 13	6.18*	.03

Note: only significant results of post-hoc analyses are included in table; Cont = Context; Lat = Laterality; Ant = Anteriority; Hemi = Hemisphere; † = p ≤.10; * = p ≤.05

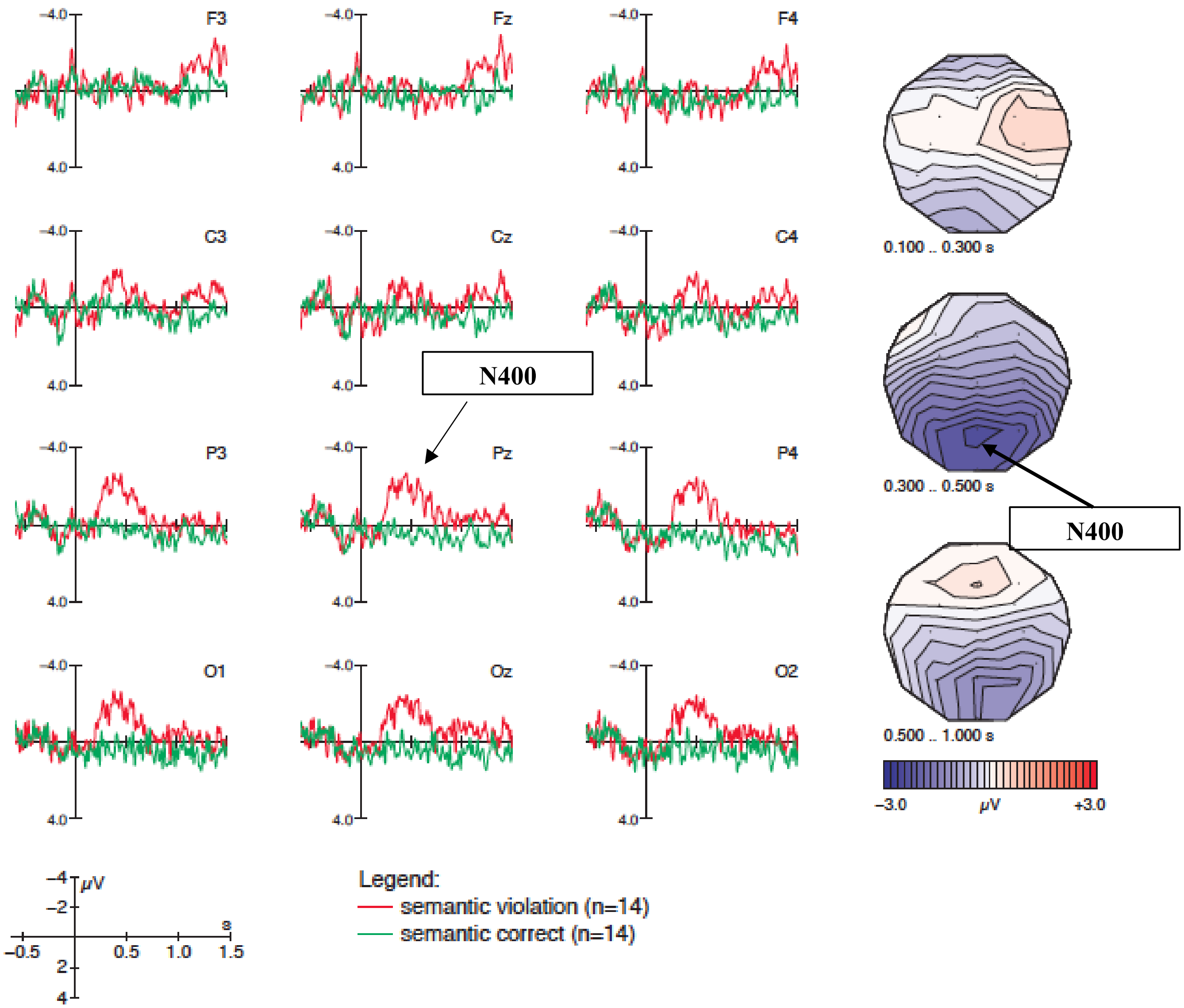

Figure 3.5. N400 effect in the conceptual semantic condition. Displayed are grand-average ERPs at midline and medial electrodes and voltage maps of difference waves (semantic violation minus semantic correct) for 14 participants, time-locked to the onset of the critical verb using a baseline of -600 to 0 ms. The vertical bar marks the onset of the critical verb. Compared with the correct control condition (green), the semantic mismatches (red) elicited a large negativity in the N400 time window. Negative polarity is plotted upwards. Voltage maps represent negativities in blue and positivities in red.

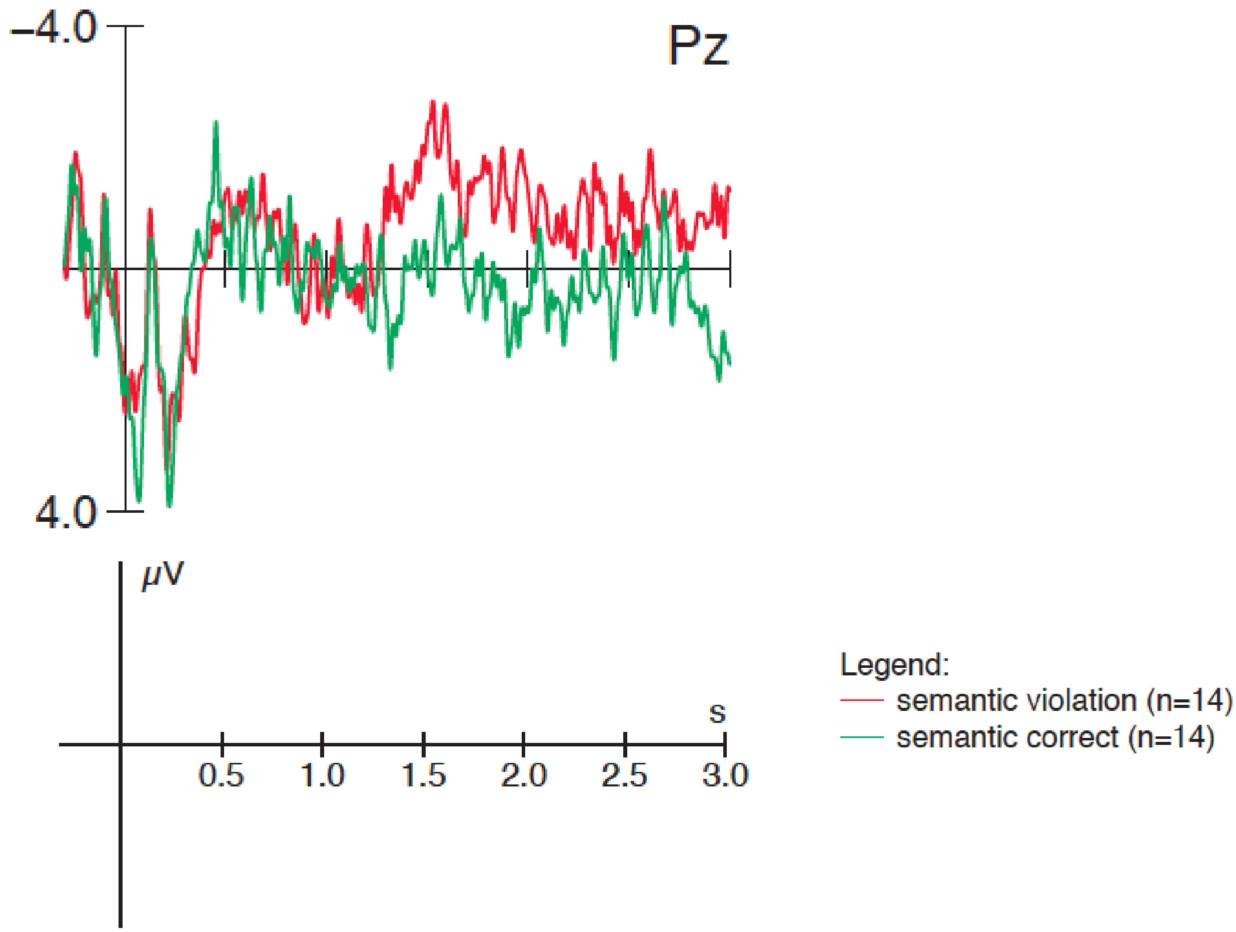

Figure 3.6. N400 effect at the sentence level in the conceptual semantic condition. Displayed are grand-average ERPs at the Pz electrode for 14 participants, time-locked to the onset of the sentence using a baseline of -300 to 0 ms. The vertical bar marks the onset of the sentence. Compared with the correct control condition (green), the semantic mismatches (red) elicited a large negativity that was visible even at the sentence level. Negative polarity is plotted upwards.

