Role of early language experience, vocabulary skills and attention on brain signatures of known and unknown words : an event-related potential (ERP) study in mono- and bilingual toddlers and monolingual 4-year-olds

Oytun Aygün

UNIVERSITÉ DE PARIS

École doctorale 261: Cognition, Comportements, Conduites Humaines

Integrative Neuroscience and Cognition Center (INCC)

Rôle de l'expérience précoce du langage, la compétence vocabulaire, et l'attention sur les signatures cérébrales de mots connus et inconnus: une étude du potentiels évoqués (PE) chez les jeunes enfants

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Oytun Aygün

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Pia Rämä, Cargé de recherche HDR, Université de Paris, directrice de thèse

Bangor, Thierry, professeur, Bangor University, rapporteur

Floccia, Carolina, professeure, Plymouth University

Moutier, Sylvain, Professeur des Universités, Université de Paris , examinateur

Hemforth, Barbara, Chercheur CNRS, Université de Paris, examinatrice

Esseily, Rana, Maitre de conférence, Université Paris-Nanterre, examinatrice

UP_vd_liste_sous_droits

dans l'ANNEXE

Questionnaire de Bilingue Babylab INCC

élément sous droit, diffusion non autorisée

CDI : MacArthur communicative development inventories

élément sous droit, diffusion non autorisée

for my grandmothers

Résumé

Il existe de nombreuses preuves comportementales et neuroscientifiques montrant que les nourrissons se spécialisent dans leur langue maternelle au cours de leur première année de vie. Au cours de leur deuxième année de vie, les nourrissons utilisent les régularités phonotactiques de leur langue maternelle lors de l'apprentissage de mots. Il a été montré que plusieurs réponses cérébrales sont liées à l'augmentation de la connaissance des mots chez les nourrissons monolingues. On en sait moins sur les signatures neuronales du développement du vocabulaire chez les nourrissons bilingues. La présente thèse a étudié le traitement des mots chez des enfants de 24 mois, monolingues et bilingues en utilisant la technique des potentiels évoqués (PE). L'objectif était d'explorer les effets de l'expérience linguistique précoce (quantité relative d'exposition au français versus une autre langue) et des compétences en vocabulaire sur le traitement des mots connus et de mots nouveaux à savoir des pseudomots qui sont phonotactiquement corrects et des non-mots qui sont phonotactiquement incorrects en français.

L'étude I avait deux objectifs, premièrement, étudier les PE lors du traitement de mots connus, de pseudo-mots et de non-mots, et deuxièmement, étudier le rôle des compétences en vocabulaire dans le traitement des mots chez les enfants monolingues en utilisant une tâche d'écoute non référentielle. Les résultats ont montré que le N200 et la négativité tardive étaient sensibles au type de mot. Les deux composantes étaient plus prononcées pour les pseudo-mots que pour les non-mots, mais aucune différence n'a été observée entre les mots connus et les pseudo-mots. Cependant, les amplitudes des composantes étaient modulées par les compétences en vocabulaire : pour le N200, les différences d'amplitude entre les mots connus et les pseudo-mots étaient positivement corrélées avec les compétences de production du vocabulaire. De même, pour la négativité tardive, seuls les enfants ayant une connaissance plus élevée de vocabulaire présentaient un schéma graduel d'activité en réponse à trois types de mots, tandis que les enfants ayant des compétences en vocabulaire inférieures présentaient une réactivité similaire à chaque type de mot. Les résultats suggèrent que les compétences en production de vocabulaire contribuent à l'amplitude des signaux cérébraux en réponse aux mots natifs et non natifs chez les enfants de 24 mois, et que les enfants avec plus de connaissances en vocabulaire sont plus sensibles au sens des mots et à la structure phonotactique de la langue natale.

Des études précédentes sur la perception ont indiqué que les jeunes enfants bilingues restent sensibles aux sons n'appartenant pas à leurs langues natives plus longtemps que les enfants monolingues. De plus, les nourrissons bilingues montrent une flexibilité plus prolongée

dans l'acceptation des sons n'appartenant pas à leurs langues natives comme de nouveaux mots dans les tâches d'apprentissage. L'étude II a cherché à savoir si la quantité relative d'apport linguistique des enfants bilingues apprenant le français et une autre langue (variant entre 15% et 50%) module le traitement des pseudo-mots et des non-mots en utilisant le même plan expérimental que dans l'étude I. Les résultats ont montré que, de la même manière chez les monolingues, les amplitudes du N200 et la négativité tardive sont plus prononcées pour les pseudo-mots que pour les non-mots mais aucune différence n'est observée entre les mots connus et les pseudo-mots. Les modulations ne dépendaient pas du pourcentage d'une autre langue. Les amplitudes étaient cependant modulées par les compétences en compréhension du vocabulaire. Chez les enfants bilingues avec un faible score de vocabulaire, les amplitudes du N200 et de la négativité tardive étaient significativement différentes en réponse aux pseudo-mots et aux non-mots, tandis que le N200 était également plus prononcé pour les pseudo-mots et les non-mots chez les enfants avec un score de compréhension de vocabulaire plus élevé. Les résultats suggèrent que la quantité d'exposition à une deuxième langue lors de l'acquisition de la première langue ne module pas le traitement de mots issus de la langue natale ou pas, du moins dans la langue dominante des enfants bilingues. Cependant, les compétences globales en vocabulaire contribuent aux signaux cérébraux en réponse aux pseudo-mots et aux non-mots.

L'étude III a étudié l'influence de l'attention sur le traitement des mots connus et des pseudo-mots chez les enfants monolingues d'âge préscolaire. Il a été présenté aux participants simultanément ou non des mots (auditifs) et des images (visuelles) lors d'une tâche d'attention intermodale. Lors de deux conditions distinctes, il leurs a été demandé de détecter soit une cible auditive (condition attentive) soit une cible visuelle (condition non attentive). Les PE ont été mesurés tout au long de l'expérience dans les 2 conditions (attentive et non attentive) et les réponses cérébrales au cours de la première et de la seconde moitié de l'expérience aux différents types de mots (mots connus ou pseudo-mots) ont été comparées. Les PE en réponse aux mots connus étaient similaires quelle que soit la condition (attentive ou non attentive), ce qui suggère que le traitement des mots connus ne dépend pas des ressources attentionnelles. Cependant, les PE en réponse aux pseudo-mots ont été modulés par la condition (attentive ou non attentive) et le temps d'exposition : dans la condition attentive, la tâche a entraîné une augmentation des amplitudes des PE pendant la seconde moitié de l'expérience. Les résultats suggèrent que l'attention et la quantité d'exposition affectent les réponses cérébrales aux nouveaux éléments lexicaux (pseudo-mots) chez les jeunes enfants.

Abstract

There is extensive behavioral and neuroscientific evidence showing that infants attenuate to their native language within the first year of life. During the second year of life, infants use the phonotactic regularities of their native language during word learning and become more efficient word learners. Several brain responses have been linked to increasing word knowledge in monolingually raised infants. Less is known about neural correlates of vocabulary development in bilingual infants. The present dissertation investigated the processing of words in monolingual and bilingual 24-month-olds using the event-related potential (ERP) technique. The aim was to explore the effects of early language experience (amount of exposure to French) and vocabulary skills on the processing of known words and novel word-forms, that is, pseudowords that are phonotactically legal, and nonwords that are phonotactically illegal in French.

Study I had two aims, first, to investigate the ERPs during processing of known words, pseudowords and nonwords, and second, to study the role of vocabulary skills in word processing in monolingual toddlers using a non-referential listening task. The results showed that the N200 and the late negativity were sensitive to the word type. Both components were more pronounced for pseudowords than for nonwords, but no difference was observed between known words and pseudowords. However, the amplitudes of the components were modulated by vocabulary skills: for the N200 the amplitude differences between known words and pseudowords were positively correlated with the productive vocabulary skills. Similarly for the late negativity, only those toddlers with higher vocabulary knowledge exhibited a gradient pattern of activity in response to three word types while children with lower vocabulary skills exhibited a similar responsiveness to each word type. The results suggest that productive vocabulary skills contribute to the magnitudes of brain signals in response to native and non-native words in 24-month-old toddlers, and toddlers with more vocabulary knowledge are more sensitive to word meaning and native phonotactic structure.

Previous perceptual studies have indicated that bilingual infants remain sensitive to non-native sounds longer than monolingual infants. Also, bilingual infants show a more prolonged flexibility in accepting non-native sounds as novel labels in word learning tasks. Study II investigated whether the relative amount of language input of bilingual toddlers learning French and another language (varying between 15%-50%) modulates the processing of pseudowords and nonwords using the same experimental design as in Study I. The results

showed that, similarly to monolinguals, the amplitudes of the N200 and the late negativity were more pronounced for pseudowords than for nonwords but no difference was observed between known words and pseudowords. The modulations were not dependent on the amount of another language input. The amplitudes were, however, modulated by comprehensive vocabulary skills. In bilingual toddlers with a low vocabulary score, the amplitudes of the N200 and late negativity were significantly different in response to pseudowords and nonwords while the N200 was equally pronounced for pseudowords and nonwords in toddlers with a high comprehension score. The results suggest that the amount of dual language exposure during first language acquisition does not modulate the processing of native and non-native word forms, at least in the dominant language of bilingual toddlers. However, the comprehensive vocabulary skills contribute to the brain signals in response to pseudowords and nonwords.

Study III investigated the influence of attention on processing of known words and pseudowords in preschool-aged monolingual children. The participants were presented with simultaneous and independent streams of words (auditory) and pictures (visual) in a cross-modal selective attention task. In two separate conditions, they were asked to detect a target in either the auditory (attentive condition) or visual stream (non-attentive condition). The ERPs were measured throughout the experiment in response to attended or unattended words and the brain responses during the first and second half of the experiment to different word types were compared. The ERPs in response to known words were similar regardless of attention condition, suggesting that processing of known words is not dependent on attentional resources. However, the ERPs in response to pseudowords were modulated by attention condition and exposure time: allocation of attention during the task resulted in an increase in the ERP amplitudes during the second half of the experiment. The results suggest that selective attention and the exposure amount affect the brain responses to novel lexical items in young children.

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"All language is but a poor translation"

- Franz Kafka

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General Introduction

Les nourrissons ont des prédispositions à traiter les stimuli vocaux (par exemple, Dehaene-Lambertz et al., 2002 ; Vouloumanos & Werker, 2004, 2007), ce qui les aide à apprendre les langues. Au cours de la première année de vie, un rétrécissement de la perception se produit lorsque les nourrissons deviennent plus sensibles à la phonologie et aux schémas phonotactiques de leur langue maternelle (par exemple, Mattys & Jusczyk, 2001 ; Mattys et al., 1999 ; Jusczyk et al., 1993, 1999 ; pour une revue, voir Werker & Tees, 1992). Entre 6 et 12 mois, la capacité des nourrissons à discriminer les phonèmes natifs s'améliore tandis que la capacité à discriminer les phonèmes non natifs diminue (par exemple, Werker & Tees, 1984 ; pour une revue, voir Werker, 2018). Pendant ce temps, les nourrissons deviennent également plus sensibles aux propriétés phonotactiques de leur langue maternelle, c'est-à-dire les combinaisons de phonèmes autorisées, ainsi que les séquences contraintes (par exemple, Friederici & Wessels, 1993 ; Mattys & Jusczyk, 2001). Il a été démontré qu'une meilleure discrimination de la phonologie native au cours de la première année de vie prédit des compétences de vocabulaire productives plus élevées au cours de la deuxième année de vie, tandis qu'une sensibilité plus élevée pour la discrimination phonétique non native prédit des scores de vocabulaire inférieurs (Kuhl et al., 2005, 2008).

Au cours de la deuxième année de vie, les nourrissons deviennent plus précis et plus rapides à reconnaître les mots (Fernald et al., 1998, 2001, 2006), et vers la fin de la deuxième année de vie, ils affichent un taux élevé de production de vocabulaire (par exemple, Goldfield & Reznick, 1990 ; Nelson, 1973 ; Reznick & Goldfield, 1992 ; pour les revues, voir Ganger & Brent, 2004 ; Nazzi & Bertoncini, 2003). Pendant ce temps, avec l'âge et le développement des compétences en vocabulaire, les nourrissons deviennent plus restrictifs vis-à-vis des sons non natifs dans les tâches d'apprentissage des mots et n'acceptent que les formes de mots qui suivent les régularités de leur langue maternelle comme nouvelles étiquettes (par exemple, Graf Estes et al., 2011 ; Hay et al., 2015 ; May & Werker, 2014). En plus des mesures comportementales, la technique du potentiel lié à l'événement (PE) a fourni des preuves importantes sur l'acquisition du langage. Les PE mesurent l'activité électrique du cerveau dans une gamme de millisecondes, permettant une grande précision temporelle pour étudier le traitement du langage. De plus, des composants PE spécifiques sont informatifs sur différents processus linguistiques et cognitifs (pour une revue, voir, Thierry, 2005). Les études PE ont montré une activité différentielle en réponse à différents types de mots : les mots connus se sont avérés susciter des négativités plus prononcées que les mots inconnus (Mills et al., 1993, 1997 ; Thierry et al., 2003). Fait intéressant, les compétences en vocabulaire ont affecté la distribution des PE, c'est-à-dire que les signaux cérébraux étaient distribués de manière plus focalisée chez les nourrissons ayant des compétences en vocabulaire plus élevées que chez les nourrissons ayant des connaissances en vocabulaire plus faibles. De plus, les propriétés phonotactiques des mots contribuent aux signaux cérébraux : les pseudo-mots, qui sont des mots sans signification suivant les régularités phonotactiques d'une langue, évoquent plus d'PE négatifs que les non-mots, qui sont des mots construits violant les règles phonotactiques d'une langue donnée (Friedrich & Friederici, 2004, 2005 ; Obrig et al., 2017 ; Steber et Rossi, 2020). On en sait moins sur l'influence du développement du vocabulaire sur le traitement des mots avec différentes propriétés phonotactiques chez les jeunes enfants.

Les nourrissons bilingues qui sont exposés à deux langues ont plus de variabilité dans leur environnement linguistique. Malgré l'acquisition de deux langues en même temps, les nourrissons bilingues franchissent leurs étapes linguistiques et produisent leurs premiers mots au même âge que les monolingues (par exemple, De Houwer 1995 ; Oller et al., 1997 ; Pearson & Fernandez 1994 ; Petitto et al., 2001). Chez les nourrissons bilingues, l'exposition relative à chaque langue s'est avérée être le prédicteur le plus prédominant du développement du vocabulaire dans la langue respective (par exemple, Floccia et al., 2018 ; Hoff, 2003 ; 2020 ; Hoff et al., 2014 ; Werker et al. al., 2009). L'exposition au langage bilingue est associée à un traitement plus flexible des sons non natifs : les nourrissons bilingues ont une plus grande sensibilité aux sons non natifs (par exemple, Garcia-Sierra et al., 2011) et ils montrent une flexibilité prolongée pour les sons non natifs. dans l'apprentissage de nouveaux mots (Graf Estes & Hay, 2015; Singh, 2018). Cependant, seules quelques études ERP étudient les signatures cérébrales de la connaissance des mots (Conboy & Mills, 2006 ; Vihman et al., 2007) ou le traitement lexico-sémantique (par exemple, Kuipers & Thierry, 2013, 2015 ; Rämä et al. , 2018 ; Sirri & Rämä, 2019) chez les jeunes enfants bilingues.

Chez les nourrissons, il a été démontré que les mesures de l'attention et les compétences linguistiques sont corrélées (par exemple, Dixon et Shore, 1997 ; Dixon et Smith, 2000 ; Kannass et Oakes, 2008 ; Mundy et al., 2003), ce qui présente l'attention comme une composante importante du langage. acquisition. De plus, des problèmes d'attention sont présents dans des troubles spécifiques du langage (par exemple, Noterdaeme et al., 2001), ce qui montre encore l'importance de l'attention pour l'acquisition de la première langue. Cependant, dans la plupart des expériences de traitement du langage chez les nourrissons, les modulations attentionnelles ne sont pas contrôlées, bien qu'il existe des preuves que le traitement lexico-sémantique est sous des mécanismes de contrôle à la fois automatiques et attentionnels (par exemple, Bastuji et al., 2002 ; Bentin et al., 1995). ; Holcomb et al., 1992 ; Rämä et al., 2006 ; Relander et al., 2009 ; Sirri & Rämä, 2015). Seules quelques études ont étudié les changements développementaux dans les réponses cérébrales chez les jeunes enfants lorsqu'ils prêtaient attention aux stimuli auditifs : les PE en réponse aux stimuli linguistiques et non linguistiques étaient améliorés par l'attribution de l'attention auditive (Coch et al., 2005 ; Karns et al., 2015 ; Sanders et al., 2006).

L'objectif de la présente thèse était d'étudier comment les compétences en vocabulaire complet et productif contribuent à l'ampleur des PE en réponse aux mots phonotactiquement légaux et illégaux chez les tout-petits monolingues et bilingues apprenant le français afin de mieux comprendre les interactions entre la connaissance du vocabulaire et le traitement de texte. Les PE ont été enregistrés dans une tâche d'écoute non référentielle au cours de laquelle les enfants ont été présentés avec des mots connus, des pseudo-mots et des non-mots. Le rôle de l'attention dans le traitement de texte a été exploré à l'aide d'une tâche d'attention sélective intermodale chez des enfants d'âge préscolaire.

Plus précisément, l'objectif de l'étude I (article publié, Aygün & Rämä, 2022) était d'étudier comment des compétences de vocabulaire compréhensives et productives contribuent à l'ampleur des PE en réponse aux mots phonotactiquement légaux et illégaux dans l'apprentissage du français monolingue de 24 mois pour mieux comprendre les interactions entre la connaissance du vocabulaire et le traitement de texte. Sur la base de découvertes antérieures chez des nourrissons apprenant l'anglais et l'allemand (Friedrich & Friederici, 2006; Graf Estes et al., 2011; Mills et al., 1993, 1997), on s'attendait à ce que les tout-petits de 24 mois apprenant le français avec un score de vocabulaire plus élevé présenterait une plus grande différence dans les amplitudes entre les types de mots indiquant une plus grande sensibilité à la naïveté des mots et à la signification également dans une tâche non référentielle. Deuxièmement, nous avons cherché à déterminer si les PE sont modulés de manière différentielle en réponse aux pseudo-mots et aux non-mots au cours de l'expérience. Nous nous attendions à ce que des modulations se produisent en réponse à des pseudo-mots phonotactiquement légaux, mais pas en réponse à des non-mots phonotactiquement illégaux.