3.2.2 Morphosyntactic violations – critical verb

Recall that our context manipulation (neutral versus subject NP context) was used to introduce a range of different cues for the morphosyntactic number mismatch at various sentence positions. We predicted that our adult participants would show mismatch ERP effects only on the first available cue. In the case of sentences with neutral contexts and liaison, the first number cue occurred at the junction between the subject pronoun and the verb, and we therefore expected to see mismatch effects on the verb. For sentences with subject NP contexts, a sentence-initial cue (subject NP determiner) was included, and we therefore expected to see no further mismatch effects on the verb (i.e., we only expected mismatch effects on the sentence-initial determiner). Analysis of ERP components, with grand averages time-locked to the onset of the critical verb (i.e., Trigger # 4), revealed that this prediction was borne out. As predicted, no P600-like effects were observed on the verb for violation sentences with subject NP contexts when compared with correct controls. In contrast, as depicted in Figure 3.7, compared with the correct control condition, the critical verb with liaison in the morphosyntactic violation condition did elicit a posteriorly distributed positivity in the P600 latency window in sentences with neutral contexts. Figure 3.9 compares the ERPs of correct and violation sentences with subject NPs and neutral contexts (shown at electrode Oz). Whereas the subject NP sentences did not differ from each other (and largely patterned with the correct neutral context sentences), the violation condition with neutral context diverged from the other three conditions and elicited a positivity between 500 and 1000 ms, with a maximum at the occipital midline (Oz) electrode, i.e., slightly more posterior than the prototypical parietal distribution of the P600 component. As shown in Figure 3.8, this effect seemed to be largely driven by sentences with plural target nouns, which yielded an even larger positive deflection in the P600 time window. No differences were observed between the processing of correct and violation sentences with singular subjects. Figure 3.10 illustrates that, at the Oz electrode, only plural violation sentences diverged to elicit a positivity, while singular sentences did not differ from each other.

Further, violations within the neutral context subcondition also elicited a negativity at left frontal electrode sites (i.e., F7 and F3), in a time-window consistent with the LAN component, although occurring slightly earlier, and more sustained (i.e., from 200-700 ms), in line with a number of auditory studies investigating agreement (e.g., Friederici, Pfeifer, & Hahne, 1993; Balconi & Pozzoli, 2005; Rossi, Gugler, Friederici, & Hahne, 2006; Hasting & Kotz, 2008; Morgan-Short et al., 2010). As with the P600, the LAN effect is largest in plural sentences (see F3 electrode in Figure 3.8). Although proper statistical analyses have not yet been carried out for the LAN component, the running t-test implemented in EEProbe software suggests a significant effect at left frontal electrode sites between 200-700 ms.

In terms of the P600, statistical analyses corroborated our observations: in the P600 (500-1000 ms) time window, global ANOVAs yielded significant CORRECTNESS×CONT×ANT ($F(2,26) = 4.76$, $p < .05$), and CORRECTNESS×CONT×NUM×LAT×ANT ($F(2,26) = 4.27$, $p < .05$) interactions at lateral electrode sites. Follow-up analysis of the CORRECTNESS×CONT×ANT interaction revealed a main effect of CORRECTNESS for the neutral context subcondition, at posterior electrode sites only ($F(1,13) = 6.39$, $p < .05$), whereas no such effect was observed for the subject NP context subcondition. Moreover, the follow-up analysis of the CORRECTNESS×CONT×NUM×LAT×ANT interaction revealed a main effect of CORRECTNESS on posterior electrodes in sentences with neutral contexts and plural ($F(1,13) = 10.99$, $p < .01$), but not singular target nouns, confirming that plural target nouns carried most of the P600 effects in the neutral context subcondition (cf. Figure 3.8 and 3.9). The role of number was further evidenced by midline analyses, whereby a CORRECTNESS×NUMBER×ELECTRODE interaction ($F(3,39) = 3.70$, $p = .05$) was observed. Follow-up analyses of this interaction revealed a highly significant main effect of CORRECTNESS at Oz for the plural subcondition ($F(1,13) = 11.60$, $p < .01$) Refer to Table 3.4 for further details.

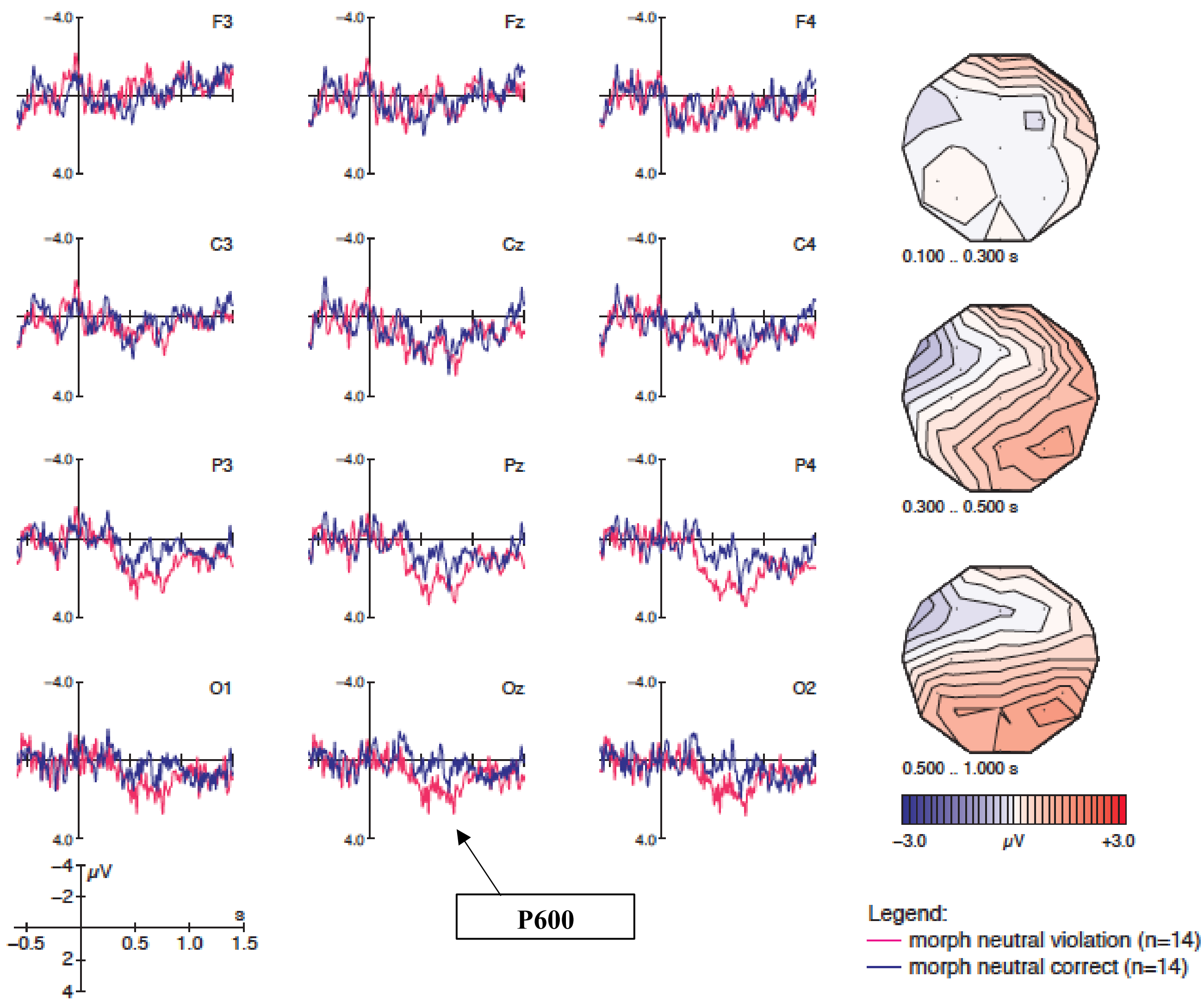

Figure 3.7. P600 effect in the morphosyntactic condition for sentences with neutral context. Displayed are grand-average ERPs at midline and medial electrodes and voltage maps of difference waves (violation minus correct) for 14 participants, time-locked to the onset of the critical verb using a baseline of -600 to 0 ms. The vertical bar marks the onset of the critical verb. Compared with the correct control condition (blue), the morphosyntactic number agreement mismatches (pink) elicited a positivity at posterior electrode sites. Negative polarity is plotted upwards. Voltage maps represent negativities in blue and positivities in red.