L'étude II (article soumis) vise à étudier si l'exposition à la double langue contribue à l'ampleur des ERP en réponse aux pseudo-mots natifs et non natifs. Les nourrissons bilingues, en général, sont exposés à une plus grande quantité de variations phonotactiques et lexicales dans leur entrée linguistique que les nourrissons monolingues. De plus, les nourrissons bilingues s'avèrent plus flexibles dans l'acceptation de sons non natifs comme nouvelles étiquettes pour de nouveaux objets (Graf Estes & Hay, 2015; Singh, 2018; Singh & Tan, 2020) que les nourrissons élevés unilingues, en particulier ceux qui ont un vocabulaire plus élevé. (Graf Estes et al., 2011 ; Hay et al., 2015 ; May & Werker, 2014). Sur la base de ces preuves, nous nous attendions à ce que les ERP en réponse aux pseudo-mots et aux non-mots soient plus similaires chez les bilingues que chez les tout-petits monolingues, en particulier chez les bilingues exposés aux deux langues de manière plus égale. Le paradigme expérimental était le même que dans l'étude I.

L'étude III (article en préparation) a étudié le rôle de l'attention sur le traitement de mots connus et de pseudo-mots au cours d'une tâche d'attention sélective intermodale (audio-visuelle). Les enfants monolingues d'âge préscolaire ont été présentés avec des flux simultanés indépendants de mots (auditifs) et d'images (visuels). Il leur a été demandé de détecter une cible auditive pendant la «condition assistée» et une cible visuelle pendant la condition «non surveillée», car les PE auditifs pour les mots étaient enregistrés. De plus, les PE des première et seconde moitiés de l'expérience ont été comparés pour explorer les effets de la répétition de mots. Nous nous attendions à ce que l'attribution de l'attention améliore une positivité précoce et une négativité ultérieure pour tous les stimuli linguistiques, comme dans les études précédentes avec de jeunes enfants (Coch et al., 2005 ; Karns et al., 2015 ; Sanders et al., 2006). Chez les enfants d'âge scolaire, les pseudo-mots ont suscité des réponses N400 plus élevées que les mots connus (Abel et al., 2018, 2020), suggérant une activation plus élevée des mécanismes de recherche lexicale. Nous nous attendions également à plus de réponses PE négatives pour les pseudo-mots par rapport aux mots connus.

La présente thèse est organisée comme suit : dans le contexte théorique, le chapitre 1 passe en revue les résultats comportementaux et électrophysiologiques sur la perception précoce de la parole, le développement du vocabulaire et le traitement de mots lors de l'acquisition d'une langue monolingue. Le chapitre 2 présente les résultats au cours du développement de la langue première bilingue. Le chapitre 3 présente des techniques et des méthodes expérimentales pour étudier le développement du langage et du vocabulaire. La section des études expérimentales présente les études I, II et II et leurs résultats. Enfin, la section Discussions générales conclut la présente thèse avec une discussion sur les principaux résultats et les perspectives futures

General Discussion

Infants have predispositions to treat speech stimuli differently than non-speech stimuli (e.g., Dehaene-Lambertz et al., 2002; Vouloumanos & Werker, 2004, 2007) which helps them to learn languages. During the first year of life a perceptual narrowing takes place where infants become more sensitive to the phonology and phonotactic patterns of their native language (e.g., Mattys & Jusczyk, 2001; Mattys et al., 1999; Jusczyk et al., 1993, 1999; for a review, see Werker & Tees, 1992). Between 6 and 12 months, infants ability to discriminate native phonemes improves while the capacity to discriminate non-native phonemes declines (e.g., Werker & Tees, 1984; for a review, see Werker, 2018). During this time infants also become more sensitive to the phonotactic properties of their native language, i.e. the phoneme combinations that are allowed, as well as the sequences that are constrained (e.g., Friederici & Wessels, 1993; Mattys & Jusczyk, 2001). Better discrimination of native phonology during the first year of life have been shown to predict higher productive vocabulary skills in the second year of life whereas higher sensitivity for non-native phonetic discrimination predicts lower vocabulary scores (Kuhl et al., 2005, 2008).

During the second year in life infants get more accurate and faster at recognizing words (Fernald et al., 1998, 2001, 2006), and towards the end of the second year of life, they display a high rate of vocabulary production (e.g., Goldfield & Reznick, 1990; Nelson, 1973; Reznick & Goldfield, 1992; for reviews, see Ganger & Brent, 2004; Nazzi & Bertoncini, 2003). Meanwhile, with age and developing vocabulary skills, infants become more restrictive to non-native sounds in word learning tasks, and accept only word-forms that follow the regularities of their native language as novel labels (e.g., Graf Estes et al., 2011; Hay et al., 2015; May & Werker, 2014). In addition to behavioral measures, the event-related potential (ERP) technique has provided important evidence about language acquisition. The ERPs measure the electrical brain activity in a millisecond range, allowing a high temporal accuracy to study language processing. Moreover, specific ERP components are informative about different linguistic and cognitive processes (for a review, see, Thierry, 2005). The ERP studies have shown a differential activity in response to different word types: known words were shown to elicit more pronounced negativities than unknown words (Mills et al., 1993, 1997; Thierry et al., 2003). Interestingly, vocabulary skills affected the distribution of the ERPs, that is, the brain signals were more focally distributed in infants with higher vocabulary skills than in infants with lower vocabulary knowledge. Also, phonotactic properties of words contribute to the brain signals: pseudowords, that are meaningless words following the phonotactic regularities of a language, evoke more negative ERPs than nonwords, that are constructed words violating the phonotactic rules of a given language (Friedrich & Friederici, 2004, 2005; Obrig et al., 2017; Steber & Rossi, 2020). Less is known about the influence of vocabulary development on processing of words with different phonotactic properties in young children.

Bilingual infants who are exposed to two languages have more variability in their linguistic environment. Despite acquiring two languages at the same time, bilingual infants go through their linguistic milestones and produce their first words in the same age as monolinguals (e.g., De Houwer 1995; Oller et al., 1997; Pearson & Fernández 1994; Petitto et al., 2001). In bilingual infants, the relative exposure to each language has shown to be the most predominant predictor of vocabulary development in the respective language (e.g., Floccia et al., 2018; Hoff, 2003; 2020; Hoff et al., 2014; Werker et al., 2009). Bilingual language exposure is associated with a more flexible processing of non-native sounds: bilingual infants have a greater sensitivity to non-native sounds (e.g., Garcia-Sierra et al., 2011) and they show a prolonged flexibility for non-native sounds in novel word learning (Graf Estes & Hay, 2015; Singh, 2018). However, there are only a few ERP studies investigating the brain signatures of word knowledge (Conboy & Mills, 2006; Vihman et al., 2007) or lexical-semantic processing (e.g., Kuipers & Thierry, 2013, 2015; Rämä et al., 2018; Sirri & Rämä, 2019) in bilingual young children.

In infants, attentional measures and language skills have been shown to correlate (e.g., Dixon & Shore, 1997; Dixon & Smith, 2000; Kannass & Oakes, 2008; Mundy et al., 2003), presenting attention as an important component of language acquisition. Moreover, attentional problems are present in specific language disorders (e.g., Noterdaeme et al., 2001), further showing the importance of attention for first language acquisition. However, in most language processing experiments in infants, attentional modulations are not controlled, although there is evidence for lexical-semantic processing to be under both automatic and attentional control mechanisms (e.g., Bastuji et al., 2002; Bentin et al., 1995; Holcomb et al., 1992; Rämä et al., 2006; Relander et al., 2009; Sirri & Rämä, 2015). Only a few studies investigated the developmental changes in the brain responses in young children when they paid attention to auditory stimuli: the ERPs in response to both linguistic and non-linguistic stimuli were enhanced with auditory attention allocation (Coch et al., 2005; Karns et al., 2015; Sanders et al., 2006).

The aim of the present dissertation was to investigate how comprehensive and productive vocabulary skills contribute to the magnitudes of the ERPs in response to phonotactically legal and illegal words in French-learning monolingual and bilingual toddlers to further understand interactions between vocabulary knowledge and word processing. The ERPs were recorded in a non-referential listening task during which children were presented with known words, pseudowords and nonwords. The role of attention in word processing was explored using a cross modal selective attention task in preschool aged children.

More specifically, the aim of Study I (**published article, Aygün & Rämä, 2022**) was to investigate how comprehensive and productive vocabulary skills contribute to the magnitudes of the ERPs in response to phonotactically legal and illegal words in French-learning monolingual 24-month-olds to further understand interactions between vocabulary knowledge and word processing. Based on earlier findings in English- and German-learning infants (Friedrich & Friederici, 2006; Graf Estes et al., 2011; Mills et al., 1993, 1997), it was expected that 24 month old French-learning toddlers with a higher vocabulary score would exhibit a larger difference in the amplitudes between the word types indicating a greater sensitivity to word nativeness and meaning also in a non-referential task. Second, we aimed to investigate whether the ERPs are differentially modulated in response to pseudowords and nonwords during the course of the experiment. We expected modulations to occur in response to phonotactically legal pseudowords but not in response to phonotactically illegal nonwords.

Study II (**submitted article**) aimed to study whether dual language exposure contributes to the magnitudes of ERPs in response to native and non-native pseudowords. Bilingual infants, in general, are exposed to a greater amount of phonotactic and lexical variation in their linguistic input than monolingual infants. Moreover, bilingual infants are shown to be more flexible in accepting non-native sounds as novel labels for novel objects (Graf Estes & Hay, 2015; Singh, 2018; Singh & Tan, 2020) than monolingually raised infants, specially those with higher vocabulary skills (Graf Estes et al., 2011; Hay et al., 2015; May & Werker, 2014). Based on this evidence, we expected that the ERPs in response to pseudowords and nonwords are more similar in bilinguals than in monolingual toddlers, especially in those bilinguals exposed to both languages more equally. The experimental paradigm was the same as in Study I.

Study III (**article in preparation**) investigated the role of attention on the processing of known words and pseudowords over the course of a cross-modal (audio-visual) selective attention task. Monolingual preschool children were presented with independent simultaneous streams of words (auditory) and pictures (visual). They were asked to detect an auditory target during the “attended condition”, and a visual target during “non-attended” condition as auditory ERPs for words were recorded. Additionally, the ERPs in the first and second halves of the experiment were compared to explore the effects of word repetition. We expected that attention allocation would enhance an early positivity and a later negativity for all linguistic stimuli, similar to previous studies with young children (Coch et al., 2005; Karns et al., 2015; Sanders et al., 2006). In school-aged children, pseudowords elicited higher N400 responses than known words (Abel et al., 2018, 2020), suggesting a higher activation of lexical search mechanisms. We also expected more negative ERP responses for pseudowords compared to known words.

The present dissertation is organized as follows: in the Theoretical Background, Chapter 1 reviews behavioral and electrophysiological findings on early speech perception, vocabulary development and word processing during monolingual language acquisition. Chapter 2 introduces the findings during bilingual first language development. Chapter 3 introduces experimental techniques and methods to study language and vocabulary development. Experimental Studies section presents Study I, II and II and their findings. Finally, General Discussions section concludes the present dissertation with discussion about the main findings and future perspectives.

Theoretical Background

Chapter 1: Word processing during monolingual language acquisition

1.1. Early speech perception

Already in the first months of life, infants prefer to listen to speech stimuli compared to similar non-speech analogues (e.g., Vouloumanos & Werker, 2004). Speech signals activate left-lateralized brain regions (e.g., Dehaene-Lambertz et al., 2002; Shultz et al., 2014) similar to adults (e.g., Dehaene-Lambertz et al., 2008), suggesting a neurobiological specialization to treat linguistic stimuli in human infants. Newborns prefer to listen to the language that their mothers spoke during pregnancy, suggesting familiarity with the native language rhythmicity even before birth (Byers-Heinlein et al., 2010). Moreover, newborns can discriminate two languages from different rhythmic classes (e.g., Byers-Heinlein et al., 2010; Nazzi et al., 1998; Ramus, 2002) and by 4-5 month-olds, infants can distinguish languages from the same rhythmic class if one is similar to their native language (e.g., Bosch & Sebastián-Gallés, 1997; Nazzi & Ramus, 2003).

Experience with the native language tunes the linguistic networks to the regularities of the surrounding native language and infants become selectively more sensitive to the phonological and phonotactic patterns of their native language within the first year of life (for a review, see Werker, 2018). Through a mechanism of perceptual narrowing the ability to discriminate native phonemes improves while the capacity to discriminate non-native phonemes declines (e.g., Kuhl, et al., 1992; Werker & Tees, 1984). In a discrimination task for phonemes, 6- to 8-month-old infants were able to discriminate both native and non-native phonemes, while at 12-month-olds of age, infants could only discriminate the sounds that are in their native language (Werker & Tees, 1984). Higher sensitivity towards the native sounds during the first year of life is adaptive for language acquisition: better discrimination of native phonetics at 7.5 months predicted higher productive vocabulary skills at 18- and 24-months, while higher sensitivity to discriminate non-native phonetics, predicted lower vocabulary (Kuhl et al., 2005, 2008). The phonotactic development, i.e. the knowledge of which phoneme combinations are allowed in a language, occurs at similar ages. At 9 months, infants can distinguish between words with high and low phonotactic probabilities (Jusczyk et al., 1994). At the same age, they prefer to listen and are able to discriminate legal phoneme combinations that occur in their native language from those that do not belong to the native set of phonotactic rules (illegal phoneme combinations) (Jusczyk et al., 1993).

Phonetic and phonotactic regularities of a language serve as cues for determining word boundaries (e.g., Jusczyk et al., 1999; Mattys et al., 1999; Mattys & Jusczyk, 2001), and serves as a "bootstrap" for word segmentation (see for reviews, Jusczyk, 2002; Nazzi & Ramus, 2003). For example, the probability of phoneme clusters occurring within or in between words is used as an information during segmentation (Mattys et al., 1999). At 8-months, infants can track the likelihood of syllables occurring next to each other (Saffran et al., 1996). Monolingual infants are able to segment words from continuous speech between 6 to 10 months with some variance depending on the native language, coarticulation or acoustic variation of the stimuli (Bosch et al., 2013; Gout et al., 2001; Nishibayashi et al., 2015; Jusczyk et al., 1999; Jusczyk & Aslin, 1995), while bisyllabic words are segmented between 8 to 12 months (Gonzalez-Gomez & Nazzi, 2013; Goyet et al., 2010; Mersad & Nazzi, 2012; Nazzi et al. 2006). In sum, the phonetic and phonotactic knowledge of the native language gained during the first year of life serve infants as cues to acquire the regularities of their native language. These cues help infants to detect 'typical' word-forms and the ability to recognize and extract words from continuous speech that is an essential skill in early language acquisition (Aslin et al., 1996; Brent & Siskind, 2001). Meanwhile the capacity to match some frequent words to objects arises also during the first year of life (e.g., Bergelson & Swingley, 2012; Tincoff & Jusczyk, 2012). During the second year of life, as the productive vocabulary develops, infants reach a linguistic milestone that opens the door to a more complex ability to communicate. The next chapter will present how vocabulary development advances during monolingual first language acquisition and which are some of the factors linked to individual variance in vocabulary development.

1.2. Vocabulary development

Infants develop basic word comprehension abilities already during the first year of their life as they tune into their native language (e.g., Hallé & de Boysson-Bardies, 1994; Jusczyk, 1997; Tincoff & Jusczyk, 1999). At 6-months, infants are able to understand a few associations of some basic words and their relative referents such as some body parts or food (Bergelson & Swingley, 2012; Tincoff & Jusczyk, 2012). Although 8- to 14-month-old infants can discriminate between minimal pairs (*bih and dih*), differing only in a single phonetic feature, they are not yet able to map them onto two different objects (Stager & Werker, 1997). Older infants, 17- to 20-months of age, were able to map phonetically similar labels to two different objects (Werker et al., 2002). The authors suggested that the advancing ability to map phonologically similar labels on different objects is due to higher attentional resources available during word learning, and reflects a passage from a "novice" to a "more expert" word-learner during the second half of the second year in life.

The speed of word recognition also increases consistently throughout the second year of life: 18-month-olds were faster than 15-month-olds, and 24-month-olds were faster than the former (Fernand et al., 1998). By 24-months, infants can recognize a word even before hearing it completely, indicating a remarkable efficiency in word processing speed. Additionally, a positive correlation between infants' speed of word recognition and their current or future vocabulary size has been found repeatedly (Fernald et al., 2006; Hurtado et al., 2007; Marchman & Fernald, 2008), demonstrating that word comprehension efficiency and vocabulary development are related during language acquisition.

Word production, which starts around the first birthday of infants, also advances rapidly in the second half of the second year of life. The growth curve for produced words steepens especially after the first 50–100 words learnt, and by 24 months, children produce on average two to three hundred words (e.g., Fenson et al., 1994; see also Braginsky et al., 2016), reaching up to learning 10 words a day (e.g., Bates et al., 1995; Dromi, 1987). This period, characterized by a high rate of word learning, is known as the "vocabulary spurt" (e.g., Goldfield & Reznick, 1990; Gopnik & Meltzoff, 1987; Nelson, 1973; Reznick & Goldfield, 1992; for reviews, see Ganger & Brent, 2004; Nazzi & Bertoncini, 2003).

Combination of behavioral and neurophysiological evidence suggests that the vocabulary spurt reflects various qualitative changes regarding the way that new words are acquired and organized in the lexicon (e.g., Goldfield & Reznick, 1996; Mills et al., 1993, 1997; for a review, see Nazzi & Bertoncini, 2003). Nazzi and Bertoncini (2003) suggested that after the first dozen words learnt, infants gain the ability to link an object category to a specified sound pattern, indicating a shift from basic association of two simultaneous events to referential word learning. This allows infants to use language as a way of representing the world and introduces a more efficient way of pairing sound pattern-category, which, in turn, increases the rate of word learning.

1.3. Behavioral insights: constraints on word learning

The period of rapid vocabulary development in the second year of life also coincides with the emergence of some constraints on word learning as infants become more familiar with the typical word-forms present in their native language. Experiments using behavioral techniques, such as Switch task and Looking-while-listening task, have demonstrated that phonotactic properties of the native language constraints infants for accepting novel labels for novel objects.

During the Switch task, infants are presented, one by one, with two novel object-word pairs. The object is displayed over a monitor as its label is simultaneously presented by speakers until the infant is habituated. The test phase, following the habituation, contains two different trial types: the "same" trials, during which the paired word-object is presented, or the "switch" trials which contain the unpaired word-object duo. If the infant learnt the initial word-object associations, then during the switch trials an unexpected event violating the infant's expectation happens, resulting in longer looking times in switch trials compared to same trials. With increasing age and vocabulary skills, infants become more resistant to accept non-native sounds as novel labels (e.g., Hay et al., 2015; MacKenzie et al., 2012; May & Werker, 2014). A progressive attunement to native word-forms with age was found even when referential cues were used to indicate that the non-native sound is intended to be a label (May & Werker, 2014). In this study, during the habituation phase, infants were presented with familiar object-label pairs (e.g., dog) before the presentation of novel object-label duos. When words with non-native click sounds (found in Khoisan) were used, 14-month-old English-learning monolinguals accepted them as object labels with referential cues. The group of 20-month-olds with low vocabulary skills behaved similarly to the younger infants, while the group of 20-month-olds with higher vocabulary skills did not accept the non-native word-forms even in the presence of referential cues, which are suggested to facilitate word learning. The results demonstrated that older infants with larger vocabulary size are more resistant to accept word-forms containing non-native sounds. A meta-analysis further confirmed that older infants were less likely to learn atypical words, such as words containing non-native phonemes, compared to younger infants, while they performed better with more typical words, such as native words pronounced with an accent (Tsui et al., 2019).

Looking-while-listening (LWL) paradigm, another looking-time measure, also demonstrated the increasing resistance to learn non-native words with increasing age and vocabulary skills in infants (Graf-Estes et al., 2011). During the LWL paradigm, an infant's ability to link linguistic stimuli to referents is measured by monitoring looking times and saccade patterns by the help of a camera. The infant is seated in front of two screens (or a large screen divided in two) that display two visual stimuli. At the same time a linguistic stimulus is presented that matches only one of the stimuli. Accuracy of word recognition is reflected by the percentage of looking time to the correct referent (the target) with respect to the distractor upon hearing the label. In the study by Graf-Estes and colleagues (2011), infants were habituated to known and novel object-label pairs during a training session. During the test phase that followed, when presented with the same objects, 18-month-olds looked at the correct object upon hearing the legal, but not illegal, label. The result indicated that they were less permissive to labels with illegal word-initial consonant clusters than those with legal phonotactic structure. Moreover, 18-month-olds with higher comprehensive vocabulary had a greater difference between accepting legal versus illegal labels than those with smaller vocabulary, suggesting that infants with higher vocabulary had accumulated more knowledge about the typical words in their native language.

Similarly, in a multiple choice manual task, where infants were first presented with novel sound-object pairs, and were subsequently asked to choose the labeled object among distractor objects (i.e., take the object from a tray), a group of 13-month-olds accepted synthetic non-speech sounds as novel labels, and chose the correct object during the test phase, whereas 20-month-olds did not learn a new sound-object correspondence (Woodward & Hoyne, 1999). In another study, 20 month old French-learning infants were able to learn English words that were phonotactically legal in French (Bijeljac-Babic et al., 2009), suggesting that at this age, infants accept words as novel labels from a foreign language as long as they followed the phonotactic rules of their native language.

In conclusion, behavioral studies show that phonotactic constraints limit acceptable novel word candidates in word learning tasks as infants become more experienced in their native language. During the second year of life, infants become less likely to learn object labels that contain non-native phonotactic patterns. In the next section, to complement behavioral findings, literature concerning electrophysiological findings regarding word recognition and word learning is reviewed.

1.4. Electrophysiological insights: neural correlates of word processing

The event-related potential (ERP) technique is particularly apt for studying language processing in infants. The ERPs can unfold the neural correlates of language processing with a high temporal precision. Moreover, different ERP components, with specific timing and distribution, have been associated with different stages of word processing (e.g., acoustic, phonological, lexical, semantic), allowing the investigation of specific elements of language processing. Previously in some infants studies, the effects of experimental condition or participant group were found using ERPs, while behavioral methods failed to detect them (e.g., De Haan & Nelson, 1997; Vihman et al., 2007), suggesting that the ERPs are a more sensitive method for detecting certain abilities in infants. In this section relevant infant ERP studies on word recognition and word learning will be presented in order to highlight the brain signatures of known and unknown word processing in infancy.

1.4.1. Spoken word recognition

There are a few studies measuring the ERPs in response to newly learned words following a short familiarization. In these studies, infants were familiarized with low-frequency or unknown words, repeated about 10 times either in isolation or in a sentence, before the test phase during which infants were presented with the newly familiarized words along with non-familiarized words (e.g., Goyet et al., 2010; Kooijman, 2007; Kooijman et al., 2005, 2009; Männel & Friederici, 2013; Von Holzen et al., 2018). The results showed that the amplitudes of a negativity between 200 ms to 500 ms after word onset increased in response to newly familiarized words in 10- to 12-month-olds, linking this negativity to increasing word familiarity in infants around the age of one year.

There are also a few studies in infants investigating the ERPs in response to known and unknown words, presented in a non-referential context (Mills et al., 1993, 1997; Thierry et al., 2003). In the studies of Mills and colleagues (1993, 1997), 13 to 20 months old infants were presented with isolated known and unknown words. Known words were chosen from a list of commonly used words (e.g., ball, dog) and parents were confident that their child knew these words. The unknown words were chosen from a list of low frequency words (e.g., tone, staff), and the parents were confident their child did not know them. The results showed that the amplitudes of the N200 and the N375 components were larger for known than for unknown words in infants during the second year of life. However, the distribution of components varied according to the age: in 13- to 17-month-olds, the N200 and the N350 components were bilaterally distributed over the scalp whereas in 20-month-olds, the components were lateralized over the left temporal and parietal recording sites. Moreover, 20-month-olds with higher productive vocabulary skills showed a more focal distribution of brain signals over the left-hemisphere compared to the 20-month-olds with lower productive vocabulary skills. These findings are in accordance with earlier behavioral evidence (e.g., Fernald et al., 1998, 2006), and further showing that brain signatures are modulated by age and developing vocabulary skills during the second year of life. During the first part of the second year of life, cortical activation is more distributed while with age and increased linguistic abilities, language processing networks show a more focal activation and a left-hemispheric specialization.

In the same study, the participants were also presented with backward words, violating phonetic, prosodic and phonotactic regularities of the native language. In 13- to 17-month-old infants, no difference in the amplitudes of the N200 or N350 responses were found between backward and unknown words (Mills et al., 1997). In 20-month-olds, on the other hand, the N200 and N350 components were attenuated for backwards words in comparison to unknown words (Mills et al., 1993), suggesting a higher sensitivity to native speech stimuli in older infants. In another experiment, 18 month old German-learning infants were presented with pseudowords with legal phonotactic structure, and nonwords with phonotactically illegal word-onset consonant clusters (from Slovak) (Steber & Rossi, 2020). The amplitude of a slow negativity, expanding from 500 to 1000 ms after stimulus onset, was larger for pseudowords compared to nonwords over the frontal and centro-parietal areas. The authors suggested that the pseudowords activated the lexical access networks as they could be potential word candidates in their native language, whereas nonwords did not launch the same pathways. Similar findings have been obtained earlier in adults during a passive listening experiment (Rossi et al., 2013), suggesting that similar activation for pseudowords is observed both in the mature brain and at early ages.

1.4.2. Word recognition in priming studies

Word recognition in infants has been investigated also in lexical-semantic priming contexts. In studies with auditory semantic priming tasks young participants are typically presented with pairs of spoken words that are either semantically related (e.g., train-bike) or unrelated (chicken-bike) (Rämä et al., 2013; Sirri & Rämä, 2015; Torkildsen et al., 2007). In studies with picture-word matching task, word-object pairs that are either congruent (e.g., word dog with picture of a dog) or incongruent (e.g., word dog with picture of a car) with each other are presented instead (Friedrich & Friederici, 2004, 2005, 2006, 2010; Torkildsen, 2006). These studies have shown that semantic incongruences evoke a larger negativity, the N400-like response, than semantic congruences in young children. Earlier studies in adults and in older children have suggested that the N400 priming effect reflects the facilitation of lexical access or semantic integration of the target stimulus following the prime (Bentin et al., 1985; Coch et al., 2002; Friederici & Hahne, 2001; Hahne et al., 2004; Holcomb et al., 1992; Kutas & Hillyard, 1980; for a review see Kutas & Federmeier, 2011). Lexical-semantic priming studies in infants have demonstrated the N400-like effect occurs already at the age of 12 months, suggesting that the mechanisms underlying the N400 component mature early.

However, infant N400 differs from that of adults: contrary to the centro-parietal distribution typically found in adults and in older children, in infant studies the distribution and the latency of the N400 response shows an extensive variability (for a review see, Junge et al., 2021). In some studies, the infant N400 response was found over the frontal recording sites (e.g., Friedrich & Friederici, 2004; Torkildsen et al., 2007), while in others it was found over broadly distributed scalp positions or over the posterior recording sites (e.g., Rämä et al., 2013; Sirri & Rämä, 2015; Friedrich & Friederici, 2011). The effect was also shown to be more extended in the left hemisphere in infants compared to the right hemisphere in adults (Friedrich & Friederici, 2004, 2005; Torkildsen et al., 2007). Some studies have found the N400-like response in toddlers (e.g., Rämä et al., 2013; Torkildsen et al., 2006) over the same time window as in adults and in older children (e.g., Bentin et al., 1985; Coch et al., 2002; Friederici & Hahne, 2001; Hahne et al., 2004; Kutas & Hillyard, 1980), while other studies reported a later effect (e.g., Friedrich, & Friederici, 2004; Torkildsen et al., 2007). There is also additional evidence suggesting that the infant N400 is likely to be delayed compared to adults, for example, the peak N400 latency seems to decrease during childhood, until adolescence (Holcomb et al., 1992). In infants, a relationship between age, vocabulary skills and the occurrence of the N400 response has been reported. During a picture-word congruence task, the N400 priming effect was observed in 19- and 20-month-olds, whereas it was present only in 12-month-olds with high vocabulary skills (Friedrich & Friederici, 2004, 2010; Torkildsen et al., 2006). Moreover, 19-month-olds with low comprehension skills showed a smaller incongruity effect than those with high comprehension, suggesting that the vocabulary knowledge correlates with brain activity that is linked to lexical-semantic processing (Freidrich & Friederici, 2004). When spoken word pairs were presented with 18 and 24 month old infants, and only those 18-month-olds with a high productive vocabulary showed the N400-like priming effect, similar to 24-month-old infants (Rämä et al., 2013).

To our knowledge, there is only one study investigating nonword processing in a picture-word context. Friedrich and Friederici (2005) presented 12- and 19-month-olds (and adults) with pictures of known objects simultaneously with congruous and incongruous words, as well as phonotactically legal pseudowords or nonwords (containing a phonotactically illegal consonant cluster in word onset position). In 19-month-olds, like in adults, pseudowords evoked an N400 response, similar to incongruous real words, while nonwords showed an attenuated response. The results indicate that at this age pseudowords activate semantic integration mechanisms whereas nonwords do not, reflecting that only phonotactically legal word forms are considered as potential word candidates. 12-month-olds on the other hand did not show a similar difference in amplitudes between pseudowords and nonwords. However, they displayed a phonotactic familiarity effect over the frontal scalp positions at an earlier time window, indicating differential processing of phonotactically legal and illegal word forms also at this age. The results complement the behavioral findings that older infants are more restrictive for accepting atypical word-forms as labels than younger infants (e.g., May & Werker, 2014; Tsui et al., 2019), although infants during the first year of life can already discriminate legal and illegal phoneme combinations (Jusczyk, Frederici et al., 1993). Vocabulary skills also affected the brain responses to non-native word forms. 19-month-olds were retrospectively grouped according to their language skills at 30-months, and divided in two groups: those with age-adequate vocabulary size and those with vocabulary skills below the age norms, at risk of developing later language problems (Friedrich & Friederici, 2006). 19-month-olds in the risk group did not demonstrate a differential processing of legal pseudowords and illegal nonwords, which was the case for their counterparts with typically developing lexicons. The results are parallel to behavioral findings demonstrating the narrowing of accepted potential object labels with higher vocabulary skills (e.g., Graf-Estes et al., 2011; May & Werker, 2014; Tsui et al. 2019), but also indicate a potential link between brain responses to word forms that violate phonotactic rules of native language and later language outcomes of infants.

1.4.3. Word learning tasks

There are also a few infant studies investigating the modulations of ERPs in response to novel word learning (Mills et al., 2005; Torkildsen et al., 2008). In these studies, the participants were first trained with novel word-object associations (e.g.; pseudoword paired with a picture of a pseudo-object). Meanwhile half of the novel words were not paired (e.g., either presented in isolation or presented with random order of novel objects). Infants were then tested with congruent or incongruent word-object pairs (e.g., a paired pseudoword from the training session is presented either with the pseudo-object it was paired with or another one). In a study conducted with 20-month-olds, the amplitude of the N200-500 for words that were paired with objects showed an increase in negativity while it was reduced for the non-paired words during the test phase, suggesting that associating meaning to words increases brain responses between 200 to 500 ms (Mills et al., 2005). The distribution of the N200-500 was bilateral for all infants, and not dependent on the vocabulary skills. The lack of a greater left hemispheric activation previously observed in infants with high vocabulary skills (c.f. Mills, 1997) was suggested to be due to the differences in the relative familiarity of the infants with the stimuli. Nonetheless, the difference between the amplitudes of the paired *versus* unpaired words showed a tendency to be greater in the left-hemisphere in the high vocabulary group, partially supporting that infants with higher vocabulary skills show a more focal processing of known words. In a similar experience, Torkildsen and colleagues (2008) presented 20-month-old infants for a few rounds with known words paired with pictures corresponding to them as well as pseudowords paired with pictures of pseudo-objects. During the test phase that just followed, the infants were presented with incongruent pairs of word-object pictures (separately for known and pseudo word-object pairs). The 20-month-olds with high productive vocabulary skills had an N400 effect for the incongruent pseudoword-picture pairs, indicating that they learnt the correct associations, whereas the same aged infants with low productive vocabulary did not show the effect. For incongruent real word-object pairs, although both high and low producers showed the N400 effect, the high producer group had showed the effect at an earlier latency than low producers (c.f., Torkildsen et al., 2006; Friedrich & Friederici, 2004). The results are complementing the previous behavioral studies showing that infants with high productive vocabularies during the second year of life are faster in word recognition than those with low vocabularies (Fernald et al, 2001, 2006; Zangl et al., 2001).

A few studies in younger infants have investigated the stability of brain signatures over time following novel word-object associations, as well as the flexibility of ERPs while learning non-native word-forms. In 14-months, a parietal N400 effect was observed when the words were presented with incongruous objects during a test session carried one day later, suggesting the brain signatures were consolidated upon referential links learnt the day before (Freidrich & Friederici, 2008). Even 6-month-olds showed rapid changes in the brain signals when presented with novel word-object associations: an increase in a negativity between 600 and 900 ms, occurring later than older infants (Freidrich & Friederici, 2011). However, when tested one day later with incongruent pairs, no N400 effect was observed in 6-month-olds, suggesting that these word-object associations were not consolidated at this age (Freidrich & Friederici, 2011). Only one study, carried with 6-months-olds, investigated the ERPs for nonwords during word learning. Infants were presented with phonotactically illegal nonwords or phonotactically legal pseudowords before and after a training session during which half of the novel words in each category were paired with pseudo-objects (Obrig et al., 2016). The results showed more negative ERPs from 250 to 450 ms for paired words, regardless of phonotactic status, over the fronto-central recording sites, suggesting a high plasticity at this age for nonwords during associative word learning. However, phonotactic status of the novel words had an overall effect on ERPs: legal pseudowords elicited more positive ERPs than illegal nonwords.

Chapter 2: Bilingual language acquisition

The linguistic diversity of the human population is remarkable with more than 7000 languages (Ethnologue., 2021) that exist in around 200 countries. Multiple languages are spoken in the borders of almost each country, and there are even a few countries that have multiple official languages. The term bilingualism refers to a subsection of plurilingualism that is the knowledge and use of two languages (see, Bhatia & Ritchie, 2008), including sign or spoken languages.

Although bilingualism seems to have a straightforward definition, studying bilinguals brings a difficulty of categorization about who is a bilingual. How much exposure (as well as what kind of exposure, and at what age) is necessary and enough to be bilingual is an essential but difficult question to answer in the field of bilingual language acquisition (for a review, see Bialystok, 2001). Adults are often classified according to the ability to use two languages in daily lives and their proficiency in them (see Grosjean, 1989). Bilinguals that are equally proficient in both languages are called “balanced bilinguals” and those who are more proficient in one of the two languages are named “unbalanced bilinguals” (e.g., Peal and Lambert, 1962). However, for infants that are at the period of language acquisition, the term bilingual depends on language exposure rather than language proficiency (e.g., Byers-Heinlein, 2015; De Houwer, 1990).

Infants usually are not exposed evenly to both of the languages in their linguistic environments, and the language that the infant is more exposed to is called the “dominant” language. Dominance is a relative measure, and it is a result of language skills or language exposure in one language being compared to that in the other language (Birdsong, 2014).

Therefore it is a continuous concept, a gradient comparison of exposure ratios to the relevant languages. Thus, bilingualism is also suggested to be a continuum with different degrees of relative proficiency or exposure, and not a categorical definition (Beardsmore, 1986; Birdsong, 2014; Byers-Heinlein, 2015).

Children who are exposed to two languages from birth or at least before the age of 3 are called simultaneous bilinguals (e.g, De Houwer, 2005). Simultaneous bilingualism also reflects the process of bilingual first language acquisition, indicating the acquisition of two first languages at the same time. Sequential bilingualism on the other hand refers to the situation when the second language is introduced usually after age 3, that is, after the first language is already established. Simultaneous bilinguals succeed to acquire two linguistic systems at the same time as monolinguals do one language even if children who are exposed to two languages get less input in each of their languages compared to monolingual counterparts (e.g., Paradis & Genesee, 1996; Petitto et al., 2001; Unsworth, 2013).

2.1. Early speech perception

Bilingual infants are exposed to two sets of phonemes, phonetic contrasts and phonotactic rules with different levels of overlapping depending on the language pairs they are learning. Some notions of bilingualism might even start before birth: newborns whose mothers spoke Tagalog and English during pregnancy showed an equal preference between Tagalog and English while newborns whose mother spoke only English prefered listening to English over Tagalog (Byers-Heinlein et al., 2010). Moreover, newborns who had heard both languages were able to discriminate between them already at birth, indicating an early differentiation of the native languages that are rhythmically different. Bilinguals with two rhythmically similar languages such as Catalan and Spanish, in turn, were found to be able to differentiate them from each other at 4 months (Bosch & Sebastian-Galles, 2001), suggesting that the closeness of the languages affect their discrimination by bilingual infants.

Bilingual infants are exposed to a richer variety of phonetic and phonotactic structures as they hear two languages. Similar to monolingual infants, linguistic experience during the first year of life tunes bilingual infants to the phonetic characteristics of their native languages. Although bilingual infants exhibit a prolonged perceptual narrowing process for non-native sounds (e.g., Garcia-Sierra et al., 2011; Ferjan Ramırez et al., 2016; Petitto et al., 2012; see also Kuhl et al., 2008), by the end of the first year of life, bilingual infants are able to discriminate phoneme contrasts in each of their native languages (e.g., Bosch & Sebastian-Galles, 2003; Burns et al., 2007; for a review, see Werker, 2018). Catalan-Spanish learning bilingual infants, and monolingual Catalan or Spanish learning infants were tested with a Catalan contrast (/e/ vs. /E/) that does not exist in Spanish (Bosch & Sebastian-Galles, 2003). Both mono and bilingual infants were able to distinguish the Catalan contrasts at 4-months, and both failed to do so by 8 months. However, bilingual infants regained this ability by 12-months, indicating a specific pattern of attunement in bilingual infants, at least for some contrasts. Phonotactic development in bilingual infants show a similar timing compared to monolinguals, and by 9 months both language groups develop a preference for the phonotactically legal sequences in their native language(s) (Friederici & Wessels, 1993; Jusczyk et al. 1993, 1994; Sebastián-Gallés & Bosch, 2002). However, in bilingual infants, the acquisition of phonotactic rules were shown to be modulated by experience with each language. A comparative study with mono- and bilingual (Catalan-Spanish) 9-month-olds found that Catalan-dominant bilinguals were as sensitive as Catalan monolinguals to the phonotactic rules of Catalan (Sebastián-Gallés & Bosch, 2002). Spanish-dominant bilinguals showed an intermediary sensitivity to the phonotactic regularities of Catalan whereas Spanish monolinguals showed the least, suggesting that relative language dominance affects bilingual infants' sensitivity to phonotactic properties of each language.