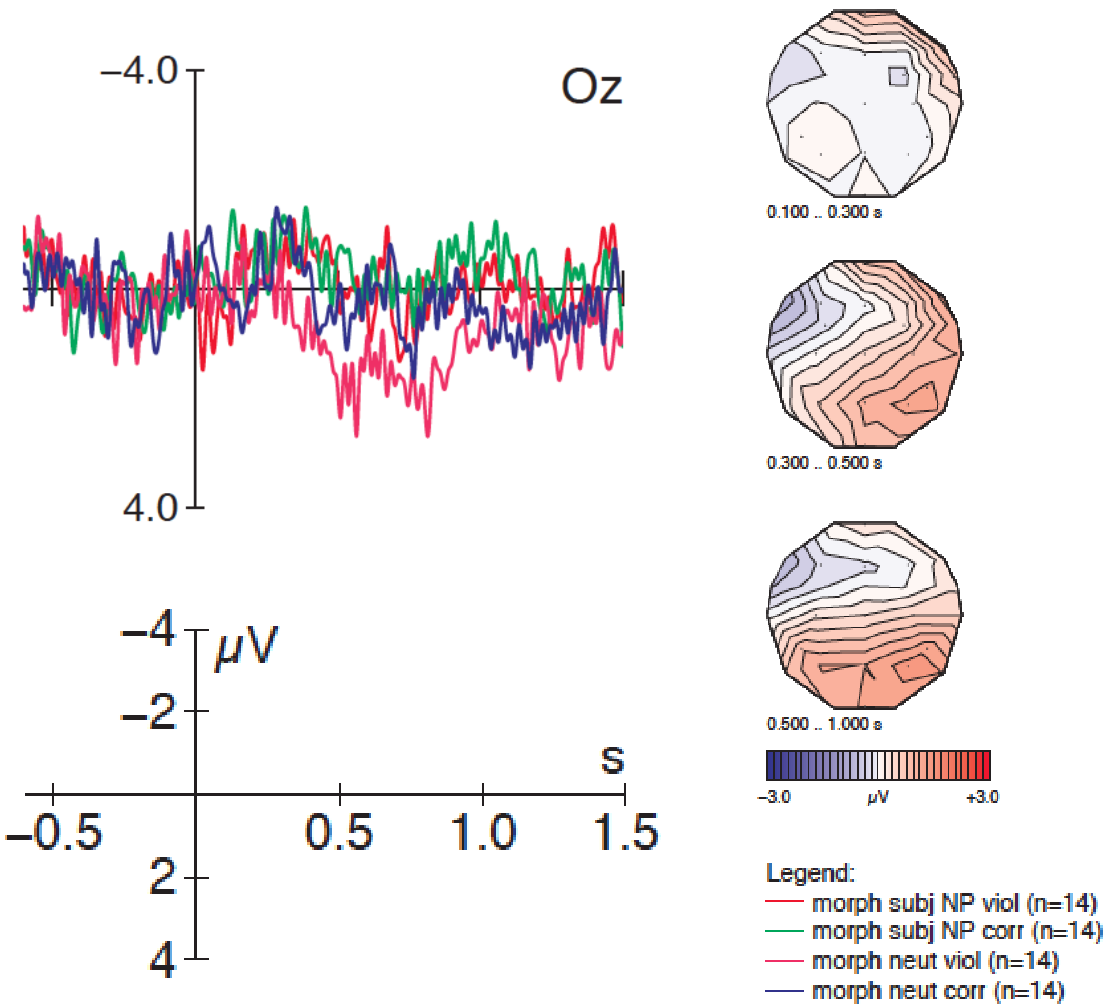

Figure 3.8. P600 effect in the morphosyntactic condition for sentences with neutral context, but not for sentences with subject NP context. Displayed are grand-average ERPs at the Oz electrode for neutral and subject NP context subconditions, and voltage maps of difference waves for the neutral context subconditions (violation minus correct), time-locked to the onset of the critical verb using a baseline of -600 to 0 ms. The vertical bar marks the onset of the critical verb. Whereas the subject NP control (green) and violation (red) sentences do not differ from each other and largely pattern with the correct neutral context sentences (blue), mismatches within the neutral context subcondition (pink) elicit a positivity within the P600 time window. Negative polarity is plotted upwards. Voltage maps represent negativities in blue and positivities in red.

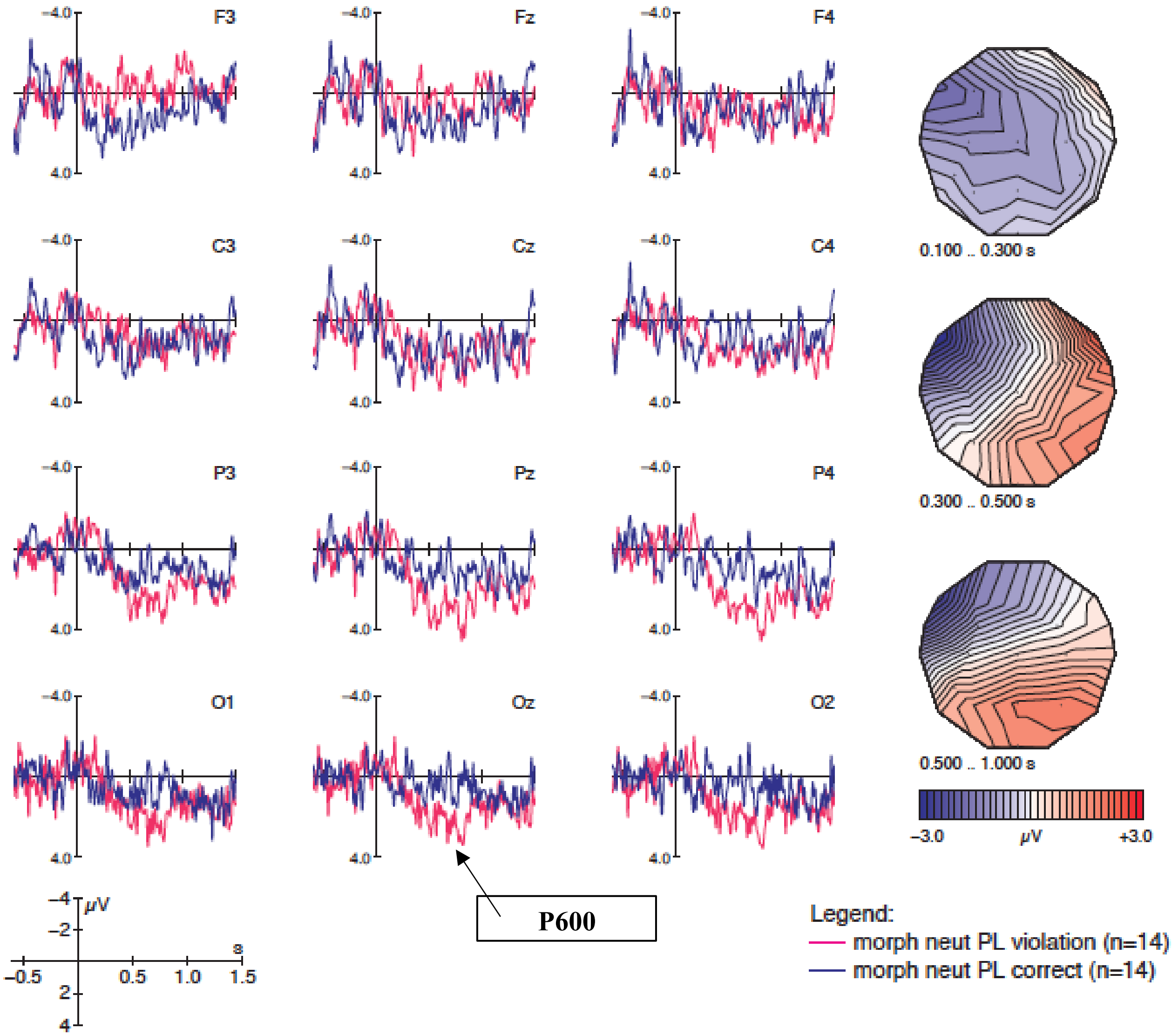

Figure 3.9. P600 effect in the morphosyntactic condition for plural sentences with neutral contexts. Displayed are grand-average ERPs at midline and medial electrodes and voltage maps of difference waves (violation minus correct) for 14 participants, time-locked to the onset of the critical verb using a baseline of -600 to 0 ms. The vertical bar marks the onset of the critical verb. Compared with the correct control condition (blue), the morphosyntactic number agreement mismatches (pink) in this subcondition elicited the largest positivity at posterior electrode sites. Negative polarity is plotted upwards. Voltage maps represent negativities in blue and positivities in red.