Infants use the phonetic and phonotactic regularities as cues for determining word boundaries (e.g., Mattys et al., 1999; Mattys & Jusczyk, 2001; Jusczyk et al., 1999). Bilinguals can use different strategies to segment words in their different languages depending on the language pairs. When English-Mandarin bilingual infants were tested in a word segmentation task with pitch or tone changes in words, at 9 months they successfully ignored the pitch change in English words, as it is not an informative cue for word boundaries (Singh & Foong, 2012). When a Mandarin tone change was used however, by 11-months, bilingual infants have taken into account pitch as an important feature for word boundaries in Mandarin. Despite having two sets of languages, bilingual infants show similar timing in word segmentation abilities to monolingual peers. Bilingual infants learning rhythmically different languages (French and English), were able to segment bi-syllabic words in both of their languages 7.5-month-olds, similar to their monolingual counterparts (Polka & Sundara, 2003). Likewise, bilingual infants learning rhythmically similar languages (Spanish and Catalan) were able to segment words at 6- to 8-months of age, also comparable to the same-aged monolinguals (Bosch et al., 2013).

In sum, studies with bilingual infants suggest that the developmental course of attunement to native languages is similar to that of monolingual infants. However, dual language learning also brings some particularities such as a higher flexibility to process non-native sounds (for reviews see, Werker & Byers-Heinlein, 2008; Höhle et al., 2020). The next chapter will present the vocabulary development in bilingual infants and discuss important aspects to consider while measuring vocabulary development trajectories in young bilinguals.

2.2. Vocabulary development

Despite the dual language input, bilingual infants have shown to achieve their linguistic milestones such as canonical babbling (Oller et al., 1997) or production of first words (Genesee, 2003; Patterson & Pearson, 2004) within the same age as monolinguals. The linguistic input is divided between two languages for bilingual infants, and thus, bilingual infants tend to have fewer exposure to each language compared to monolinguals of that language. This often results in young bilinguals to lag behind in vocabulary size if their vocabulary is measured separately in each language and compared to monolingual peers of that language (e.g., Bialystok et al., 2010; Hoff et al., 2012; for review, see Hoff & Core, 2013). In spite of this, the vocabulary size of bilingual infants remains in the typical developmental range of monolinguals (e.g., Paradis & Genesee, 1996; Petitto et al., 2001), and the difference in the vocabulary size is smaller if the bilinguals are tested in their dominant language (Hoff et al., 2012). Bilinguals also tend to have a smaller *Total Conceptual Vocabulary* compared to monolinguals (Core et al., 2013). In this way of measuring bilingual vocabulary, all words corresponding to one concept are counted as one; for example, "house" and "maison" count as one known word. When *Total Vocabulary* is measured, however, bilingual toddlers do not lag behind monolinguals in lexicon size (e.g. Core et al., 2013; Hoff et al., 2012; Pearson et al., 1993). In this method all tokens in both languages are counted. For example, "house" in English and "maison" in French would count as two known words even if their meaning is the same. In order to obtain the total vocabulary score, the number of words the bilingual infant has in each language would be summed. Although contrasting monolingual and bilingual first language acquisition can provide important evidence about shared and distinct language acquisition patterns, comparisons must be done consciously of the differences that can be seen depending on the method of vocabulary estimation (see, Bhatia & Ritchie, 2008).

Word processing efficiency of a bilingual infant in one language was shown to be linked to the vocabulary skills in that language only and no link to the vocabulary skills across languages was found (Marchman et al., 2010; Hurtado et al., 2014). Similar to monolinguals (Fernald et al., 2006; Hurtado et al., 2007; Marchman & Fernald, 2008), also in bilingual infants, a positive correlation between infants' speed of word recognition and their vocabulary size has been found (Hurtado et al., 2014). In bilinguals, relative amount of exposure to each language was found repetitively to be the most important predictor of language skills in each language (e.g., Floccia et al., 2018; Hoff, 2003, 2006; Hoff et al., 2014; Law & So, 2006). Floccia and colleagues (2018) collected data from a wide range of bilingual two-year-olds, whose languages were English and another language out of 13 other languages. They explored a range of factors that impact vocabulary development in bilingual toddlers, such as exposure levels and linguistic distance of the two languages. The results found that a phonological overlap between translations of a word in two languages increased expressive vocabulary. Additionally, similarity of morphological complexity and word order between the languages had a positive effect on comprehension skills of toddlers, providing evidence that bilinguals learning different pairs of languages are not necessarily identical in language development.

Bilingual first language acquisition is not a "deviant" form of typical (monolingual) language acquisition but it is a normal type of first language acquisition that shares some similarities and differences with monolingual development. Bilingual experience does not affect mechanisms of word-object pairing for dissimilar sounds: 14-month-olds bilingual infants (English with another language) were able to map (lif and neem) on different objects, similarly to same-aged monolinguals (English-learning). In fact, a meta-analysis of experiments found that bilingual infants in general perform better than monolinguals in word learning experiments (Tsui et al., 2019), which could partially be due to higher cognitive processing abilities in bilingual infants. On the other hand, early bilingual experience seems to have an effect on the mapping of similar sounds. When English-French learning bilingual 17-month-olds were presented with minimal pairs containing a phonemic contrast in both languages (*bowce and gowce*) (Mattock et al., 2010), they could learn the labels, whether the stimuli were pronounced bilingually or only in one of the languages, whereas monolinguals could only learn the labels if they were pronounced in one of the languages. The results suggest that the bilingual infants are well adapted to the phonetic variability that is present in their linguistic environment and word learning is not haltered by converging these phonological elements during a task. However, when minimal pairs differing by an other phoneme pair (e.g., *bih and dih*) were used with various groups of (French-English, Chinese-English and English with an other language) bilingual infants, none of the groups could map the labels to different objects before 20-months of age (Fennell et al., 2007), whereas monolinguals could already do so a few months earlier, at 17-months (Werker et al., 2002). The authors suggested that the bilingual infants may be directing the limited cognitive resources onto the main task of word learning rather than processing phonetic details during word learning as an adaptive mechanism. Two other studies found bilingual advantage in learning minimal pairs: Singh and co-workers (2018) compared the abilities of mono- and bilingual (English-Mandarin) 18-month-olds to learn two novel labels that differed by a vowel. Bilinguals were able to learn the words whereas monolinguals in each language could not, suggesting that bilinguals, at least in some language pairs, may have a higher / earlier sensitivity to vowel categories than monolinguals.

In sum, the language exposure in each language is essential to understand vocabulary development of bilingual infants. However, multiple variables in the linguistic environment of bilingual infants can also affect language outcome, which results in some heterogeneity between bilinguals.

2.3. Behavioral insights : higher flexibility in word-learning of bilingual infants

Bilingual infants exhibit a greater phonological sensitivity to non-native phonetic discrimination, along with a prolonged perceptual narrowing process compared to monolingual peers (e.g., Garcia-Sierra et al., 2011; Ferjan Ramırez et al., 2016; Petitto et al., 2012; see also Kuhl et al., 2008). Only a few studies investigated whether bilingual infants show more flexible patterns than monolingual peers also in word learning tasks (e.g., Graf Estes & Hay, 2015; Liu & Kager, 2018; Singh, 2018). Many of these studies used the Switch task, containing labels with different kinds of non-native sounds (e.g., tonal contrasts or click sounds). The results of these studies showed that bilingual infants either had a prolonged flexibility for accepting word-forms with non-native sounds (Graf Estes & Hay, 2015; Singh, 2018) or performed similarly as monolingual peers (Liu & Kager, 2018). Bilingual 19-month-old infants (learning English and an other non-tonal language) accepted lexical tone variations of novel words as object labels and demonstrated this flexibility until the age of 22 months (Graf Estes & Hay, 2015) whereas English-learning 19-month-olds failed to learn the same labels (Hay et al., 2015). Similarly, when 18- to 20-month-old English monolingual and English-Mandarin bilingual infants were presented with non-native click sounds (present in Ndebele), bilingual infants accepted these sounds as object labels whereas monolinguals did not (Singh, 2018). The results suggest that exposure to two languages may enhance the ability of infants to learn new words containing non-native sounds. However, bilingual exposure in 18-month-old infants learning Dutch and another non-tonal language did not increase flexibility to learn novel words containing Mandarin tones (Liu & Kager, 2018). The difference in the findings between the latter study and the previous ones, was suggested to be due to the difference in the tonal contrasts used. In sum, behavioral studies of word learning suggest a higher flexibility in accepting atypical word-forms as object labels in bilinguals compared to monolinguals during first language acquisition.

2.4. Electrophysiological insights: neural correlates of word processing in dominant and non-dominant languages of bilingual infants

There are only a few ERP studies investigating lexical processing in bilingual infants and toddlers. These studies indicate that dual language processing in bilingual infant is interacting with prevalence of the language in the society, relative dominance of the languages and vocabulary skills (Conboy & Mills, 2006; Rämä et al., 2018; Sirri & Rämä, 2019; Vihman et al., 2007).

Previously two ERP studies measured brain signals in response to known and unknown words in a non-referential context in bilingual infants and toddlers (Conboy & Mills, 2006; Vihman et al., 2007). In a study conducted in 11-month-olds Welsh-English bilinguals, as well as Welsh or English monolingual peers, the participants were presented with familiar (e.g., "apple") and unfamiliar (e.g., "Eiffel") words in an oddball paradigm (Vihman et al., 2007). Bilingual infants showed a familiarity effect both in English and in Welsh, neurophysiologically and behaviourally: the amplitudes of the N2 and N4 for familiar words were more negative than for unfamiliar words, and infants preferred to listen to the familiar words over the unfamiliar ones. However, the N2 and N4 in response to familiar words occurred later in Welsh, the less prevalent language in the community, compared to English, the more prevalent language of the region. In another study Conboy and Mills (2006) presented known and unknown words (i.e. low frequency words) to 19- to 22-month-old bilingual (Spanish-English) infants from both of their languages in a passive listening task. The study further investigated the N200–400 and the N400–600 for known and unknown words in dominant and non-dominant languages in different vocabulary groups. Infants with higher total conceptual vocabulary exhibited higher N200-400 and N400-600 amplitudes for known words compared to unknown ones in both of their languages, whereas those with low total conceptual vocabulary had the same effect only in their dominant language. Additionally, for the non-dominant language of the infants with low conceptual vocabulary, the effect occurred at a later latency, from 600 to 900 ms. The results suggest that an overall language ability affects the processing speed, the latency and the amplitudes of the brain responses to known and unknown words in the non-dominant language, whereas it does not affect word processing in the dominant language. The study also demonstrated that language dominance and skills can be important factors that interact with ERPs that are related to language processing in bilingual infants. Additionally both studies further suggest that the different languages of bilingual infants are treated in a non-equal manner.

The few ERP priming studies on language processing in bilingual young children at lexical-semantic level (Kuipers & Thierry, 2013; 2015; Rämä et al., 2018; Sirri & Rämä, 2019) indicate that language processing in bilingual infants seems to have some differences in comparison with monolinguals, depending on the dominance status of the tested language. In one study, French-Spanish learning 2- and 4-year-old bilinguals were tested with an auditory semantic priming task, during which semantically related or unrelated prime and a target word were presented, separately for each of their languages (Sirri & Rämä, 2019). The results revealed that the amplitudes of the N2 component was more negative for unrelated than related words in both languages, similar to monolingual infants (Sirri & Rämä, 2015), suggesting that N2 is linked to semantic processing in dominant and non-dominant languages of bilingual toddlers and young children. However, there was an N400 priming effect over the right posterior recording sites only on the dominant language, suggesting a mechanism of activation of the lexical semantic network similar to monolingual toddlers only in the dominant language (c.f. Rämä et al., 2013). Bilingual two-to-three year-olds also showed similar lexical semantic processing mechanisms to monolingual peers only in the dominant language, as indicated by N400 amplitudes in a semantic integration study (Kuipers & Thierry, 2015). In another auditory semantic priming study, 18-month-old bilingual infants (French and another language) were presented with semantically related (e.g., elephant-bear) or unrelated (e.g., plane-bear) word pairs (Rämä et al., 2018) with two different stimulus onset asynchronies (SOA), 1000 and 1600 ms. The results revealed that the bilingual infants showed the N400 priming effect only when the SOA was long while the monolingual infants showed the effect in both SOAs (c.f. Sirri & Rämä, 2015). The results suggest that even though bilingual toddlers show sensibility to the semantic relations between words; the activation of the semantic networks may be slower in bilingual toddlers compared to their monolingual peers.

Chapter 3: Methodologies in language development studies

Infant language developmental studies have used different experimental paradigms to study speech perception, word learning and word processing. Likewise, stimulus properties differ between the studies. In some studies, infants are presented with known or newly familiarized words along with unknown, low-frequent, or pseudowords, in order to compare behavioral or electrophysiological responses to known and unknown words. In studies investigating non-native word processing, infants are often presented with words with non-native sounds and sometimes with non-speech sounds.

Although attentional measures were shown to correlate with language skills in infants (e.g., Dixon & Smith, 2000; Kannass & Oakes, 2008; Mundy et al., 2000; Yu & Smith, 2012), there are only a few studies that investigated attentional effects during word processing in infants and toddlers (Kuipers & Thierry, 2013; 2015; Thierry et al., 2003; Vihman et al., 2007). Both known words and rare words were suggested to attract the attention of infants automatically (Thierry et al., 2003; Vihman et al., 2007). The effect of controlled attention on language processing on the other hand was studied mainly in preschool aged children (e.g., Coch et al., 2005; Karns et al., 2015; Sanders et al., 2006).

Parental reports have also been widely used in language developmental research in order to assess comprehensive and expressive vocabulary growth in infants (for a review, see Law, & Roy, 2008) as well as to estimate exposure to different languages (for a review, see Byers-Heinlein, 2015). This chapter will review some of the methodologies used in experimental research on infant word processing that are relevant to this dissertation. More specifically, it will discuss more in detail different stimulus properties in language processing experiments, and the role of attention in these experiments. It will then present relevant methods to measure early language processing abilities of infants, notably the ERPs method to measure the brain responses, and parental evaluation questionnaires to measure infants' linguistic abilities and background.

3.1. Stimulus properties in language development studies

The linguistic stimuli used in language development studies show a great variability depending on the aim of the studies and the age of the infants: familiar or known words, unfamiliar or unknown words, constructed word-forms, such as phonotactically legal pseudowords or phonotactically illegal nonwords and finally non-speech sounds.

In experiments on early speech processing, infants are typically presented with native and non-native sounds imported from another language to investigate the ability of infants to process native and non-native sounds during the first year of life (e.g., Kuhl et al., 1992, 2005; Werker & Tees, 1984) For example, /i/ from English and /y/ from Swedish was presented to English and Swedish learning monolingual infants (Kuhl et al., 1992). Similarly, the processing of native English contrasts were compared with the processing of non-native contrasts from other languages such as Mandarin Chinese (Kuhl et al., 2005) or Hindi (Werker & Tees, 1984). In another study, pseudowords with high and low phonotactic probability patterns were constructed, in order to investigate infants' sensitivity to the phonotactic regularities of native language (Jusczyk et al., 1994).

In behavioural and ERP studies investigating word processing in a lexical-semantic level, infants were often presented with known or familiar words (e.g., Friedrich & Friederici, 2004, 2005, 2006, 2010; May & Werker, 2014; Mills et al., 1993, 1997; Rämä et al., 2013; Sirri & Rämä, 2015; Thierry et al., 2003; Torkildsen et al., 2006, 2007). However, estimating which words are "known" by young word learners might be a challenging task and different methods have been used to determine the stimuli. In many studies, these words are chosen based on normative data of early words of infants, and are also often part of the CDI in the tested language (e.g., Hallé & Boysson-Bardies, 1996; Friedrich & Friederici, 2004; Rämä et al., 2013; Swingley, 2005;). In some experiments, parents were also asked to estimate the infant's knowledge on the specific stimuli chosen (Mills et al, 1993; 1997). Unknown words were also often part of infant word processing experiments either to study the familiarisation of novel words (e.g., Goyet et al., 2010; Männel & Friederici, 2013; Von Holzen et al., 2018) or as a comparison to the processing of known words (e.g., Mills et al., 1993, 1997). These unknown words were either rare real words that infants are less likely to know, such as low frequency words (e.g., *cobaye* in French) (e.g., Hallé & Boysson-Bardies, 1996; Goyet et al., 2010; Männel & Friederici, 2013; Mills et al., 1993, 1997; Von Holzen et al., 2018) or constructed pseudowords that follow the regularities of native language (e.g., Graf Estes et al., 2011; Rossi et al., 2013; Swingley, 2005).

Infants were also presented with various non-native word-forms in word processing (e.g., Friedrich & Friederici, 2005; Mills et al., 1993, 1997) and word learning experiments (e.g., Hay et al., 2015; MacKenzie et al., 2012; May & Werker, 2014; Tsui et al., 2019). These stimuli were often non-native words from foreign languages (e.g., Bijeljac-Babic et al., 2009;

MacKenzie et al., 2012), constructed words containing non-native sounds (e.g., Hay et al., 2015) or phonotactically illegal sound combinations (e.g., Friedrich & Friederici, 2005; Graf-Estes et al., 2011). For example, in a study investigating infants' sensitivity to linguistic properties of native language, English-learning infants were presented with Japanese real words that differ phonetically and Czeck real words that are phonotactically illegal in English (MacKenzie et al., 2012). In other experiments, nonwords were constructed using two different methods. First by importing non-native sounds from other languages, for example, in a word learning study, nonwords containing non-native pitch contours from Mandarin were constructed to test English-learning infants (Hay et al., 2015). Alternatively, the phonemes of the native language were sequenced in a manner that violate the phonotactic rules while composing nonwords, notably by creating a phonotactically illegal consonant cluster in word onset position (Friedrich & Friederici 2005; Obrig et al., 2017; Steber & Rossi, 2020). Additionally, in some studies more atypical sound forms were also used; for example, backwardly presented words violating phonetic, phonotactic and prosodic properties of a given language (Mills et al., 1993, 1997), or even synthetic non-speech sounds (Woodward & Hoyne, 1999).