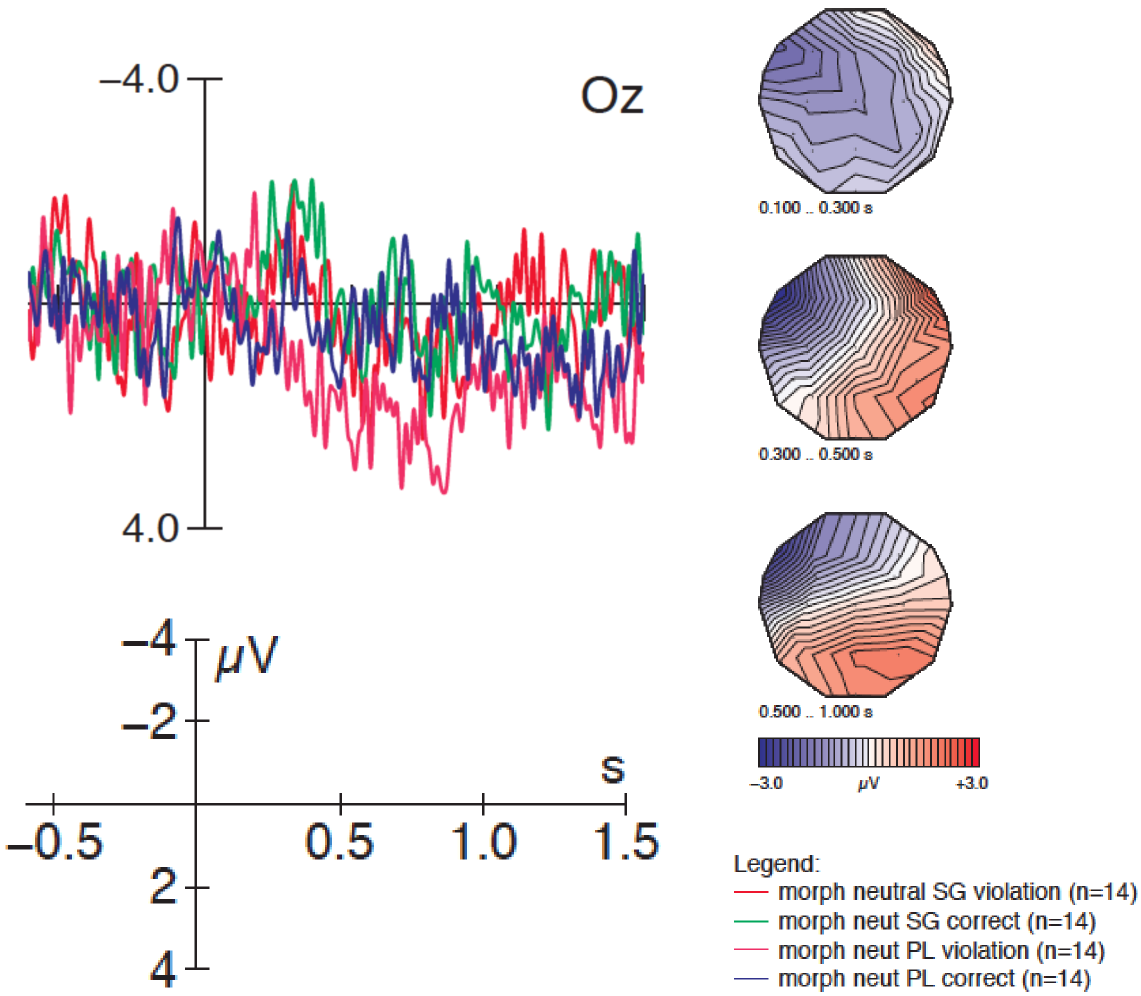

Figure 3.10. P600 effect in the morphosyntactic condition for plural (but not singular) sentences with neutral contexts. Displayed are grand-average ERPs at the Oz electrode for singular and plural sentences with neutral contexts, and voltage maps of difference waves for the plural subcondition (violation minus correct), time-locked to the onset of the critical verb using a baseline of -600 to 0 ms. The vertical bar marks the onset of the critical verb. Whereas the singular correct (green) and violation (red) sentences do not differ from each other and largely pattern with the correct plural sentences (blue), mismatches within the plural subcondition (pink) elicit a positivity within the P600 time window. Negative polarity is plotted upwards. Voltage maps represent negativities in blue and positivities in red.

Table 3.4. Global and post-hoc repeated measures ANOVA results for the morphosyntactic condition within a 500-1000 ms time window

Global ANOVAs - midline	***df***	***F***	***p***
Correctness	1, 13	.26	.62
Correctness × Context	1, 13	.33	.57
Correctness × Number	1, 13	1.10	.31
Correctness × Electrode	3, 39	3.13†	.07
Correctness × Context × Number	1, 13	.23	.64
Correctness × Context × Electrode	3, 39	1.25	.30
Correctness × Number × Electrode	3, 39	3.70*	.05
Correctness × Context × Number × Electrode	3, 39	.53	.57
Post-hoc ANOVAs - midline	*df*	*F*	*p*
Oz: Correctness × Number	1, 13	7.34*	.02
Oz plural: Correct vs. Violation	1, 13	11.60**	.005
Global ANOVAs - lateral	*df*	*F*	*p*
Correctness	1, 13	3.68	.55
Correctness × Context	1, 13	1.02	.75
Correctness × Number	1, 13	1.57	.90
Correctness × Laterality	1, 13	6.70	.98
Correctness × Anteriority	2, 26	4.33*	.05
Correctness × Hemisphere	1, 13	2.29	.64
Correctness × Cont × Num	1, 13	7.13	.41
Correctness × Cont × Lat	1, 13	3.60	.56
Correctness × Cont × Ant	2, 26	4.76*	.04
Correctness × Cont × Hemi	1, 13	1.45	.25
Correctness × Num × Lat	1, 13	1.60	.23
Correctness × Num × Ant	2, 26	6.51**	.01
Correctness × Num × Hemi	1, 13	5.65*	.03
Correctness × Lat × Ant	2, 26	1.59	.23
Correctness × Lat × Hemi	1, 13	6.23	.44
Correctness × Ant × Hemi	2, 26	2.15	.68
Correctness × Cont × Num × Lat	1, 13	5.24	.94
Correctness × Cont × Num × Ant	2, 26	3.08	.09
Correctness × Cont × Num × Hemi	1, 13	9.74	.34
Correctness × Cont × Ant × Lat	2, 26	5.44	.55
Correctness × Cont × Ant × Hemi	2, 26	2.21	.66
Correctness × Cont × Lat × Hemi	1, 13	7.67	.40
Correctness × Num × Lat × Ant	2, 26	5.02	.91
Correctness × Num × Lat × Hemi	1, 13	3.40	.09
Correctness × Num × Ant × Hemi	2, 26	1.68	.22
Correctness × Lat × Ant × Hemi	2, 26	9.11	.86
Correctness × Cont × Num × Lat × Ant	2, 26	4.27*	.03
Correctness × Cont × Num × Lat × Hemi	1, 13	2.05	.66

Correctness × Cont × Num × Ant × Hemi	2, 26	1.98	.18
Correctness × Cont × Lat × Ant × Hemi	2, 26	3.65	.63
Correctness × Num × Lat × Ant × Hemi	2, 26	1.46	.25
Correctness × Cont × Num × Lat × Ant × Hemi	2, 26	3.57	.61
Post-hoc ANOVAs - lateral	*df*	*F*	*p*
Correctness × Context × Anteriority			
Neutral context: Correctness × Ant	2, 26	10.03**	.005
Neutral posterior: Context × Violation	1, 13	6.39*	.03
Corr × Cont × Num × Lat × Ant			
Lateral: Corr × Cont × Num × Ant	2, 26	5.88*	.02
Neutral context: Corr × Lat × Ant × Num	2, 26	7.36**	.004
Neutral plural: Corr × Num × Ant	2, 26	13.42**	.002
Posterior: Correct vs. Violation	1, 13	10.99**	.006

Note: only significant results of post-hoc analyses are included in table; Corr = Correctness; Cont = Context; Lat = Laterality; Ant = Anteriority; Hemi = Hemisphere; † = p ≤.10; * = p ≤.05; ** = p ≤.01

3.2.3 Morphosyntactic violations – sentence-initial effects

Recall that our context manipulation (neutral versus subject NP context) was used to introduce a range of different cues for the morphosyntactic number mismatch at various sentence positions. The fact that (unlike the neutral context condition) the determiner of the subject NP context already included an early sentence-initial clue, along with the absence of a P600 on the target verb in this subcondition, suggested that an ERP mismatch effect might have occurred earlier in the sentence. We therefore also computed ERP averages time-locked to the sentence onset (i.e., Trigger # 1).

Figure 3.11 compares the ERPs of the 4 relevant morphosyntactic conditions at sentence onset, i.e., correct and violation sentences with both neutral and subject NP contexts (shown at electrode PZ). As expected, whereas the neutral sentences do not differ from each other (and largely pattern with the correct subject NP sentences), the violation condition with subject NP contexts diverges from the other three conditions and elicits a positivity between 600 and 1200 ms. The corresponding voltage maps (violation minus correct in the subject NP context condition) illustrate that this positivity displays the typical parietal scalp distribution of a P600. Note that this analysis includes only twelve of the fourteen data sets, as two participants had to be excluded due to excessive EEG artifacts at sentence onset. While proper statistical analyses will be postponed until more data sets are available, the rather conservative 'running t-test' implemented in EEProbe software suggests a significant effect near the peak of the P600 around 750 ms (gray line in the box below the ERP plot).