3.2. Role of attention in language processing

Word learning and language abilities of infants were linked to attentional measures in multiple studies. Attentional measures were shown to correlate with receptive and expressive language skills in infants (e.g., Dixon & Smith, 2000; Kannass & Oakes, 2008; Mundy et al., 2000; Yu & Smith, 2012), presenting attention as an important component of language acquisition. Joint attention patterns with parents as well as sustained attention of infants at 9-months predict child vocabulary size at 12 and 15-months (Yu et al., 2019). Duration to looking at objects or pictures were found to predict later language learning abilities (Kannass & Oakes, 2008; Lawson & Ruff, 2004; Ruff et al., 1990). Allocation of attention on objects at 9-months was shown to predict vocabulary learning skills at 30-months, that is, infants that have longer durations of visual fixation on objects have higher receptive vocabulary later (Kannass & Oake, 2008). Toddlers who were visually attending longer to named objects are more likely to learn the labels (e.g., Macroy-Higgins & Montemarano, 2016; Pereira et al., 2014; Salley et al., 2013; Yu & Smith, 2012) and late talkers showed reduced attention allocation to objects during word-naming (Macroy-Higgins & Montemarano, 2016). Similarly, in children between 3 to 10 years, vocabulary skills were linked to the efficiency of directing attention to labeled objects

(Borovsky et al., 2012), suggesting that attentional stays linked to language development during early childhood. In early school years, attention skills and literacy were found to be closely related (e.g., Bosse & Valdois, 2009). Selective auditory attention has also been linked to reading ability of school-aged children (Obrzut et al., 1997). These examples illustrate the importance of attentional skills on language development, as many situations in life contain competing stimuli and require effortful focus of attention (for reviews, see Gomes et al., 2000; Stevens & Bavelier, 2012). Moreover, attentional problems are present in developmental psychopathologies such as specific language disorder (e.g., Noterdaeme et al., 2001), further showing the importance of attention for language development.

Already in the first year of life infants are able to use selective attention to speech signals for maintaining speech processing in noisy environments. Even in the presence of noise signals, infants can identify phonetic differences (ba *versus* ga) (Nozza et al., 1991), segment words from continuous speech (Newman & Jusczyk, 1996), recognize their own name (Newman, 2005) and distinguish their mother's voice (Barker & Newman, 2004). Some external cues relevant to the stimuli, may also help infants to focus easier on speech such as attention getters and infant directed speech (IDS). Attention getters are often salient images or short videos which are used to bring or keep the infant's attention on the task during an experiment (e.g., Domsch et al., 2010; Lewkowicz, 2010; Pons, F., & Lewkowicz, 2014; Frick and Richards, 2001). It was shown that attention getter leads to a decrease in heart rate, reflecting a state of sustained attention; moreover, infants have been shown to encode information more efficiently when attention getters were present (e.g., Frick, & Richards, 2001; Domsch et al., 2010). IDS is characterized by simpler sentences, slower rate of speech, higher fundamental frequency, pitch variation, and repetitive intonation during speech (for a review, see, Golinkoff, et al., 2015). IDS facilitated word learning in toddlers (Ma et al., 2011) and exposure to IDS predicted vocabulary growth in toddlers growing in families with low socioeconomic background (Weisleder & Fernald, 2013). IDS was suggested to increase the salience of language input (e.g., Pegg et al., 1992; Fernald & Kuhl, 1987) and attract infants' attention to the most relevant linguistic items (e.g., known words and/or unknown words), depending on the age (Zangl & Mills, 2007).

Although studies with infants and young children link attentional mechanisms to language development, allocation of attention to speech is rarely controlled in infant studies. Previously, a few infant and toddler studies have investigated the automatic capture of attention by speech stimuli, using an oddball (or similar) paradigm (Thierry et al., 2003; Vihman et al., 2007) or the allocation of attention to expected and unexpected stimuli using word-picture semantic relatedness paradigms (Kuipers & Thierry, 2013; 2015). When 11-month-olds were presented with familiar and unfamiliar words in a non-referential ERP experiment, the amplitudes of the N200 increased for familiar words within 250 ms of word onset. The authors suggested that the N200 modulation was due to known words automatically attracting the attention of 11-month-old infants (Thierry et al., 2003). Dual language exposure was also suggested to impact infant's ability to allocate attention to speech (Kuipers & Thierry, 2013; 2015; Vihman et al., 2007). In another study, combining pupil size and ERP recordings, increasing pupil dilation (more attentive state) was associated with more reduced N400 amplitudes in bilingual toddlers in a word-picture semantic integration task, suggesting that allocation of attention to unexpected stimuli facilitates lexical-semantic processing in bilingual toddlers (Kuipers & Thierry, 2013). In another semantic integration task, congruous words preceding pictures elicited an early frontal positivity only in bilingual toddlers, suggesting an increased attention to words matching pictures (Kuipers & Thierry, 2015). Most studies with controlled attentional conditions on speech processing were carried out with young children (Coch et al., 2005; Karns et al., 2015; Sanders et al., 2006; Stevens et al., 2009), partially due to the difficulty of infants to reliably allocate attention on demand in a controlled manner. These studies employed a dichotic listening paradigm with pre-school and school-age children with certain adaptations (e.g., easier vocabularies, shorter blocks): two different stories that contained linguistic (syllable /ba/) and non-linguistic (a buzz) probes were alternating between left and right ears via located speakers while the participants were asked to attend to only one story. The 3- to 5-year-olds and the 6- to 8- year-olds showed a single broad positivity in the first 300 ms for both probe types when they were in the attended channel, which lasted longer for the youngest group of children (Karns et al., 2015; Sanders et al., 2006). Additionally, children from 3 to 8 shared a broad negativity from 300 to 500 msec for attended linguistic probes, suggesting a modulation of ERPs for linguistic stimuli with controlled attention in young children.

3.3. Event related potential (ERP) technique

The Electroencephalogram (EEG) is a method of recording the ongoing electrical activity in the brain using electrodes attached to the scalp. The electric activity in the brain is generated by the current flows during the postsynaptic potentials of the pyramidal neurons in the cerebral cortex. These voltage fluctuations are small in amplitude and need to be amplified before treatment for analysis. The brain produces electrical responses when there is externally or internally driven stimulation (e.g., sensory or cognitive), named an event. These responses are submerged among a background activity (noise) that is a result of physiological functions such as muscle movement or eye-blinks. The ERPs are obtained by averaging brain responses to a large number of events of the same category. The fact that the ERPs are time-locked to the event, and signals are averaged reduces the random, non-synchronized noise, and thus the ERPs are considered to reflect the brain's electrophysiological responses to the controlled stimulation. There are various factors that affect the ERPs during experimental conditions: for instance, physical properties of the stimuli such as pitch or duration, or cognitive tasks such as passive listening or attention allocation (for more details on the ERP technique see Kutas et al., 2006; Luck, 2005; Picton & Taylor, 2007; Thierry, 2005).

ERP components are certain parts of an ERP waveform, such as peaks, that are sensitive to specific physiological or cognitive processes. The ERP components are defined by the polarity of the waveform and the time of their occurrence relative to the stimulus onset. For example, the P100 is a positive response around 100 ms after stimulus onset and the N400 is a negative response around 400 ms (for more details, see Luck, 2005). Different ERP components have been associated with different cognitive processes and they reflect the activation of neural networks, which could be automatic or under attentional control (Thierry, 2005). Variations in physical parameters of the stimulus usually cause a change in the earlier components, which are considered "exogenous" as they are stimulus dependent and are often not modulated by the participant's attention. Endogenous components on the other hand are triggered by a cognitive event and are responsive to task demands, attention and decisions of the subjects and are observed at least 100 ms after the stimulus onset (Kutas et al., 2006).

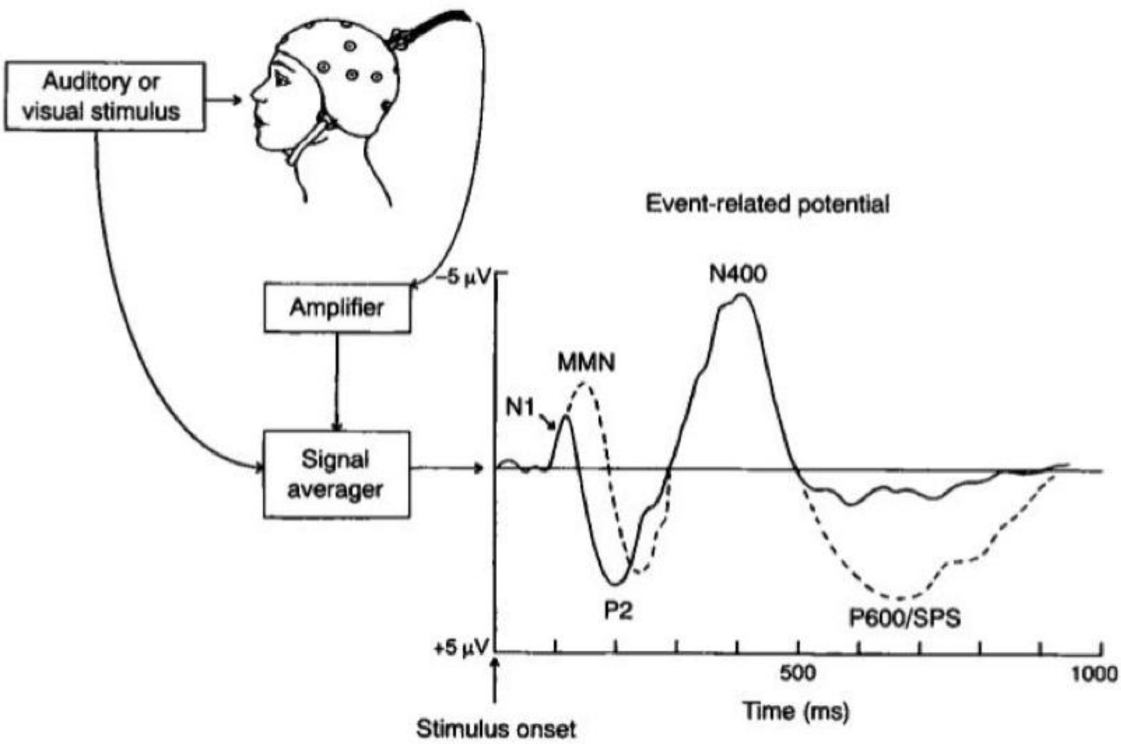

Figure 1: Illustration of how ERPs are obtained. During the experiment, electrical activity is recorded from the scalp. The signals are amplified, averaged and time-locked to the stimulus producing the ERP. Figure from Osterhout et al., 1997.

The ERPs have multiple advantages for studying language processing. First, there is a continuous data collection with a very high temporal resolution (to the millisecond) corresponding to the rapidity of language comprehension. Second, various ERP components have been related to specific language processes (e.g., acoustic, phonological, lexical, semantic etc) which allows the researchers to study them separately as well as in relation to each other. Third, although it can be coupled with a behavioral task (such as a button press), it does not require an overt response or a meta-linguistic awareness (Kaan, 2007; Kutas, et al., 2006). Moreover, ERPs allow researchers to study automatic language processing as well as attentional modulations acting on different aspects of language processing. Thus, the ERP technique has been widely used in developmental psycholinguistics for example to investigate early linguistic development or organization of the brain with respect to linguistic experiences such as bilingualism.

However, continuous EEG recordings and ERP components in infants have certain differences compared to adults (for a review, see Thierry, 2005). Background noise in EEG recordings are usually more prevalent in infant brain recordings. Additionally, infants usually move more than adults during testing and may not accept capping before the procedure. Individual variance in ERP recordings has also been shown to be higher in infants than in adults. Another difference is that the ERP components in infants usually have smaller amplitudes and higher latencies compared to adults (for a review, see Dehaene-Lambertz, 2000; Kurtzberg et al., 1984). More rarely, polarity inversion of some components have been observed in young children (e.g., He et al., 2007). When adult and infant components differ in peak latencies or polarity, other factors such as brain networks that are implied in the activation, can be important to decide if these components reflect similar cognitive processes.

3.4. Parental evaluations of language development and background

Parental reports have been widely used in language developmental research to assess vocabulary skills of infants (for a review, see Law, & Roy, 2008), as well as to estimate exposure amounts to different languages in bilingual language acquisition (for a review, see Byers-Heinlein, 2015).

3.4.1. MacArthur communicative development inventories (CDIs)

Scientific studies of early vocabulary development use different methods, such as looking times or parental questionnaires, to evaluate word comprehension and production abilities of infants (for a review, see Fernald & Weisleder, 2011). Parental reports on infants' language skills help collect developmental norms of language development (e.g., Bates et al., 1995; Fenson et al., 2007) and identify language delays in developing populations (for a review, see Law & Roy, 2008).

One of the most widely used parental questionnaires for language assessment is the MacArthur Communicative Development Inventories (CDIs) (Fenson, 2007; Fenson et al., 1994). CDIs are grouped according to the age of the child; CDI Infant form is used to evaluate infants from 8- to 18-months of age, whereas the CDI Toddler form is used for toddlers from 16- to 30-months of age (for more information on the forms, see: https://mb-cdi.stanford.edu, and Annex for the French adaptation of the CDI toddler form). CDIs have two columns of checklists with about 750 words designated for receptive and productive vocabulary, and the words are organized in semantic categories in the form. Additionally, there are standardized shorter versions of the CDI with less than 100 items (Fenson et al., 2000). Over the past few decades, the CDIs have been adapted and translated to more than forty languages (see Dale & Penfold, 2011 for a list), a few sign language versions of the inventory are also available (e.g., Anderson & Reilly, 2002; Woolfe et al., 2010).

Parental reports have some important advantages as well as some disadvantages that should be kept in mind while employing them. One particular value of CDIs is that they use the parents' extensive knowledge of their child and are likely to capture the most naturalistic performance of the child. However, CDIs also have some downsides, such as potential bias of the parents which can cause an over- or underestimation of the child's linguistic skills (Oliver et al., 2003). Although CDI has shown to have an acceptable reliability, accuracy and validity (for a review, see Law & Roy, 2008), it is affected by multiple factors. For example, if the information assessed was more recent, it was also more accurate (Dale et al., 1989). If the form was filled by multiple people, instead of a single person, a higher validity was found (De Houwer et al., 2005). Additionally, the education level of the parents can also influence the CDI: higher education level was associated with more accurate reports (Feldman et al., 2000).

The evaluation of bilingual language development has some challenges due to the variability of the linguistic environment (see, Floccia et al., 2018; Patterson & Pearson, 2004). Although the CDIs are available in multiple languages (Wordbank: Jørgensen et al., 2009), considering the diversity of bilingual environments measuring language skills of infants in both languages is not always feasible. Additionally, even though total vocabulary or total conceptual vocabulary scores of bilingual toddlers, measured by CDI, were previously reported to be comparable to monolingual peers (e.g., Junker & Stockman, 2002; Pearson et al., 1993), there is also evidence suggesting that these measures do not captivate the linguistic knowledge of balanced bilinguals accurately (Thordardottir et al., 2006). Moreover, total vocabulary scores in CDI showed a considerable variability in bilingual groups learning different language pairs (O'Toole et al, 2017), suggesting that linguistic distance also affects vocabulary scores of bilinguals. In order to tackle these problematics in evaluating bilingual language development, Floccia and colleagues (2018) collected detailed data on linguistic environment and language development of bilingual toddlers learning English and another language (among thirteen different languages). As a result they developed a language assessment tool in English (UKBTAT, UK Bilingual Toddler Assessment Tool) to evaluate the receptive and expressive vocabulary of bilingual toddlers learning English and another language. The model takes into account multiple variables such as exposure levels, linguistic distance between the languages.

Although the tool provides reliable estimates of English skills of bilingual toddlers, there are not yet such tools for bilinguals in other languages.

In sum, CDIs are widely used as parent inventories of early language development. Although they should be interpreted with caution, considering potential reporting biases, they are internationally recognized in developmental research and have various advantages, such as being standardized. However, despite the availability of CDIs in multiple languages, the evaluation of bilingual toddlers' vocabulary skills remains challenging.

3.4.2. Assessing language exposure in bilingual infants

For early bilingualism, language background is often measured by parental reports, using structured or semi-directive interviews (e.g., Bosch & Sebastián-Gallés, 2001; Hoff & Luz Rumiche, 2012; see, Byers-Heinlein, 2015). In such a methodology, parents are asked about the family language background, the native languages of the parents and the languages they use within the family. The weekly routine of the child is asked, focusing on the awake hours of exposure to each language through different speakers during each day. It is noted if exposure amounts changed during different periods of an infant's life, such as when the child started daycare or if the family travels to another country during holidays. This information helps the parents reflect better on the relative exposure of the child to each language and is used to calculate an estimation of percentages. The evaluation of exposure to each language is a complex measure with multiple compound variables, such as mode of exposure which include who is the speaker, how many persons speak each language around the child or where each language is heard (e.g., home or daycare) (see Floccia et al., 2018). Mode of exposure includes if the speech is directed directly to the child (infant or child directed speech, e.g., Weisleder & Fernald, 2013) or it is the speech that the child hears when other people talk among themselves (overheard speech, e.g., Floor & Akhtar, 2006). At the end of the evaluation, the child will be situated in the continuum of exposure to the languages and may be placed in a group of bilinguals depending on the criteria of the study.

Aims of the Thesis

Behavioral and neuroscientific evidence shows that infants attenuate to their native language within the first year of life. This attunement allows infants to use the phonotactic regularities of native language during word learning as they become more efficient word learners during their second year of life. Previous studies have indicated that bilingual infants show a prolonged sensitivity in processing and learning of non-native sounds. Multiple ERP experiments have previously studied language development in monolingual toddlers, linking some ERP components to word processing and increased vocabulary skills, although less is known about the brain signatures of word processing in bilingual peers. Moreover, there is considerable variability in experimental conditions and stimuli types used in previous studies. The present dissertation aimed to study the effects of dual language exposure, vocabulary skills and attention allocation on word processing during language acquisition.

In order to explore the effects of early language experience (amount of exposure to French) and vocabulary skills on the processing of known and unknown words, monolingual (Study I) and bilingual (Study II) 24-month-olds were presented with known words (e.g., "bateau", boat), phonotactically legal pseudowords (e.g., "meautai") and phonotactically illegal nonwords (e.g., "zbaiton") in a non-referential task using the event-related potential (ERP) technique. Study I aimed to investigate the effect of comprehensive and expressive vocabulary skills on the magnitudes and the timings of the ERPs responses to different word types in monolingual toddlers. We expected that 24-month-olds with higher vocabulary skills would have differential ERP amplitudes for known words and pseudowords, indicating a greater sensitivity to word meaning and more attenuated ERPs for nonwords, reflecting a higher sensitivity to phonotactic structure in novel lexical items. Study I also aimed to investigate the effect of word repetition on the ERPs for different word types. We expected ERP modulations in response to phonotactically legal pseudowords in the course of the experiment but not in response to phonotactically illegal nonwords.