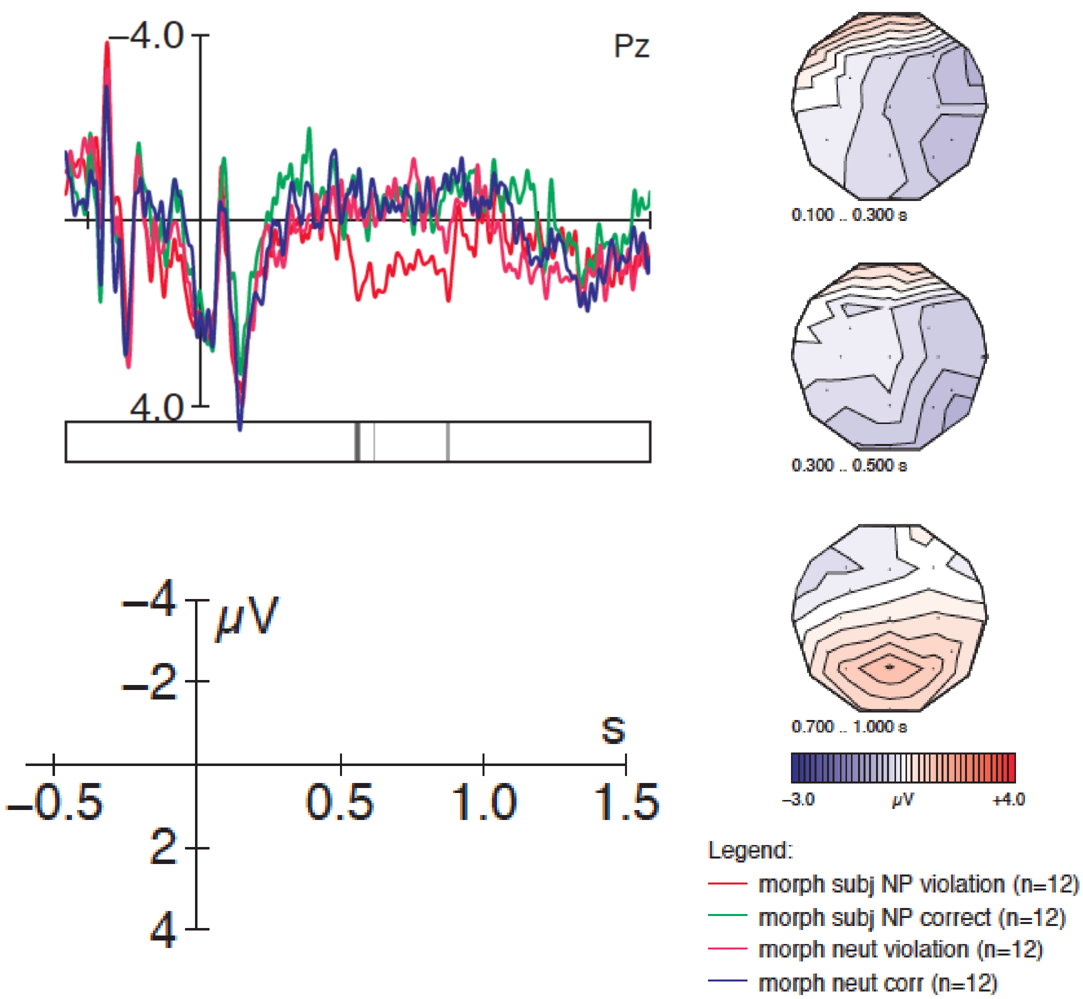

Figure 3.11. P600 effect in the morphosyntactic condition for sentences with subject NP contexts. Displayed are grand-average ERPs at the Pz electrode for neutral and subject NP context subconditions, and voltage maps of difference waves for the subject NP context subcondition (violation minus correct), time-locked to the onset of the critical determiner using a baseline of -600 to 0 ms. The vertical bar marks the onset of the critical determiner. Whereas the neutral control (blue) and violation (pink) sentences do not differ from each other and largely pattern with the correct subject NP context sentences (green), mismatches within the subject NP context subcondition (red) elicit a positivity resembling a P600.

4. Discussion

The present paper reported on two sub-experiments probing questions concerning the neurocognitive mechanisms underlying the online processing of different types of linguistic information, namely lexico-conceptual semantics, and morphosyntax, during real-time auditory sentence comprehension in French. These sub-experiments, involving adult control subjects, were the initial steps taken as part of a larger research project aiming to provide a better understanding of French language acquisition and comprehension abilities in children with DLI. To our knowledge, we are the first to implement such a rigorous design with the aim of studying language processing in French, all while using a methodologically sound design (see Steinhauer & Drury, 2012) in a paradigm that obviates reading processes that may not be robust in children, while maintaining their interest and attention. Experimental findings for the semantic and verb Type-2 morphosyntactic conditions will be discussed in turn in the sections below.

4.1 Response accuracy

The high response accuracy scores obtained for the semantic condition demonstrated that participants were able to successfully discriminate violation from control sentences across subconditions (i.e., across context types). We did observe a GENDER×NUMBER interaction which revealed a relative difficulty with singular sentences containing feminine subjects. This peculiarity may simply be due to the types of stimuli we included (i.e., item effects), but we are also currently investigating sociolinguistic factors that may have played a role. However, it should be noted that response accuracy was very high for these items nevertheless, so this interaction should not point to any serious issues. Response accuracy for the morphosyntactic verb Type-2 condition was also high and participants could also successfully discriminate violation from correct control sentences. Statistical analyses revealed interactions involving CORRECTNESS×CONTEXT, CORRECTNESS×NUMBER, and CONTEXT×NUMBER, which pointed to a relative difficulty with the rejection of mismatch singular sentences with neutral contexts. We surmise that this difficulty can be explained in terms of the phonological salience of different number cues, with the absence of liaison in singular sentences being the least salient cue. As this pattern also affected our ERP components, this will be discussed in greater detail in the corresponding section below. Again, response accuracy was high for all subconditions nonetheless. The overall excellent performance by our participants on the judgment task demonstrates that our choice of task (i.e., a binary acceptability judgment task in which participants provided ratings of 'acceptable' or 'unacceptable'), and the type of auditory-visual mismatches created were appropriate. Importantly, this also demonstrates that our participants were alert throughout the experiment, which may suggest that our alien-learning paradigm will keep children engaged as well.

4.2 Lexico-conceptual semantic violations

4.2.1 N400 effects

ERP analyses across participants revealed that, compared to matched controls, the lexico-conceptual semantic violations created by auditory-visual mismatches elicited a large N400 component beginning 300 ms after the onset of the critical verb. These results were consistent with our predictions. Recall that we expected cross-modal action mismatches to elicit an N400 effect on the critical verb, as this is the first point at which the mismatch becomes evident (i.e., you see *elle* ***chante*** 'she sings' but hear *elle* ***!nage*** 'she swims', therefore the violation occurs on the verb, when you expect to hear *chante* but hear *nage* instead). The fact that we obtained an

N400 in response to these semantic mismatches is not highly surprising. After all, this component has been the most consistent ERP response to semantic anomalies since Kutas and Hillyard (1980; for a review, refer to Kutas & Federmeier, 2011) and has also been observed more recently in bimodal (auditory-visual) lexical semantic violations where an incongruous or unexpected image is presented concurrently with an auditory or written utterance (see e.g., Friedrich & Friederici, 2004; Willems et al., 2008; Royle et al., 2013). However, of importance here is the fact that our study focused on cross-modal mismatches involving verbs/actions, and not nouns/objects like most previous studies have done. We have therefore demonstrated that an N400 can be reliably elicited in adult French native speakers in response to these types of mismatches. An interesting question is whether we will replicate this finding in children with DLI, as verb-action matching is arguably more complex than noun-object matching, the former requiring analysis of the entire picture and the latter simply requiring analysis of the noun phrase.

Interestingly, the observed N400 showed a large peak, which was even evident during visual inspection conducted at the sentence level (i.e., before grand averages time-locked to the onset of the critical verb were computed). In auditory studies, spoken words unfold over time, creating great variability in the speech signal contained in each audio file, and causing processing of a given type of information to be initiated at different points in time. This variability is reflected in the N400 component by it being more spread out in time and, therefore, being more sustained and smaller in size (i.e., it shows less of a peak). This is contrary to reading studies with word-by-word presentation methods, whereby the entire word information becomes available at once, leading to more uniformity of the N400 latency across items. It is therefore noteworthy to mention that, despite the variability of the speech signals contained in our auditory stimuli, an N400 with a large peak was elicited in response to semantic mismatches.

4.2.2 Sustained and frontal negativities

Visual inspection of our data did not reveal the slightest indication of any positivities following the N400 effects. Instead, we find a sustained negativity lasting until 1500 ms. This could possibly be interpreted as a reflection of the fact that our study was partly auditory, such that this sustained negativity simply reflects that the N400 was more spread out in time due to variability in the speech signal, as explained above. If this were the case, we would predict a small, sustained N400. However, recall that we observed an N400 with a rather large peak, demonstrating that time-locking our analyses to the target word eliminated at least some effects of this variability. Another avenue we can explore concerns the functional interpretation of the N400 component, and whether it simply reflects automatic expectancy based processing (i.e., lexical access processes) (for reviews see: Federmeier, 2007; Kutas et al., 2006; Lau et al., 2008) or whether it also reflects controlled post-lexical integration (i.e., integration of the spoken word into a higher order meaning representation) (e.g., Brown & Hagoort, 1993; Holcomb, 1993). Our data seem to lend more support to the latter interpretation, as the sustained negativity may very well reflect ongoing efforts to integrate the anomalous word in a semantic context, especially in the absence of a P600. Recall that the P600 has sometimes been elicited by semantic anomalies in conjunction with the N400 (Hagoort, 2003; Royle et al., 2013; Steinhauer et al., 2010), and has therefore been argued to reflect the processing load related to language reanalysis (i.e., it is not specific to grammatical processing) (Kolk et al., 2003; Steinhauer & Connolly, 2008; van de Meerendonk et al., 2010). As sentence reanalysis is clearly not indexed by the P600 in our data, it is entirely possible that the sustained negativity we observe reflects an ongoing effort to integrate anomalous words into a higher-order meaning representation in order to build an interpretation of the sentence.