Study II aimed to explore whether dual language exposure contributes to the ERPs for known words, pseudowords and nonwords in a non-referential listening task. Previous studies show evidence that the lexical-semantic activation in the dominant language of bilingual toddlers is similar to monolingual peers (Sirri & Rämä, 2019; Kuipers & Thierry, 2015). We expected that dual language exposure would not affect the processing of known words and pseudowords, while the vocabulary skills could have an impact on the processing of different word types. In the light of previous behavioral evidence indicating that bilingual infants show high flexibility in accepting non-native sounds as novel object labels (Graf Estes & Hay, 2015; Singh, 2018; Singh & Tan, 2021), we expected bilingual toddlers to process nonwords and pseudowords similarly. Additionally, we investigated whether the relative amount of language input of bilingual toddlers modulates the brain responses to different word types.

Attentional mechanisms and language development are linked in infants, toddlers and children (e.g., Bosse & Valdois, 2009; Borovsky et al., 2012; Dixon & Smith, 2000; Kannass & Oakes, 2008; Macroy-Higgins & Montemarano, 2016; Mundy et al., 2000; Obrzut et al., 1997; Pereira et al., 2014; Yu & Smith, 2012). Study III aimed to investigate whether selective attention to novel lexical items affects the brain responses in preschool aged children. The influence of attention on word processing was explored in preschool children using an intermodal (audio-visual) selective attention design. The participants were asked to attend either to the auditory stream (attentive condition) where they heard known words and pseudowords, or the visual stream (unattentive condition), where they saw animal pictures. The ERPs were measured throughout the experiment in response to words and the brain responses during the first and second half of the experiment to different word types were compared.

Experimental Studies

Study I

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Brain signatures of native and non-native words in French-learning 24-month-olds: the effect of vocabulary skills

Aygün, O.[a] & Rämä, P.[a,b]

[a] Université de Paris, Paris, France, [b] Université de Paris, INCC UMR 8002, CNRS, F-75006 Paris, France

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Abstract

The event-related potential (ERP) technique provides a temporally accurate measure to distin- guish among different linguistic processes. Here, we measured ERPs in response to known words, pseudowords and nonwords in 24-month-old French-learning children to investigate how indi- vidual vocabulary skills contribute to the processing of native-like and non-native-like words during a listening task. The N200 was more pronounced for pseudowords than for nonwords while no difference was found between known words and pseudowords. The amplitude difference between known words and pseudowords was, however, correlated with the productive vocabu- lary. Toddlers with a higher vocabulary score exhibited a bigger difference than toddlers with a lower vocabulary score. Similarly for the frontally distributed late negativity, only those toddlers with higher vocabulary knowledge exhibited a gradient pattern of activity in response to three word types while children with lower vocabulary skills exhibited a similar responsiveness to each word type. Our results suggest that vocabulary skills contribute to the magnitudes of brain signals in response to native and non-native words in a non-referential listening task.

Keywords: Lexical processing Vocabulary skills Phonotactics Event-related potentials Developing brain Toddlers

1. Introduction

Between 6 and 12 months of age, infants improve their ability to discriminate between native phonemes while discrimination of non-native phonemes declines (e.g., Werker & Tees, 1984; Kuhl et al., 2006; for a review, see; Werker, 2018). Native and non-native phonetic discrimination ability at the age of 7.5 months has been shown to predict later vocabulary development: better native language perception predicted higher productive vocabulary score at 18- and 24-months while better non-native phonetic perception predicted lower vocabulary score (Kuhl et al., 2008; Kuhl, Conboy, Padden, Nelson, & Pruitt, 2005). Infants become also sensitive to language-specific phonotactic features of their native language before their first birthday (e.g., Friederici & Wessels, 1993; Jusczyk, Friederici, Wessels, Svenkerud, & Jusczyk, 1993). Phonotactic knowledge helps infants to segment words from continuous speech which then allows infants to recognize and understand frequently heard nouns (e.g., Bergelson & Swingley, 2012; Parise & Csibra, 2012; Tincoff & Jusczyk, 1999, 2012). Vocabulary growth has a slow pace in the beginning but children start to produce new words at a remarkable rate around the end of the second year of life (e.g., Ganger & Brent, 2004; Reznick & Goldfield, 1992). Consequently, by 24 months children produce (with an extensive individual variation) in average two to three hundred words (e.g., Fenson et al., 1994). At the same time, they also increase the speed and accuracy of native word recognition from speech and lexical representations become more stable (Fernald, McRoberts, & Swingley, 2001; Fernald, Pinto, Swingley, Weinbergy, & McRoberts, 1998). On the other hand, the ability to learn non-native words diminishes with age and increasing vocabulary knowledge during the second year of life: 14-month-- old infants were capable of associating novel visual items with non-native sounds, while older infants (18- to 20-months), especially with higher vocabulary skills, associated only native sounds with novel pictures (Graf Estes, Edwards, & Saffran, 2011; Hay, Graf Estes, Wang, & Saffran, 2015; May & Werker, 2014). Less is, however, known about brain signals associated with processing of phono- tactically native and non-native words in the developing brain.

Neuroimaging and electrophysiological techniques, such as near-infrared spectroscopy (NIRS) and event-related potentials (ERPs), have been recently used to study language development in infant populations. These techniques capture linguistic processes even in the absence of an overt (motor or verbal) reaction or attention that are often required in behavioral tasks. While the NIRS detects neural activity with relatively high spatial accuracy, the ERPs measure electrical brain activity in a millisecond range, thus providing a temporally accurate measure of language processes. The ERP components correspond, at least partly, to distinct linguistic sub- processes (e.g., acoustic, phonological, or lexical-semantic) providing a possibility to investigate the timing and the sequence of these processes. Besides, the ERP technique is easily applicable to young children (for reviews see, e.g., Johnson et al., 2001; Thierry, 2005). Moreover, several studies have shown that even though the effects were not found behaviorally, the ERPs showed sensitivity to experimental or participant group manipulations (e.g., de Haan & Nelson, 1997; Rivera-Gaxiola, Csibra, Johnson, & Karmiolff-Smith, 2000a, b; Kozou et al., 2005; Sokka et al., 2016) providing further benefits to use the ERPs to map language development.

Increasing word knowledge during the second year of life has been associated with specialized electrophysiological activity. When infants were presented with known and unknown words, the amplitudes of two ERP components, the N200 and N375, were larger for known than for unknown words (Mills, Coffey-Corina, & Neville, 1993, 1997; Conboy & Mills, 2006). In younger infants (13- to 17 months), the components were broadly distributed over the scalp (Mills, Coffey-Corina, & Neville, 1997) while in 20-month-olds they were observed mainly over the left temporal and parietal recording sites (Mills et al., 1993). Also vocabulary skills contributed to the findings: the N200 was more pronounced for known than for unknown words both in low- and high-producers while the difference in the amplitude of the N375 between word types was found only in the high-producers. In bilingual infants, the occurrence and the distribution of ERPs were different for dominant and non-dominant languages (Conboy & Mills, 2006). Another ERP study, conducted in 11-month-old English-learning infants, suggested that a more pronounced N2 component in response to familiar words compared to unfamiliar words is associated with an automatic capture of attention towards familiar words (Thierry, Vihman, & Roberts, 2003). These findings suggest that age, vocabulary skills, and language experience are associated with an increased neural specialization in processing of word meaning.

In a picture-word congruency task, a more pronounced frontally distributed negativity between 100 and 500 ms post word-onset was observed for congruous words, that is, for those words that correctly labeled the pictures when compared to the same words in incongruous picture contexts (Friedrich & Friederici, 2004, 2005). Also, a short-term familiarization to previously unknown word-forms augments the magnitude of the N200-500 component in 10-

to 12-month-old infants during the test phase (e.g., Goyet, de Schonen, & Nazzi, 2010; Kooijman, Hagoort, & Cutler, 2005; Kooijman, Hagoort, & Cutler, 2009; Männel & Friederici, 2010). These familiarity effects between 200 and 500 ms after word onset were observed mainly over the frontal recording sites (Goyet et al., 2010; Kooijman et al., 2009). While the N200-500 component (or temporally similar early negativity) has been associated with word familiarization and lexical congruence, the N400 component has been linked to more mature lexical-semantic processing, semantic integration, and lexical expectancy both in adults (for review, see Kutas & Federmeier, 2011) and in children (e.g., Friedrich & Friederici, 2004; Rämä, Sirri, & Serres, 2013; Sirri & Rämä, 2015; Torkildsen et al., 2006). The N400 effect (more negative response to incongruent *versus* congruent stimulus pairs) in adult participants typically appears over the central-posterior recording sites. In young children, the N400 effect has been observed over distributed scalp positions and also in variable time windows from 400 ms to 1200 ms. Some studies have also reported a late frontally distributed negativity, appearing 600 ms–1200 ms after word-onset (e.g., Friedrich & Friederici, 2004; Mills, Coffey-Corina, & Neville, 1997, 1993; Torkildsen, Syversen, Simonsen, Moen, & Lindgren, 2007a). This late component has been suggested to reflect further lexical search (Junge, Kooijman, Hagoort, & Cutler, 2012), lexical-semantic pro- cessing (e.g., Friedrich & Friederici, 2004) or increased attentional processes during language tasks in young children (e.g., Friedrich & Friederici, 2004; Torkildsen et al., 2006, 2007a).

Some evidence shows that the infant brain is also differentially responsive to meaningless pseudowords (i.e., nonsense words that obey the phonetic, prosodic, and phonotactic rules of a given language) and to nonwords (i.e., nonsense words that violate phonotactic regularities of a language). The N200 and N375 components were found for pseudowords but not for backwardly presented words in 20-month-old, English-learning infants (Mills et al., 1993) while in younger infants (13- to 17-months) no significant difference be- tween pseudowords and backwardly presented words was found (Mills et al., 1997). Differences between the two word types were found over the right hemisphere with a broad distribution from anterior to posterior sites. It should be noted that while backwardly presented words serve as a control for the auditory stimuli by having similar physical characteristics of speech stimuli, they violate not only phonotactic, but also phonetic and prosodic features of speech signal. In another study, conducted in 18-month-olds, German-speaking infants were presented with monosyllabic pseudowords either with a phonotactically legal or illegal consonant onset structure (Steber & Rossi, 2020). The results demonstrated a larger negativity for legal than for illegal words over the anterior and posterior scalp positions in a time window of 500 ms–1000 ms. In a lexical-semantic picture-word context, a (short-lived) larger negativity for pseudo-than for nonwords was obtained over the frontal scalp positions in 12-month-olds while only in the 19-month-- olds, a larger broadly distributed negativity was found (Friedrich & Friederici, 2005). The broadly distributed negativity might reflect a more mature mechanism of semantic integration, in response to phonotactically legal, but not to illegal words (Friedrich & Friederici, 2005). Interestingly, only those 19-months-olds whose later language outcome (tested at 30-months) was age-adequate presented a significant difference between the processing of pseudo- and nonwords while children with lower vocabulary knowledge eleven months later did not show differential responses between the word types (Friedrich & Friederici, 2006). These effects regarding the retrospective language outcome were found over two temporally separate time-windows: between 250 ms and 500 ms, and between 600 ms and 800 ms. To sum up, previous behavioral evidence shows that increasing vocabulary knowledge diminishes the ability to associate novel visual items with phonotactically non-native labels or non-linguistic sounds (Graf Estes et al., 2011). There are only a few previous ERP studies that investigated brain signals in response to phonotactically legal *versus* illegal words in 12–20 month old infants (Friedrich & Friederici, 2005; Mills et al., 1997; Steber & Rossi, 2020). However, in these ERP studies either stimulus properties or concurrent comprehensive and expressive language skills were not fully controlled or systematically analyzed. The current study aims to clarify whether the magnitudes and the timings of the ERPs in response to pseudowords and nonwords are dependent on vocabulary knowledge to further understand the role of vocabulary in nonnative word processing.

In the present study, 24-month-old, French-learning toddlers were presented with known words, pseudowords and nonwords during the experiment in a non-referential context and their comprehensive and expressive vocabulary skills were evaluated by a parental questionnaire. The participants were presented with four different pseudowords (e.g., “meautai”), four phonotactically illegal nonwords (e.g., “zbaiton”), and four familiar words in French (e.g., “bateau”, boat). Our aim was to investigate how comprehensive and productive vocabulary skills contribute to the magnitudes and the timings of the ERPs in response to phonotactically legal and illegal words in French-learning toddlers. Based on earlier behavioral findings (Graf Estes et al., 2011), we expected that 24 month old French-learning children with higher vocabulary skills would exhibit a larger difference in the amplitudes between the word types indicating a greater sensitivity to word nativeness and meaning also in a non-referential task. Second, we aimed to investigate whether the ERPs are differentially modulated in response to pseudowords and nonwords during the course of the experiment. A short exposure to previously unknown words has been shown to augment the magnitude of the N200-500 component in 10- to 12-month-olds (e.g., Goyet et al., 2010; Kooijman et al., 2005) while in older infants an increase in the amplitudes of the N200-500 component for novel words was observed only after a referential training task (Mills, Plunkett, Prat, & Schafer, 2005). We expected modulations to occur in response to phonotactically legal pseudowords but not in response to phonotactically illegal nonwords.

2. Material and methods

2.1. Participants

The final participant sample included twenty-three (17 girls) 24-month-old children (min: 23 months 7 days, max: 25 months 5 days, mean: 24 months 9 days). All children came from monolingual French-speaking families in the Parisian region. They were recruited through a database of parents who previously volunteered to participate in child development studies. All children were born full-term and none of them suffered from any known hearing or language impairment. Also, there was no atypical development of language in the families. The mean number of years for maternal education was 16 (range from 11 to 19 years). Parents gave written informed consent before participation. Twenty-four other participants were tested but their data were rejected due to noisy (less than ten accepted trials in one experimental condition) electroencephalogram (EEG) recording (n = 14), due to technical problems while recording (n = 1), or refusal to put on the EEG cap (n = 9).

The French translation of the MacArthur-Bates Communicative Development Inventory for Words and Sentences (CDI; Fenson et al., 1993) was used to measure the productive vocabulary size. The parents were asked to fill the inventory at home during the two weeks following the study. The mean number of produced words was 274 (SD = 190, range from 16 to 686 words) and the mean number of comprehended words was 496 (SD = 143, range from 262 to 751 words). The mean numbers and the ranges were similar to those reported in earlier studies testing French-learning children of the same age (e.g., Helo, Azaiez, & Ra¨ma¨, 2017; Helo, van Ommen, Pannasch, Danteny-Dordoigne, & R¨am¨a, 2017; R¨am¨a et al., 2013). Based on the median split (467 words for comprehension) of the comprehensive vocabulary inventory scores, the participants were divided into comprehensive language groups: normal-to-high comprehenders (9 girls) and normal-to-low comprehenders (8 girls). Independently, based on the median split (243 words for pro- duction) of the productive vocabulary inventory scores, the participants were divided into productive language groups: normal-to-high producers (11 girls) and normal-to-low producers (6 girls). Children in the low comprehender group comprehended on average 378 words (SD = 66, range 262–449 words) and in the low producer group produced on average 120 words (SD = 77, range 16–231 words) words while children in the high comprehender group comprehended on average 605 words (SD = 99, range 467–751 words) and in the high producer group produced on average 415 words (SD = 145, range 243–686 words). The study was conducted in conformity with the declaration of Helsinki and approved by the Ethics Committee of the University of Paris Descartes.

Table 1
Average biphoneme frequency, word frequency and duration of the stimuli.

	AvbiF	WordF	Duration (ms)
Known Words			
ballon/balɔ̃/	6469	27	506
maison/mɛzɔ̃/	6371	570	496
bateau/bato/	4209	107	585
cheveux/ʃəvø/	2907	116	657
Means	**4989**	**205**	**561**
Native Pseudowords			
lechon/ləʃɔ̃/	786	0	487
vabeux/vabø/	3600	0	533
meautai/motɛ/	5449	0	523
bonsa/bɔ̃za/	1285	0	561
means	**2780**	**0**	**526**
Nonwords			
vchonbe/vʃɔ̃bə/	397	0	628
chbeula/ʃbøla/	5208	0	627
bmeausai/bmozɛ/	1703	0	690
zbaiton/zbɛtɔ̃/	4059	0	637
means	**2842**	**0**	**646**
Total means			**578**
SD			69

2.2. Stimuli

The audiostimuli consisted of three types of CVCV or CCVCV words: (a) familiar French words (ballon/balɔ̃/(ball), cheveux/ʃəvø/ (hair), maison/mɛzɔ̃/(house), bateau/bato/(boat)), (b) pseudowords (lechon/ləʃɔ̃, vabeux/vabø, meautai/motɛ, bonsa/bɔ̃za, and (c) nonwords (vchonbe/vʃɔ̃bə, chbeula/ʃbøla, bmeausai/bmozɛ, zbaiton/zbɛtɔ̃ (Table I). Words were selected from three databases: Cross Linguistic Lexical Norms (cdi-clex.org), Stanford Word bank (wordbank.standford.edu) and from our own BabyLab database. Before the experiment, the parents were sent a questionnaire and asked to evaluate if their child understood and/or produced the (familiar) words used in our experiment (among nine other words). They were also asked to express their confidence about the judgement for each word with a 5-point scale (*I am sure my child knows the word, I am somewhat confident that my child knows the word, I don't know, I am somewhat confident that my child does not know the word, I am sure my child does not know word*). Three parents were not sure whether their child knew one of the words. These children were presented with a visual display of four images, and were asked to point to the correct image after naming. Two of them were able to point to the correct image and were included, one could not, and he was excluded.

Pseudowords and nonwords were constructed by swapping phoneme positions between two word pairs: ballon/balɔ̃and cheveux/ ʃəvø, and maison/mɛzɔ̃and bateau/bato). As an example, pseudoword/lechon/was constructed from the words/ballon/and/cheveux/ by combining the third phoneme of ballon/balɔ̃, the second phoneme of cheveux/ʃəvø, the first phoneme of cheveux/ʃəvø and the fourth phoneme of ballon/balɔ̃. Three other pseudowords and also CCVCV nonwords were constructed in a similar manner but an additional consonant was added to CCVCC words to create an illegal onset consonant cluster in French (Dell, 1995). There was no meaning in any of the pseudo- or nonwords. Bi-phoneme (token) frequencies were retrieved from the database Lexique (New, Pallier, Brysbaert, & Ferrand, 2004). Average phoneme frequencies and word durations (ms) are shown in Table I. The duration of words varied between 487 ms and 690 ms (mean duration 578 ms, SD = 69 ms). Mean durations of familiar, pseudowords, and nonwords were 561 ms, 526 ms, and 646 ms, respectively.

The words were recorded with TASCAM Linear PCM Recorder (DR-07MKII). The speaker was a female native French phonetician, and she pronounced the words written in the phonetic alphabet. She was asked to pronounce the words slowly, clearly and as neutral as possible. The stimuli were normalised with Praat software (version 6.0.28).

2.3. Procedure

Before the testing, parents received a picture book that explained in a child-directed manner what happens during their laboratory visit (e.g., EEG capping, testing session). This book was meant to help both parents and children to be prepared for the testing session. After arriving at the laboratory, the children were allowed to play in the laboratory environment, and they were also familiarized with the EEG cap. During the experiment the child sat on the lap of a parent in a dimly lit room at 70 cm from a computer screen and two loudspeakers from which the sound was delivered. Parents were instructed not to communicate with the child during the experiment. Children were allowed to watch a silent cartoon on the screen throughout the experiment or to play with small toys positioned on the table in front of them during the experiment. Each word (12 words) was presented 60 times during the experiment. Each word type (familiar words, pseudowords and nonwords) included four examples, thus, each child heard each word type 240 times and the total number of stimuli was 720. The presentation order was pseudo-randomised (with consecutive sets of 12 trials) to ensure an even distribution of each word type during the experiment. The same word was never repeated more than twice. The mean stimulus onset asynchrony (SOA) was 1000 ms with a jitter ranging from 950 to 1050 ms. The experiment lasted about 12 min.

2.4. EEG recording and pre-processing

Continuous electroencephalogram (EEG) was recorded (band-pass was 0.1–100 Hz, sampling rate was 250 Hz) from 128 electrodes using a Geodesic Sensor Net (GSN, NetStation EGIS V2.0). Impedances were kept below 50 kΩ. EEG was filtered (0.3–30 Hz), segmented (900 ms, beginning 100 ms before target word onset), and ocular artefacts were removed with an ocular artefact removal (OAR) algorithm (Gratton, Coles, & Donchin, 1983). The 100-ms pre-stimulus period determined the baseline for amplitude measures. The epochs including eye-movement artefacts, using the electrodes above and below the eyes, as well as motion artefacts, exceeding ±180 lV in any channel were excluded. The epochs with more than 30% contaminated channels were also rejected. Individual bad channels were replaced using spherical spline interpolation.

The data was divided into three equal bins according to the number of repetitions of each word type. Each bin consisted of twenty repetitions of each word, thus 80 repetitions of each word type, and lasted about 4 min. The ERPs were analyzed for early, middle and late bins. To obtain ERPs, the epochs were averaged separately for each subject, word type (known word, pseudoword, nonword), and phase (early, middle, late). The averaged waveforms were re-referenced to the average of mastoids and baseline corrected. The average waveforms were grand-averaged across all participants. The mean number of accepted EEG epochs was 46 (range: 23–73; SD = 15), 46 (range: 20–73; SD = 15), and 45 (range: 20–72; SD = 16) for the known words, native pseudowords, and non-native pseudowords, respectively. The mean number of accepted EEG epochs was 48 (range: 25–72; SD = 16), 46 (range: 15–72; SD = 17), and 43 (range: 16–73; SD = 18) for the early, middle, and late bin, respectively. The mean number of accepted trials was not significantly different among the word types (one-way ANOVA: $F(2, 68) = 0.004$, $p = 0.996$) or bins (one-way ANOVA: $F(2, 206) = 0.485$, $p = 0.618$).

2.5. Data and statistics analyses

Similarly to previous literature (e.g., Bosseler et al., 2020; Friedrich & Friederici, 2005; Kooijman et al., 2005; Mills et al., 1997, 1993), the following three measurement windows were identified from our data: early positivity (time window of 100–250 ms), N200 (time window of 250–500 ms) and late negativity (time window of 500–800 ms). Mean amplitudes were measured over the time-windows post stimulus, relative to a − 100 to 0 ms prestimulus baseline period.

Repeated measures analysis of variance (ANOVA) included Word Type (known word, pseudoword, nonword), Phase (early, middle, late), Recording Area (frontal, parietal) and Hemisphere (left, right) as within-subject factors and Productive or Comprehensive Vocabulary Group (separately) as between-subject factors. The mean amplitudes extracted from 16 electrodes over the frontal and the parietal recording areas were included in the statistical analyses. The frontal and the parietal recording sites included the following electrode positions: 12, 13 (FC1), 18, 19 (F1), 20, 24 (F3), 28 (FC5), and 29 (FC3) (frontal left), 5, 112 (FC2), 10, 4 (F2), 118, 124 (F4), 117 (FC6), and 111 (FC4), (frontal right), 52 (P5), 53, 59 (P7), 60 (P3), 61 (P1), 65 (PO7), 66, and 67 (PO3) (left parietal), and 92 (P6), 86, 91 (P8), 85 (P4), 78 (P2), 90 (PO8), 84, and 77 (PO4) (right parietal). The statistical analyses were conducted with SPSS (IBM SPP statistics, version 24) and the Greenhouse-Geisser correction was applied for non-sphericity when appropriate.

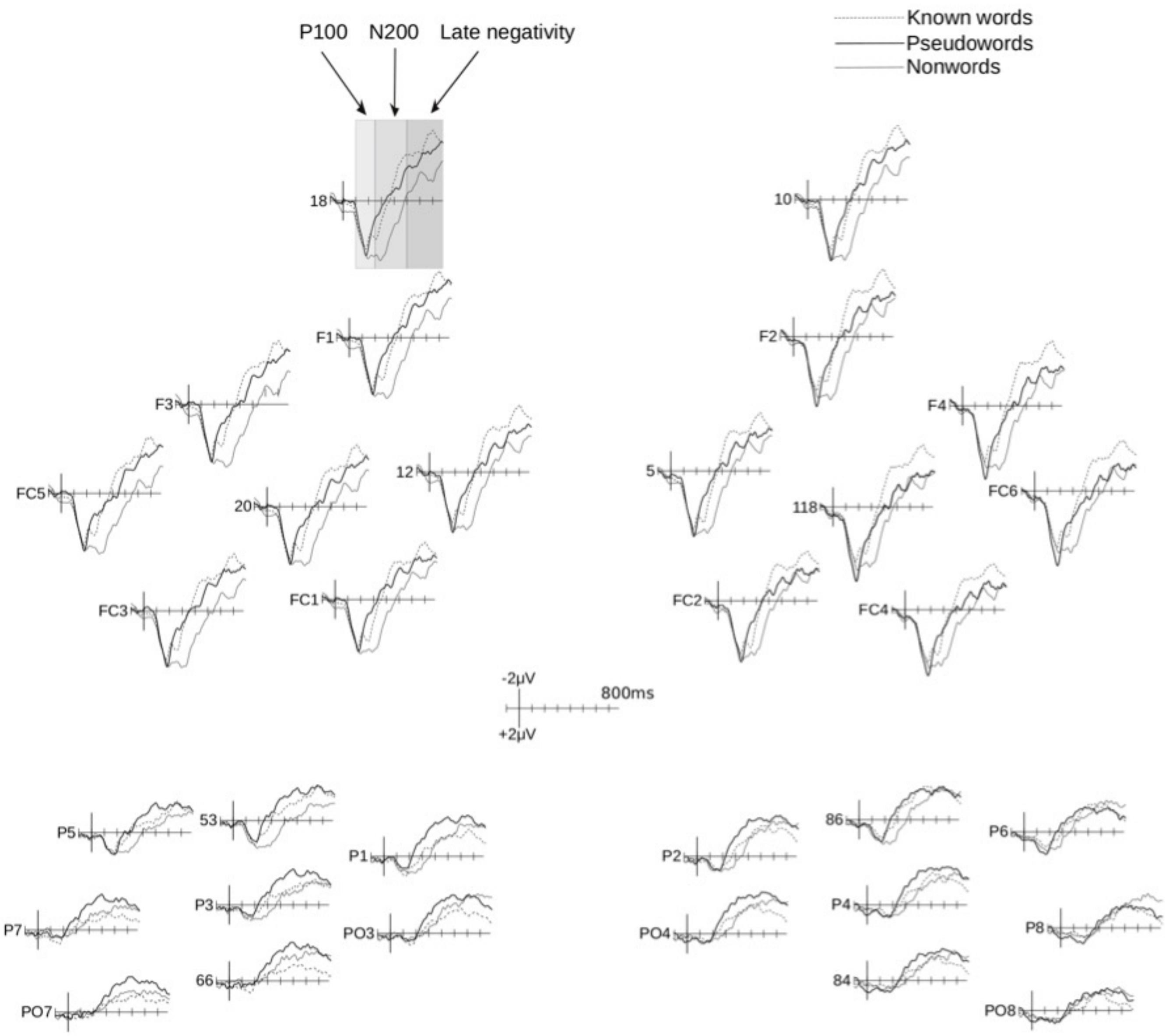

Fig. 1. The grand-average ERPs to known words (dashed lines), pseudowords (thick lines), and nonwords (thin lines) over the frontal and parietal recording sites. Vertical lines indicate word onset. The light, medium, and dark grey boxes indicate the time windows for Positivity (100–250 ms), N200 (250–500 ms), and late negativity (500–800 ms) amplitude analyses, respectively. The x-axis of the scale is from − 100 ms to 800 ms with respect to word onset.

3. Results

3.1. Early positivity (P100)

The amplitudes of the P100 were slightly more pronounced for nonwords (mean = 2.52 μV, SD = 3.87 μV) than for known words (mean = 2.10 μV, SD = 3.65 μV) and pseudowords (mean = 2.12 μV, SD = 3.61 μV). There was, however, no main effect of Word Type ($F(2, 44) = 0.52$, $p = 0.588$, $\eta^2 = 0.023$) or Hemisphere ($F(1, 22) = 1.48$, $p = 0.236$, $\eta^2 = 0.063$) on the amplitudes of positivity, but the interaction between Word Type and Hemisphere reached the significance ($F(2, 44) = 3.48$, $p = 0.041$, $\eta^2 = 0.137$). In further analyses, however, significant main effect of Word Type were not observed either over the left ($F(2, 44) = 0.92$, $p = 0.402$, $\eta^2 = 0.040$) or the right ($F(2, 44) = 0.52$, $p = 0.590$, $\eta^2 = 0.023$) hemisphere, suggesting that the P100 is not modulated by word type (Fig. 1).

When we re-examined the positivity with Productive and Comprehensive Vocabulary Groups as between subject variables, we observed, besides the interaction between Word Type and Hemisphere (Comprehension: $F(2, 42) = 3.40$, $p = 0.045$, $\eta^2 = 0.139$; Production: $F(2, 42) = 3.37$, $p = 0.046$, $\eta^2 = 0.138$), an interaction between Word Type and Comprehensive Vocabulary Group ($F(2, 42) = 3.85$, $p = 0.037$, η2 = 0.155). The amplitudes were more positive for nonwords than for pseudowords in the normal-to-low comprehenders ($t(10) = -2.31$, $p = 0.044$, d’ = 0.773) while in the normal-to-high comprehenders, there was a tendency for more positive amplitudes for pseudowords than for nonwords ($t(11) = -2.09$, $p = 0.061$, d’ = 0.624). Also, an interaction between Hemisphere and Productive Vocabulary Group ($F(1, 21) = 5.96$, $p = 0.024$, η2 = 0.221) was found. However, even though the am- plitudes were larger over the right hemisphere in the high-vocabulary group and larger over the left hemisphere in the low-vocabulary group, significant differences between the left and right hemispheres in either vocabulary group were not found (all $p > 0.05$).

3.2. N200

The amplitudes of the N200 were more negative for known words (mean = − 0.98 μV, SD = 4.61 μV) and pseudowords (mean = − 1.22 μV, SD = 4.80 μV) than for nonwords (mean = 1.02 μV, SD = 4.58 μV). The main effect of Word Type ($F(2, 44) = 9.95$, $p = 0.000$, $\eta^2 = 0.311$) and the interaction between Word Type and Recording Area was significant ($F(2, 44) =$

12.35, $p < 0.001$, $\eta^2 = 0.359$) on the amplitudes of the N200. The main effect of Word Type was observed over the frontal ($F(2, 44) = 17.98$, $p < 0.001$, $\eta^2 = 0.450$) but not over the parietal ($F(2, 44) = 2.85$, $p = 0.072$, $\eta^2 = 0.115$) recording sites (Figs. 1 and 2). The amplitudes were significantly more negative for known words than for nonwords ($t(22)=-5.03$, $p<0.001$, $d'=0.973$) over the frontal recording sites (Fig. 3 A). The difference between pseudowords and nonwords was also significant ($t(22) = -4.63$, $p < 0.001$, $d' = 0.907$) while no difference was found between known words and pseudowords ($t(22)=-0.97$, $p=0.341$, $d'=0.199$). No other main effects (Phase or Hemisphere) or interactions were observed.

When we re-examined the N200 component with Productive and Comprehensive Vocabulary Groups as between subject variables over the frontal recording sites, we observed, besides the main effect of Word Type (Comprehension: $F(2, 42) = 19.18$, $p < 0.001$, $\eta^2 = 0.477$; Production: $F(2, 42) = 18.14$, $p < 0.001$, $\eta^2 = 0.463$), the main effect of Comprehensive Vocabulary Group ($F(1, 21) = 9.18$, $p = 0.006$, $\eta 2 = 0.304$). The amplitudes were significantly more negative in the normal-to-low than in the normal-to-high comprehenders ($t(21) = 3.03$, $p = 0.006$, $d' = 0.814$, Fig. 3 C). Even though the interaction between Word Type and Vocabulary Group was not significant ($F(2, 42) = 2.20$, $p = 0.132$, $\eta 2 = 0.095$), we calculated correlations between vocabulary scores and differences in am- plitudes between two word types (known words *minus* pseudowords, known words *minus* nonwords, and pseudowords *minus* non-words). The results showed that the number of produced words correlated with the difference in amplitudes between known words and pseudowords. The bigger the difference was in the amplitudes (more negativity for known words than for pseudowords), the bigger the productive vocabulary size was ($r = -0.597$, $p = 0.003$) indicating that children with higher vocabulary skills were more sensitive to word meaning. No other correlations were found.

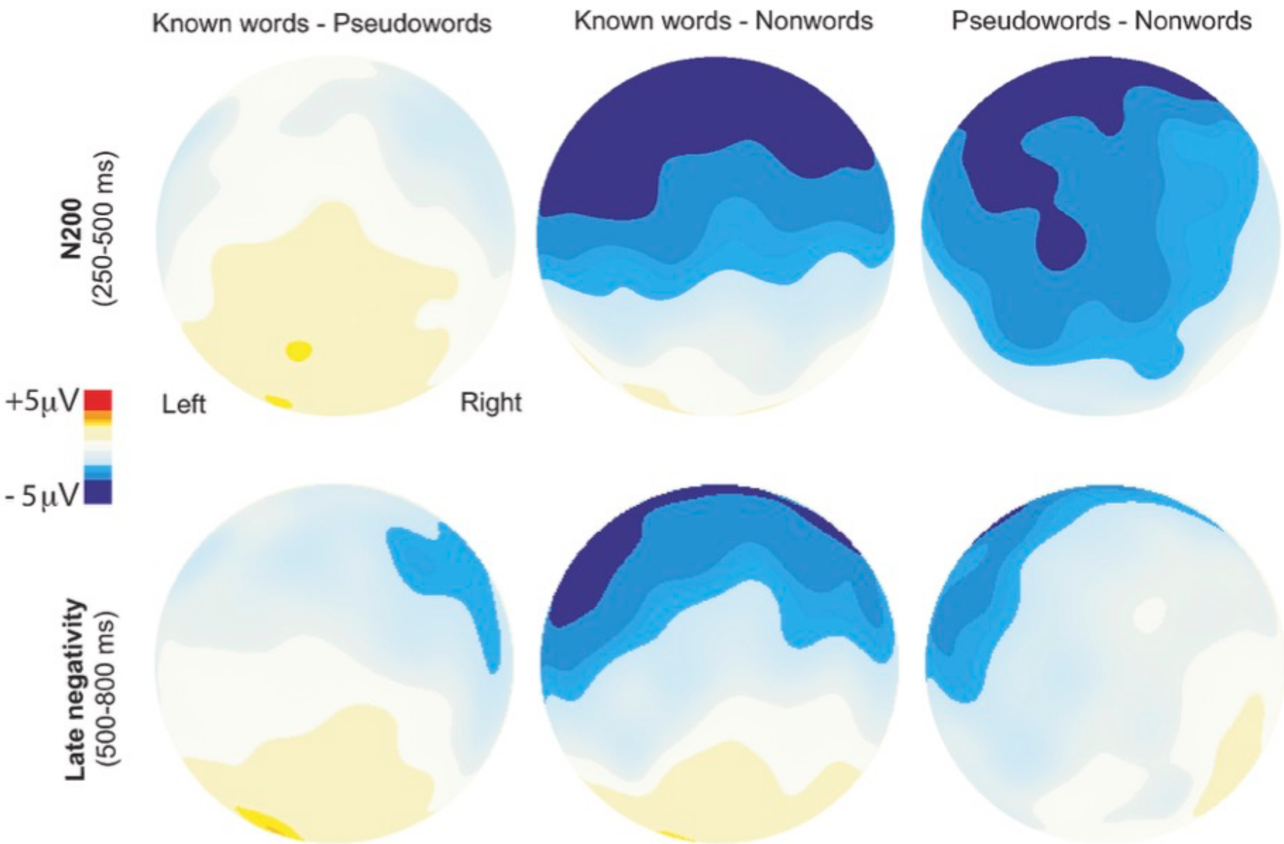

Fig. 2. Isopotential maps showing the across-participants calculated scalp distributions of the difference between the ERPs to (known words – pseudowords), (known words – nonwords), (pseudowords – nonwords), separately for the N200 (250–500 ms after word onset) and the Late negativity (500–800 ms after word onset). The head viewed from above. L = left, R = right.

3.3. Late negativity

The amplitudes of the late negativity were more pronounced for known words (mean = − 3.45 µV, SD = 5.50 µV) and for pseudowords (mean = − 3.25 µV, SD = 5.03 µV) than for nonwords (mean = − 2.36 µV, SD = 4.84 µV). The main effect of Word Type ($F(2, 44) = 2.51$, $p = 0.104$, $\eta^2 = 0.102$) was not significant on the amplitudes of the late negativity, but the interaction between Word Type and Recording Area reached significance ($F(2, 44) = 8.95$, $p = 0.001$, $\eta^2 = 0.289$). Similarly to the N200, the main effect of Word Type was observed over the frontal ($F(2, 44) = 5.58$, $p = 0.014$, $\eta^2 = 0.202$) but not over the parietal ($F(2, 44) = 2.01$, $p = 0.147$, $\eta^2 = 0.084$) recordingsites (Figs.1 and 2).The amplitudes were more negative for known words than for nonwords (t(22)=− 2.67, p=0.014, d'= 0.480) over the frontal recording sites (Fig. 3 B). The difference between pseudowords and nonwords was almost significant (t(22) = − 2.07, p=0.050, d'=0.397) while no difference was found between known words and pseudowords (t(22)=− 1.88, p=0.074, d'= 0.374). No other main effects (Phase or Hemisphere) or interactions were observed.