Lastly, we observed a third negativity in frontal electrodes beginning at approximately 1000 ms. Similar late frontal negativities have been reported in some of the literature, and are often believed to reflect working memory load increases, whereby information must be held in working memory during interpretation (see Steinhauer & Connolly, 2008; Steinhauer et al., 2010). Considering that our verb-picture mismatches likely required analysis of the entire sentence/image, it is highly possible that this caused an increase in working memory load, with the late anterior negativity reflecting this process. However, these negativities occur inconsistently in the literature and their exact nature is still unknown. As mentioned briefly in the introduction, sustained negativities believed to reflect working memory load are sometimes argued to be a type of a LAN (i.e., *sustained* LAN), but this is still a question of debate.

4.2.3 P600 effects

As mentioned, our data did not reveal any P600 effects in response to our semantic violations, thus no statistical analyses were performed in the P600 time window. The absence of a positivity may be explained by the type of violations included in our study. It is possible that violations involving nouns/objects, such as those included in most previous studies, involve different cognitive components and therefore lead to a P600, while the verb mismatches included in our study are somehow distinct. As we are the first to investigate these types of auditory-visual verb/action mismatches, we do not have a precise point of comparison, but for the moment we can hypothesize that the analysis of these types of violations is somewhat distinct from the analysis of violations involving nouns/objects.

4.3 Morphosyntactic violations

4.3.1 P600 effects

ERP analyses across participants revealed that, some 500 ms after onset of the critical verb, the cross-modal number agreement mismatches elicited a P600 (albeit with a slightly more posterior distribution, i.e., reaching its maximum at the Oz electrode rather than at Pz), but only for sentences with neutral contexts. No such positivities were observed on the verb for sentences with subject NP contexts. Conversely, for sentences with subject NP contexts, visual inspection of the sentence-initial critical determiner in subject-verb agreement violation conditions revealed a P600-like positivity around 750 ms (only substantiated by running t-tests thus far), while no such positivities were observed for sentences with neutral contexts. These results are consistent with what we intended with our manipulations, as our data show that if multiple cues are available to identify the subject number (and therefore also to detect number matches or mismatches with the image), adult participants (1) use the first available cue in the sentence to detect the mismatch, reflected by P600s, and (2) do not show an additional mismatch effect at the position of the second cue, reflected by the absence of a P600 at the liaison in sentences with subject NP contexts. Based on these results, we can expect to observe the same pattern in the verb Type-3 condition, except that mismatch effects on the verb should be visible on the verb ending (as cues for number in Type-3 verbs are contained in verb endings). Important questions involving children with DLI is whether they will be equally efficient in extracting the relevant information from the speech signal as adults (i.e., such that effects are only seen on the first relevant cue) and whether they will be equally sensitive to the different types of morphological cues included (i.e., liaison vs. verb-final consonants). As this is the first study to test different cues for number violations this systematically, our data will clearly provide some advancement in the ERP literature on French-speaking children with DLI, but also typical language development.

Interestingly, not all types of mismatches involving sentences with neutral contexts were processed in the same manner. ERP analyses across participants revealed that, while plural sentences elicited the expected P600 component on the critical verb in response to agreement violations, this was not the case for singulars, which showed no such effects post verb onset. This finding is consistent with the interactions found in our behavioural data thus far. Recall that response accuracy results revealed relative difficulties with the rejection of mismatch singular sentences with neutral contexts (e.g., *Au dessert, elle aime* … 'For dessert, she likes…' concurrently with a plural image), but not with corresponding correct sentences, and this difficulty was completely absent for singular sentences with subject NP contexts. (e.g., *La fille, elle aime* … 'The girl, she likes…' concurrently with a plural image). The lack of ERP mismatch effects for singular sentences with neutral contexts may therefore be a reflection of this difficulty. In trying to account for this pattern, we can explore two avenues of reasoning, one involving the concept of phonological salience, and the other involving the type of interpretation that was assigned to these sentences.

Phonological salience is a term that is often used interchangeably with perceptual salience, which refers to the ease with which we can hear or perceive a given structure (Goldschneider & DeKeyser, 2005). If we apply the concept of phonological salience to our present sentence materials, we would expect that arriving at an accurate sentence interpretation is facilitated in the presence of overt phonological cues for number (as they are clearly more salient than a lack thereof). In our study, we included two overt cues for number: (1) the determiner of the subject NP, present in half of singular as well as plural sentences (i.e., in the subject NP context conditions), and (2) the pronoun-verb liaison, present in the other half of both singular and plural sentences (i.e., the neutral context conditions). However, whereas all three determiners of the subject NP (i.e., *le/la/les*) are phonologically equally distinct from one another and are available sentence initially (i.e., in a position where attention can fully focus on the number match), the liaison in the plural condition (e.g., *elles aiment*) is arguably more salient – due to the presence of an 's' – than the absence of liaison in the singular condition (*elle aime*). In other words, it seems very unlikely that a participant – after hearing '*elles aiment*' – would be willing to deny the presence of the 's' and assume he may have hallucinated, just because the picture only shows a single girl. However, if the same participant sees a picture with two girls and hears '*elle aime*', it seems possible that he concludes to having missed the plural 's' at the liaison position. Similar differences between the presence versus absence of phonological (and visual) evidence have previously been found for prosodic boundaries and commas (leading to the 'Boundary Deletion Hypothesis', cf. Steinhauer & Friederici, 2001; Pauker, Itzhak, Baum, & Steinhauer, 2011). The phonological salience account thus seems to provide a plausible explanation for the absence of ERP mismatch effects for singular sentences with neutral contexts.

Sentence interpretation. We can also discuss this pattern in terms of the type of interpretation our participants assigned to this subset of sentences, which can either be more logical or pragmatic in nature. For example, the sentence "*Some triangles have three edges*" is logically true, but pragmatically odd. Similarly, if you are presented with an image of two girls eating and hear the sentence "*she is eating*" (as in our study), this is also logically true, but pragmatically odd. The literature suggests that people differ in their bias towards logical versus pragmatic processing (e.g. Barbet & Thierry, 2016). If some of our participants were biased towards logical processing, we would expect a reduced mismatch effects for the neutral singular violation sentences. Crucially, however, even though one could argue that this effect should be limited to sentences in the singular, there is no reason why it should be limited to neutral context sentences; seeing an image of two girls eating and hearing "*the girl, she is eating*" would be expected to be as acceptable as "*right now, she is eating*". However, our data only showed a lack of violation detection (and the absence of a P600) for the sentences with neutral contexts. Therefore, the phonological salience account seems like more of a compelling explanation for our data. Analysis of our Type-3 verbs condition will provide some interesting insight here. As it can be argued that both singular and plural verb endings for this verb type are equally salient (unlike the singular vs. plural liaison triggered by Type-2 verbs), it is possible that we will not observe this pattern (i.e., involving singular sentences with neutral contexts) for Type-3 verbs. It will also be interesting see whether this pattern is observed in children with DLI, as it is likely that they will affected by the phonological salience of number cues as well.

4.2.2 LAN effects

Although proper statistical analyses have not yet been carried out, it is noteworthy to mention that visual inspection of ERP data at the critical verb revealed a significant (as per running t-tests) anterior negativity at left frontal electrode sites, between approximately 200 to 700 ms post onset. This negativity appeared in response to mismatches involving sentences with neutral contexts, but not those involving subject NP contexts. We can cautiously surmise that this negativity is, in fact, a LAN component. Recall that this is precisely what we intended with our context manipulation, following the same reasoning we used for the P600. Similar to the P600, this negativity was most visible with plural sentence mismatches, consistent with the 'congruent' interpretation assigned to a subset of singular mismatch sentences, as discussed above. We expect future LAN analyses to reveal the same patterns as the P600. For example, analyses conducted on the sentence-initial determiner should reveal a mismatch LAN effect for sentences with subject NP contexts. Sentences containing Type-3 verbs should show the same mismatch effects (i.e., on the verb for sentences with neutral contexts and on the determiner for sentences with subject NP contexts), but those elicited on the verb should be visible on the verb ending. Some interesting questions for the children with DLI is whether they will elicit a LAN in response to our number mismatch violations, and what the latency and distribution of this negativity would look like (i.e., immature vs. atypical).

At present, the appearance of LAN-type negativities in agreement conditions is still a question of debate, even in adults, and might be modulated by the languages and structures used to elicit them (Royle et al., 2013). For example, while most studies cited by Molinaro et al. (2011a) show LANs in response to subject-verb agreement violations, in Frenck-Mestre and colleagues' (2008) reading study on French verbal agreement, French native speakers did not elicit LANs in response to violations such as **je mangez*. They state that the absence of a LAN may be indicative of a lack of an early syntactic checking mechanism (cf. Friederici, 2002). However, our data clearly show a LAN in response to our cross-modal number mismatches. It should be noted that the "subject-verb agreement" violations studied in Frenck-Mestre et al. (2008) are, in fact, finiteness violations. Further, their study presents a number of methodological flaws (for a review of methodology issues see Steinhauer & Drury, 2012). In light of these issues, their view cannot be maintained. Importantly, therefore, we have shown, on the one hand, that LANs can reliably be elicited by French native speakers (i.e., their absence in Frenck-Mestre et al. (2008) was not simply due to a property of French), and on the other, that the cross-modal number mismatches included our study elicit LANs similar to those observed in response to subject-verb agreement violations in reading studies.

5. Conclusion and future directions

With the aim of reaching a better understanding of French language acquisition and processing in children with DLI, we developed two sub-experiments with auditory-visual sentence-picture matching paradigms and an acceptability judgment task. In Sub-experiment 2, we implemented a rigorous and balanced methodological design to investigate neurocognitive mechanisms underlying lexico-conceptual semantics and morphosyntactic number agreement. ERP results from the neurotypical adult control group demonstrated that adult native French speakers reliably exhibit an N400 component in response to the auditory-visual verb-action mismatches included in our study, but not a P600 as has been observed in previous studies including mismatches involving nouns/objects. Further, auditory-visual morphosyntactic number mismatches reliably elicited a P600 (preceded by a LAN on the critical verb thus far), and our context manipulation demonstrated that if multiple cues are available to identify the subject number (and therefore also to detect number match or mismatches with the image), adult participants use the first available cue in the sentence to detect the mismatch, and do not show an additional mismatch effect at the position of the second cue.

Together, these results suggest that our choice of subject task and experimental paradigm/ manipulations were highly appropriate, and can therefore be used to test our child populations. Further investigation into the sociolinguistic and phonological factors affecting sentence interpretation is warranted, however, and is currently underway. We will also continue with data analysis so we can completely establish the prototypical ERP correlates in neurotypical adults for the various linguistic anomalies included in our study, as this will allow us to establish clear predictions for child ERPs, and meaningfully interpret the child data we will be collecting shortly.

Our adult data will also provide a significant contribution to the field of the cognitive neuroscience of language by providing high-quality cross-linguistic evidence regarding the generalizability of ERP profiles across modalities and languages. Once we have tested children with DLI as well as developmentally and chronologically age-matched peers, we will also be able to provide a substantial contribution to the field of DLI research, which will bring us closer to understanding underlying deficits characterizing this developmental disorder. This research is therefore also of great clinical significance, as it will inform clinical practice and undoubtedly benefit individuals with DLI in the future.

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Appendix A

Preliminary IRB approval

McGill

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15 September 2017

Dr. Karsten Steinhauer
School of Communication Sciences & Disorders
2001, avenue McGill-College, Suite 800
Montreal QC H3A 1G1

RE: **IRB Review Number A00-B49-17A**
Tracking language acquisition and processing in specific language impairment (Part 1: Adult control group)

Dear Dr. Steinhauer,

On 11 September 2017, at a meeting of the Institutional Review Board, a full Board review was conducted for the above-referenced study. This study was reviewed on behalf of your Masters Student, Lisa Martignetti.

The Committee identified the following concerns for your response:

Scientific Protocol & Ethical Considerations

1. In reference to both the protocol and the Initial Review Form:
    a. Part 5: Redefine the benefits for study participants, if any; it is unlikely that participants benefit from the 'basics of EEG research'.
    b. Part 6: The text distinguishes between personal and experimental data, and specifies that personal data will be retained for up to 10 years, but offers no information on how long experimental data will be kept. Additionally, please justify the retention of personal information for a period of 10 years.
    c. Part 6: Personal data should not be shared with anyone; remove any statement that suggests personal data may be shared with third parties.
    d. In the study protocol, update the reference to the Declaration of Helsinki or, more appropriately, reference the Tri-Council Policy Statement, 2014, to which SSHRC funded projects must adhere.
2. Please submit a copy of the student's Advisory Committee/Science review of this project.

Consent Form

3. Correct the inconsistencies between the consent form and the protocol with respect to data confidentiality and data retention.

This study received ethics approval pending the submission and an assessment of an appropriate response to the above-listed concerns.

Regards,

Roberta Palmour, PhD
Chair
Institutional Review Board

Appendix B

Consent Form

Comité d'éthique à la recherche en Santé, Université de Montréal

Étude de l'acquisition et du traitement du langage dans les troubles primaires du langage
(Tracking language acquisition and processing in specific language impairment)

Chercheur principal
Phaedra Royle, Ph.D. – Professeure agrégée
École d'orthophonie et d'audiologie, *Université de Montréal, et* CRBLM
Co-chercheures principales
Karsten Steinhauer, Ph.D. – Professeur agrégé
School of Communication Sciences and Disorders, McGill, et *CRBLM*
Lauren Fromont, M.Sc. – Étudiante au doctorat
École d'orthophonie et d'audiologie, *Université de Montréal, et* CRBLM
Emilie Courteau, M.P.O, – Orthophoniste, étudiante au doctorat
École d'orthophonie et d'audiologie, *Université de Montréal, et* CRBLM
Lisa Martignetti – Étudiante à la maîtrise,
School of Communication Sciences and Disorders, McGill
Collaborateurs
Boutheina Jemel, Ph.D. – Professeur adjointe, *École d'orthophonie et d'audiologie,* Université de Montréal, et *Hôpital Rivière des Prairies*
Alexandra Marquis, Ph.D. – Professeur adjointe, *Linguistics,* United Arab Emirates University
Marie Pourquié, Ph.D. – Chercheure postdoctorale, *Université de Montréal* et *BCBL*

Financement
Conseil de recherche en sciences humaines du Canada (CRSH 435-2015-1280), à Royle Steinhauer, Courteau, Jemel, Marquis et Pourquié.

Invitation à la recherche : Nous avons le plaisir de vous inviter à participer à une étude sur la compréhension des mots (sémantique), de l'accord (masculin féminin) et la structure de la phrase (syntaxe) chez les enfants d'âge scolaire avec (et sans) trouble primaire du langage (TPL). Cette recherche vise une meilleure compréhension de l'apprentissage du français.
Liberté de participation : La participation à cette recherche est volontaire et les participants sont libres de se retirer à tout moment sans conséquence ou préjudice. Les données des participants qui se retirent du projet seront détruites. Un refus de participer ou un retrait de participation n'aura aucun impact sur les services reçus en dehors de ce projet de recherche.
But de l'étude : Le but de ce projet est d'étudier le développement du langage chez les enfants présentant un TPL. Nous voulons établir (a) comment le cerveau de l'enfant comprend les structures du langage et (b) si les enfants avec un TPL les comprennent de la même façon. La méthode utilisée lors de cette recherche est l'électroencephalographie (ÉEG). Les enregistrements de ÉEGs mesurent les potentiels électriques générés par le cerveau au moyen de capteurs attachés à un bonnet (similaire à un casque de bain). Les résultats obtenus seront comparés à ceux obtenus par des enfants sans trouble de langage afin de pouvoir déterminer les similitudes et différences dans leurs apprentissages.
Procédures : Avant l'expérimentation, vous passerez le test « Edinburgh Handedness Inventory » pour certifier que vous êtes vraiment droitier. Si vous êtes gaucher, vous ne pourrez participer à cette expérimentation. Les gauchers démontrent plus de variabilité dans l'organisation du langage dans

leur cerveau que les droitiers. De plus, vous remplirez un questionnaire sur votre histoire éducationnelle, votre état de santé actuelle, la consommation récente de café, de tabac, etc. Ces facteurs peuvent influencer les processus cognitifs comme le traitement du langage et ces informations pourraient être utiles lors de l'analyse des données.

Une rencontre de trois heures est prévue. Cette rencontre comprend l'enregistrement de PÉs et le remplissage de questionnaires. L'enregistrement de l'activité de votre cerveau au moyen de l'ÉEG. L'ÉEG est une technique non invasive (sans blessure) qui fait usage de capteurs attachés à un bonnet similaire à ceux des nageurs. Ceux-ci peuvent enregistrer l'activité électrique du cerveau grâce aux capteurs qu'ils contiennent. Ce gel permet la conduction de l'activité électrique du cerveau à l'électrode. L'installation du casque à électrodes prend environ trente minutes. Par la suite, vous serez installé(e) dans un siège devant l'écran d'un ordinateur qui est installé dans une cabine isolée du bruit.

Au cours de l'étude, votre tâche consistera à écouter une série de phrases et à comprendre leur sens. Des essais pratiques sont prévus afin de vous familiariser avec l'activité. L'expérimentation durera environ une heure et demie en incluant des courtes pauses. À la suite de l'expérimentation, pour nettoyer le surplus de gel, vous pourrez vous laver et sécher vos cheveux à l'aide d'un lavabo prévu à cet effet si vous le désirez. Pour ce faire, nous aurons du shampoing, une serviette, et un séchoir à votre disposition. La durée totale de la rencontre sera d'environ 2 heures 30 à 3 heures, incluant la passation des questionnaires, l'installation et l'enlèvement du bonnet ainsi que l'expérimentation.

Avantages : Il n'y a aucun avantage direct à participer à cette étude. Les études ÉEG sont des tests et non des traitements. L'information recueillie à partir des données venant de votre participation et d'autres études pourront éventuellement contribuer à une meilleure compréhension des processus reliés à l'apprentissage du langage.

Risques et inconvénients : Les ÉEG ont été utilisés dans le passé dans de nombreuses études et aucun effet secondaire significatif n'a été rapporté. Comme mesure préventive contre tout risque pour la santé, les bonnets sont toujours nettoyés et désinfectés après chaque session expérimentale. Vous pourriez souffrir d'un mal de tête léger ou ressentir de l'inconfort dû à la pression exercée par le bonnet. La fréquence des maux de tête liée au port du bonnet est très faible (moins de 1% selon les données de notre laboratoire). L'expérimentation avec le bonnet dure 2 heures au total.

Alternatives et participation volontaire : Votre participation est entièrement volontaire. Si vous êtes inconfortable à quelque moment que ce soit ou si vous demandez d'arrêter, les activités seront discontinuées. Vous pouvez vous retirer de l'étude à tout moment et sans motif. L'examinateur vous expliquera, dans un langage que vous comprendrez, le déroulement de la recherche et répondra à toutes vos questions sur le projet.

Compensation pour vos dépenses et inconvénients : À la fin de l'étude, vous recevrez un montant de 50$ pour votre déplacement. Si vous vous retirez avant la fin de l'étude, vous serez compensé proportionnellement à la durée de votre implication.

Confidentialité : Les mesures suivantes seront appliquées pour assurer la confidentialité des renseignements fournis par les participants : les noms ou l'identité des participants ne paraîtront dans aucun rapport; Les divers documents de la recherche seront codés. C'est-à-dire que votre nom sera remplacé par un code et seulement la chercheuse principale aura accès à la liste des noms et des codes. La recherche fera l'objet de publications et de présentations dans des revues scientifiques, mais il ne sera pas possible de vous identifier. Si vous acceptez que les données soient conservées au-delà du présent projet (après sept ans), la liste reliant votre nom au code utilisé sera détruite. Il ne sera alors plus possible de vous identifier. Les dossiers resteront sous la responsabilité de la Dre. Phaedra Royle à l'Université de Montréal et seront conservés pendant toute la carrière de Mme Royle (environ 20 années).

Problèmes ou questions : Si vous avez des questions au sujet de cette étude ou vous désirez vous en retirer, n'hésitez pas à communiquer avec nous : Dre. **Phaedra Royle**, chercheure responsable, 514-343-6111, poste 0925 (phaedra.royle@umontreal.ca).
Pour toute information d'ordre éthique concernant les conditions dans lesquelles se déroule votre participation à ce projet, vous pouvez contacter le conseiller en éthique de la recherche du Comité d'éthique de la recherche en santé (CERES) par courriel : ceres@umontreal.ca ou par téléphone au 514-343-6111 poste 2604.
Pour plus d'information sur vos droits comme participant/e à la recherche, vous pouvez consulter le portail des participants de l'Université de Montréal à l'adresse suivante : http://recherche.umontreal.ca/participants.
Toute plainte concernant cette recherche peut être adressée à l'ombudsman de l'Université de Montréal, au numéro de téléphone 514-343-2100 ou à l'adresse courriel : ombudsman@umontreal.ca. L'ombudsman accepte les appels à frais virés. Il s'exprime en français et en anglais et prend les appels entre 9h et 17h.

Consentement de participation

Titre du projet: Étude de l'acquisition et du traitement du langage dans les troubles primaires du langage

Je comprends que je peux prendre mon temps pour réfléchir avant de donner mon accord ou non à participer à la recherche.
Je peux poser des questions à l'équipe de recherche et exiger des réponses satisfaisantes.
Je comprends qu'en participant à ce projet de recherche, je ne renonce à aucun de mes droits ni ne dégage les chercheurs de leurs responsabilités.
J'ai pris connaissance du présent formulaire d'information et de consentement et j'accepte de participer au projet de recherche.

Prénom et nom du participant (caractères d'imprimerie)	Signature du participant DDate :

Engagement du chercheur
J'ai expliqué les conditions de participation au projet de recherche au participant. J'ai répondu au meilleur de ma connaissance aux questions posées et me suis assuré de la compréhension du participant. Je m'engage, avec l'équipe de recherche, à respecter ce qui a été convenu au présent formulaire d'information et de consentement.

Prénom et nom du chercheur (caractères d'imprimerie)	Signature du chercheur DDate :

Je consens à ce que les données recueillies dans le cadre du présent projet de recherche soient conservées par Mme Phaedra Royle à des fins de recherche, de publications scientifiques et pour l'enseignement, sans qu'il soit possible de m'identifier, conditionnellement à leur approbation par un comité d'éthique de la recherche. Oui ❑ Non ❑

Appendix C

Handedness questionnaire

Test de latéralité – préférence manuelle. Adaptation maison du test de Oldfield (1971)[1]

FICHE PARTICIPANT adulte # ________

Sexe (F/M):

Date de passation :

Indiquez votre préférence, main droite ou main gauche, pour effectuer les activités suivantes. Afin de définir votre préférence, utiliser les signes suivants :
+ : préférence pour l'activité
++ : préférence forte pour l'activité, où vous n'êtes jamais tenté d'utiliser l'autre main pour cette activité
+/+ : préférence indifférente, vous pouvez utiliser une ou l'autre des mains. Mettre un + dans chaque colonne.

Main utilisée :	Gauche	Droite
Écrire		
Dessiner		
Lancer		
Ciseaux		
Brosse à dents		
Couper (sans une fourchette)		
Cuillère		

[1] Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia*, *9*(1), 97-113.

Utiliser un balai (la main supérieure) (Bâton de Hockey)		
Ouvrir une boite		
Avec quel pied préférez-vous kicker un objet?		
Si vous devez regarder avec un œil, lequel préférez-vous ?		

Pour l'examinateur : total : ____

Appendix D

Language background questionnaire

Questionnaire – Utilisation des langues

Veuillez répondre aux questions suivantes sur l'histoire d'acquisition des langues, pour vos parents et vous-même. Le traitement en ligne des mots et des phrases peut être influencé par ce facteur.

1. Prénom et nom :____
2. Langue première de votre mère : _____________ Son âge d'acquisition___________
3. Langue seconde de votre mère : _____________ Son âge d'acquisition___________
4. Langue première de votre père : _____________ Son âge d'acquisition___________
5. Langue seconde de votre père : _____________ Son âge d'acquisition___________
6. Langues connues et comprises, de la mieux maîtrisée à la moins connue :

Indiquez, en pourcentage, votre exposition quotidienne à chacune de ces langues à chacune de ces périodes de votre vie.

Âge		Français	Anglais	Autre : ________	Total
0-5 ans	**École**				100%
	Maison				100%
5-11 ans	**École**				100%
	Maison				100%
12-14 ans	**École**				100%
	Maison				100%
15-16 ans	**École**				100%
	Maison				100%
17-18 ans (CÉGEP)	**École**				100%
	Maison				100%
18 ans et plus	**École**				100%
	Maison				100%

7. Quel âge aviez-vous lorsque vous avez commencé à communiquer à l'aide du français de façon régulière avec des locuteurs natifs du français? ____________________________

8. Quel âge aviez-vous lorsque vous avez commencé à communiquer à l'aide d'une autre langue (laquelle ? __________) de façon régulière avec des locuteurs natifs de cette langue? _________________________________

9. Utilisiez-vous le français avec des membres de votre famille? _______________________

   a) Si oui, avec qui (mère, père, frère, sœur, etc) ? _______________________________

10. Utilisiez-vous une autre langue avec des membres de votre famille? ___________________

   a) Si oui, avec qui (mère, père, frère, sœur, etc) ? _______________________________

Indiquez, en pourcentage, votre exposition quotidienne actuelle à chacune de ces langues dans chacune des situations suivantes :

	Français	**Anglais**	**Autre : ________**	**Total**
Amis				100%
Conjoint(e)				100%
Membres de la famille				100%
École/Travail				100%
Temps libres (sport, hobby, etc)				100%
TV/Radio				100%
Lecture (livres, journaux, Internet)				100%

11. Quelle langue considérez-vous comme votre langue dominante ?

Français ☐ Anglais ☐ Français et anglais de façon égale ☐ Français et autre (________) de façon égale ☐

12. Avez-vous suivi des cours d'anglais avant 18 ans ? Oui ☐ Non ☐

a) Si oui : Quand ? _____________ Pour combien de temps ? _____________ Niveau ? __________

Suivez-vous actuellement de cours d'anglais? Oui ☐ Non ☐ Niveau ? __________