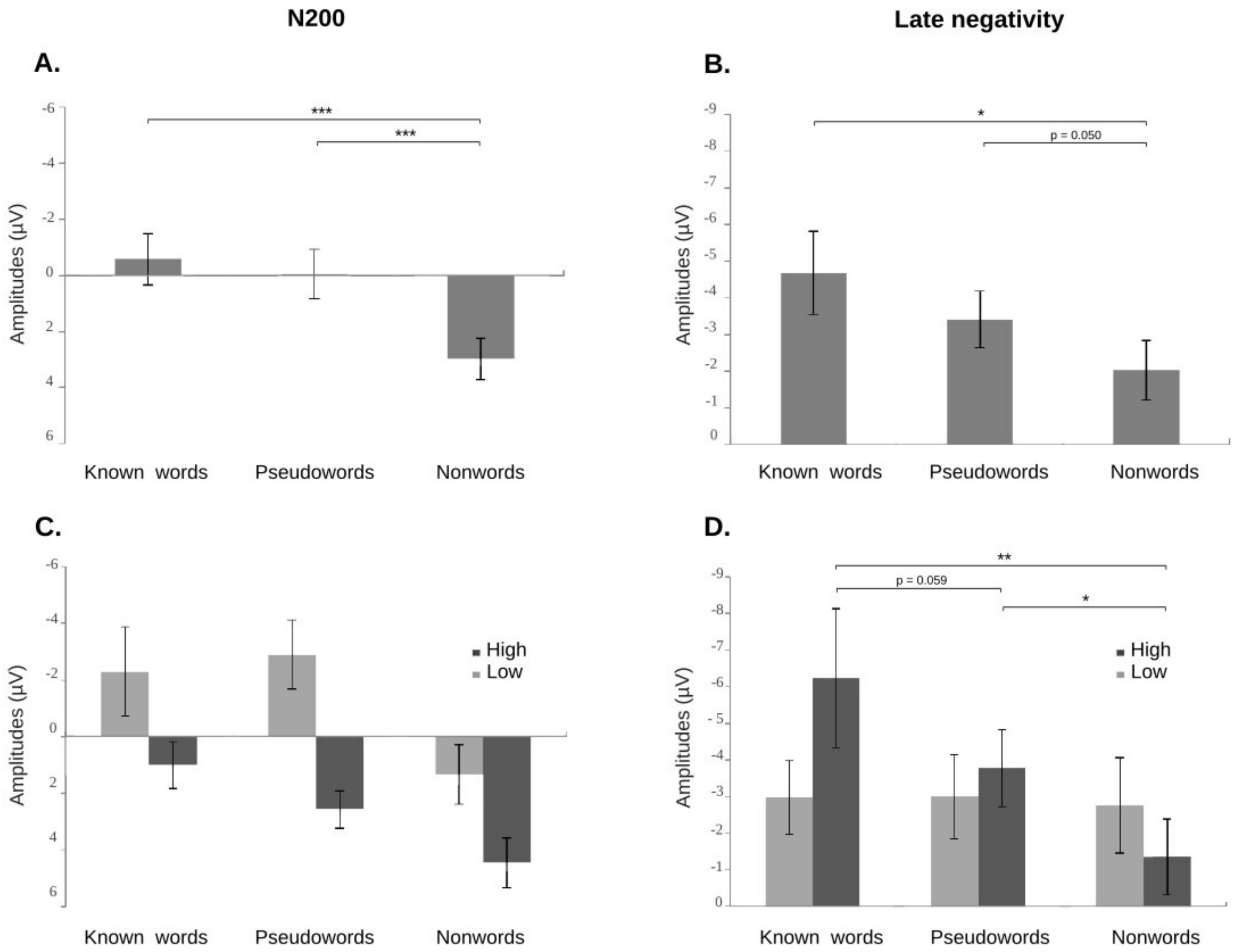

Fig. 3. A. Mean amplitudes for the N200 over the frontal recording sites for known words, pseudowords and nonwords in all participants. **B.** Mean amplitudes for the late negativity over the frontal recording sites for known words, pseudowords and nonwords in all participants. **C.** Mean am- plitudes for the N200 over the frontal recording sites for known words, pseudowords and nonwords in the normal-to-low (light grey bars) and normal-to-high (dark grey bars) word comprehenders. **D.** Mean amplitudes for the late negativity over the frontal recording sites for known words, pseudowords and nonwords in the normal-to-low (light grey bars) and normal-to-high (dark grey bars) word producers. Vertical bars indicate SEMs * p < 0.05, **p < 0.01, ***p < 0.001.

When we re-examined the late negativity with Productive and Comprehensive Vocabulary Groups as between subject variables over the frontal recording sites, we observed, besides the main effect of Word Type (Comprehension: $F(2, 42) = 5.28$, $p = 0.017$, $\eta^2 = 0.201$; Production: $F(2, 42) = 6.11$, $p = 0.008$, $\eta^2 = 0.225$), a significant interaction between Word Type and Productive Vocabulary Group ($F(2, 42) = 5.10$, $p = 0.016$, $\eta 2 = 0.196$). There was a significant difference between amplitudes for known words and nonwords ($t(11) = -3.51$, $p = 0.005$, $d' = 0.949$), and pseudowords and nonwords ($t(11) = -2.73$, $p = 0.020$, $d' = 0.782$) in normal-to-high word producers (Fig. 3 D). Also, the difference between known words and pseudowords almost reached the significance ($t(11) = -2.11$, $p = 0.059$, $d' = 0.652$). No significant differences were found in the normal-to-low word producers (all $p > 0.05$). The results indicate that the late negativity was modulated as a function of word type only in the group of normal-to-high producers. Moreover, there was a tendency for correlation between productive vocabulary skills and the difference in amplitudes between words and pseudowords. The bigger the difference was in the amplitudes, the bigger the productive vocabulary size was. However, the correlation did not quite reach statistical significance ($r = -0.402$, $p = 0.057$). No other correlations were found.

4. Discussion

In the present study, we investigated the effects of comprehensive and productive vocabulary skills on brain activity in response to known words, pseudowords and nonwords during the course of an ERP experiment in French-learning toddlers. The N200 was more pronounced for pseudowords than for nonwords while no difference was found between known words and pseudowords. The amplitude difference between known words and pseudowords was, however, correlated with the productive vocabulary. Toddlers with a higher vocabulary score exhibited a bigger difference than toddlers with a lower vocabulary score. Also, the amplitude of the frontally distributed late negativity, measured in the time window of 500 ms–800 ms, was modulated by an interaction between word type and vocabulary group: children with higher (productive) vocabulary knowledge exhibited a gradient pattern of activity in response to different word types while children with lower vocabulary skills responded similarly to each word type. There are only a few earlier ERP studies investigating brain signals in response to phonotactically illegal nonwords in an explicit (Friedrich & Friederici, 2005) or an implicit (Mills et al., 1993; Steber & Rossi, 2020) experimental context in a similar age group. The effects of concurrent vocabulary skills were not systematically evaluated in these studies. In accordance with earlier findings, our results showed that the N200 and late negativity were larger for pseudowords than for nonwords, suggesting that phonotactically legal pseudowords activate lexical search more efficiently than illegal nonwords also in 24-month-old toddlers. In addition, our results provided further evidence about the influence of concurrent vocabulary skills on processing of pseudowords and nonwords.

A negative component around 200–500 ms after word onset has been earlier associated with word recognition, word meaning, familiarity, and learning (Friedrich & Friederici, 2005; Goyet et al., 2010; Kooijman et al., 2005, 2009; Männel & Friederici, 2010; Mills et al., 1993, 1997). Our results showed that the vocabulary group had the main effect on the N200 amplitudes: the amplitudes were more negative for normal-to-low than for normal-to-high comprehenders, regardless of the word type. This finding is interesting in the light of previous evidence showing that the N200 in response to lexical priming (higher negativity for congruent *versus* incongruent lexical items) was shown to be more pronounced in infants at a familial risk of dyslexia (Torkildsen, Syversen, Simonsen, Moen, & Lindgren, 2007b) and in infants with lower language skills (Friedrich & Friederici, 2006). The enhanced lexical priming effect in children with lower vocabulary skills was suggested to be due to a slower or more effortful lexical-phonological processing (Frie- drich & Friederici, 2006). Our results further suggest that more effortful processing in children with lower vocabulary skills might explain the increased N200 also in a non-referential experimental condition. The N200-500 is typically observed over the frontal sites, and it is larger for familiar or known words compared to unknown words. In the current experiment, the negative response between 250 and 500 ms was larger for phonotactically familiar compared to phonotactically unfamiliar words but equally strong for known words and for pseudowords. A similar finding regarding known words and unfamiliar words has been earlier reported in 17- to 21-month-old English learning infants (Mills et al., 2005). The authors suggested that the use of infant directed speech in their study may have boosted attention towards the unfamiliar words thereby masking effects of semantic processing of familiar words. In our study, the words were not pronounced in infant directed speech so participants' word knowledge is a more likely explanation than a boosted attention towards pseudowords. The amplitude difference between known words and pseudowords was shown to be corre- lated with productive vocabulary skills, demonstrating that the higher the vocabulary score was, the bigger the difference was in amplitudes between known and pseudowords. In toddlers with higher vocabulary scores, the amplitude was more negative for words than for pseudowords while in toddlers with lower vocabulary scores, the amplitudes for known and pseudowords were similar than for pseudowords in high producers. Even though all the participants, independent of their vocabulary score, knew the experimental words, the strength of word representations as well as the age of their acquisition might have differed in the two groups, that could explain the correlation effect.

The amplitude of the late negativity, measured in the time window of 500–800 ms, was modulated by an interaction between lexical status and vocabulary group: children with higher (productive) vocabulary knowledge exhibited a gradient pattern of activity in response to different word types while children with lower vocabulary skills exhibited a similar responsiveness to each word type. Earlier research has shown that vocabulary skills modulate the occurrence (e.g., Rämä et al., 2013; Torkildsen et al., 2009), distribution (e.g., Mills et al., 1993, 2005), and timing (e.g., Junge, Kooijman, et al., 2012) of the language-related ERPs. For instance, 20-month-old toddlers with high productive vocabularies presented an N400 incongruity effect to violations of newly trained asso- ciations between novel words and pictures, whereas 20-month-olds with low productive vocabularies did not (Torkildsen et al., 2009). Also, the N400 priming effect for spoken words was obtained in 24-month-olds and a subgroup of 18-month children with normal-to-high productive skills, which suggests that more advanced productive vocabulary skills contribute to the taxonomic or- ganization of the developing lexical-semantic system (Rämä et al., 2013). Children with lower vocabularies have been shown to present a bilateral or a more scattered distribution of ERPs in response to known and unknown words than children with higher vocabularies, suggesting that neural networks become more specialized with increasing vocabulary skills (Mills et al., 1993, 2005). Moreover, it has been shown that, even though both high and low vocabulary groups displayed a familiarity effect at the time window of 200 ms–500 ms, only infants with greater vocabularies continued to exhibit the effect at a later time window from 500 ms to 650 ms which led the authors to suggest that the extended response might reflect an additional processing stage related to lexical search for the word (Junge, Kooijman, et al., 2012). Our results demonstrated the amplitude difference between pseudowords and nonwords both at the earlier and the later time windows, suggesting that both word (phonotactic) familiarity and lexical search processes were affected by vocabulary knowledge. However, even though the ERP technique provides a temporally accurate measure to distinguish among different (linguistic) processes and track their time courses (Kutas & Federmeier, 2011), several cortical processes and components contribute to the scalp distribution of the ERP responses (for review, see Näätänen & Picton, 1987). Accordingly, our results do not suggest that there are two distinct neural processes and further investigations are needed to distinguish between different cognitive and neural events underlying the waveforms.

In accordance with earlier findings in 11- (Thierry et al., 2003) and 20- (Mills et al., 1993) month-olds, the P100 was insensitive to word type also in our study. Previously, the P100 was shown to be more pronounced over the left hemisphere in 20-month-olds (Mills et al., 1993) and in 13- to 17-month-olds with higher comprehension skills (Mills et al., 1997) while in 13- to 17-month-olds with lower comprehension skills, the P100 was bilaterally distributed (Mills et al., 1997), suggesting that age and vocabulary skills contribute to a more focalized, left-hemispheric, distribution of activity. In our study, the distribution of the P100 was not asymmetrically distributed. Also, none of the components were modulated during the course of the experiment. Earlier studies have demonstrated that only a few repetitions of novel words cause an increase in negativity both in explicit (Friedrich & Friederici, 2011; Junge, Cutler, & Hagoort, 2012) and implicit (e.g., Kooijman et al., 2005; Kooijman et al., 2009) tasks, at least in younger infants. In older infants, an increase in N200-500 amplitude was observed only when the novel words were paired with new objects, not when repeated in isolation (Mills et al., 2005). Similar to our finding, a greater negativity in response to pseudowords than to nonwords (when repeated in isolation) was not modulated during the course of the experiment in 18-month-olds (Steber & Rossi, 2020). There are at least two possibilities to explain the lack of modulation in our study: it is possible that the modulation in toddlers occurs only in the presence of a referential learning, or modulation occurs already after presentation of a few items and thus not detectable in our study.

To conclude, our results demonstrated that frontally distributed N200 and late negativity were modulated by word type and vo- cabulary skills. The responses were more pronounced for pseudowords than for nonwords while no difference was found between known words and pseudowords. However, vocabulary knowledge affected toddlers' reactivity to different word types: only toddlers with larger vocabularies exhibited a gradient pattern of signal magnitude in response to different word types. It has been earlier suggested that children with less vocabulary knowledge might have less detailed phoneme perception (Graf Estes et al., 2011) or weaker memory representations for native phoneme clusters (Friedrich & Friederici, 2006). Also, accumulation of vocabulary and phonotactic knowledge may limit the pertinent lexical candidates to be learnt and children with larger vocabulary are more likely to reject phonotactically illegal labels in a word learning task (Graf Estes et al., 2011). Based on our findings, we further propose that vocabulary knowledge contributes to the processing of native-like and non-native-like words in a non-referential task both at the level of word recognition and lexical search. Our results also support the use of ERP technique to investigate temporal sequences of linguistic processes in developmental populations.

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Study II

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Brain signatures of native and non-native words in bilingual French-dominant toddlers: the effect of vocabulary knowledge

Aygün, O.[a] & Rämä, P.[a,b]

[a] Université de Paris, Paris, France, [b] Université de Paris, INCC UMR 8002, CNRS, F-75006 Paris, France

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Abstract

Bilingual infants demonstrate behavioural flexibility compared to their monolingual peers in accepting non-native sounds as novel labels in word learning tasks. Here, we investigated whether vocabulary knowledge and the amount of language input in bilingual toddlers affect event-related potentials in response to pseudowords and nonwords. The participants were exposed to 15% to 50% of their linguistic input to another language than French. The amplitudes of N200 and late negativity were more pronounced for pseudowords than for nonwords, suggesting a reduced activation of the lexical networks for words with a phonotactically illegal consonant structure. Amount of comprehensive vocabulary, however, contributed to the brain signals: only toddlers with lower comprehension skills responded differentially to pseudowords and nonwords, while toddlers with higher comprehension skills responded equally to two word types. The results demonstrated that bilingual toddlers only with higher vocabulary skills considered phonotactically legal and illegal nonsense words as similarly potential word candidates.

Keywords: Lexical processing, bilingual, vocabulary skills, phonotactics, event-related potentials, developing brain, toddlers

1. Introduction

Even though bilingually raised infants are shown to reach certain language developmental milestones, such as babbling, first word productions, and vocabulary development, at a similar age as their monolingual peers (e.g., Pearson, Fernandez, & Oller, 1993; Oller, Eilers, Urbano & Cobo-Lewis, 1997; Petitto, Katerelos, Levy, Gauna, Tetreault, & Ferraro, 2001; Genesee, 2006), there are differences in the developmental trajectories of early language acquisition in infants raised in monolingual and bilingual linguistic environments. For example, monolingually raised infants improve their discrimination ability of speech sounds between 6 and 12 months of age and simulteneously discrimination of non-native sounds declines (e.g., Werker & Tees, 1984; Kuhl, Stevens, Hayashi, Deguchi, Kiritani, & Iverson, 2006; for a review, see Werker, 2018). Bilingual infants are capable of discriminating between the sound contrasts in their both languages, but in contrast to monolingual infants, they remain sensitive also to nonnative contrasts during their second year of life (Burns, Yoshida, Hill, & Werker, 2007; Sundara, Polka, & Molnar, 2008; Petitto, Berens, Kovelman, Dubins, Jasinska, & Shalinsky, 2012; Garcia-Sierra, Ramırez-Esparza, & Kuhl, 2016; Singh, Loh, & Xiao, 2017; for review see, Höhle, Bijeljac-Babic, & Nazzi, 2019). During the first year of life, monolingual infants become also sensitive to language-specific phonotactic features, that is, permissible combinations of phonemes, of their native language (e.g., Friederici & Wessels, 1993; Jusczyk, Friederici, Wessels, Svenkerud & Jusczyk, 1993; Gonzalez-Gomez & Nazzi, 2012). Bilingual infants are capable of acquiring phonotactic regularities similarly to monolinguals, but they show a preference for phonotactically legal phoneme combinations of their dominant language (Sebastián-Gallés & Bosch, 2002).

Speech sound discrimination both in mono- and bilingual infants has shown to predict later vocabulary development. Better native speech sensitivity at 7.5 months predicted higher productive vocabulary score at the age of 18 and 24 months while sensitivity to non-native speech sounds predicted lower vocabulary score in monolingual infants (Kuhl, Conboy, Padden, Nelson & Pruitt, 2005; Kuhl, Conboy, Coffey-Corina, Padden, Rivera-Gaxiola & Nelson, 2008). A similar finding has been obtained in bilingual infants: a bigger amount of language exposure was associated with more pronounced brain signals in response to language-specific contrasts, and better vocabulary skills at 15 months of age (Garcia-Sierra, Rivera-Gaxiola, Percaccio, et al., 2011). There is also evidence that perceptual narrowing restrains later word learning in monolingual infants, that is, their ability to learn non-native words diminishes with age and increasing vocabulary knowledge during the second year of life. It has been shown that 14-month-old infants are capable of associating novel visual items with non-native sounds, such as phonotactically illegal words, click consonants, or non-native lexical tones while older infants (18- to 20-months), especially with higher vocabulary skills, associated only native sounds with novel pictures (Graf Estes, Edwards, & Saffran, 2011; May & Werker, 2014; Hay, Graf Estes, Wang, & Saffran, 2015). In contrast, bilingual infants demonstrate an extended period of flexibility to accept non-native words as potential word forms and behave similarly to monolinguals only a few months later (Graf Estes & Hay, 2015; Singh, 2018; Singh & Tan, 2021).

During the second year of life, both productive receptive and productive vocabulary knowledge increases. Language input has been shown to be related to (expressive) vocabulary development (for review, see Hoff & Core, 2013; Thordardottir, 2011; Hoff, Welsh, Place, Ribot, Grüter, & Paradis, 2014) and speed of on-line language processing (Hurtado, Grüter, Marchman, & Fernald, 2014). Bilingual children tend to have a smaller conceptual vocabulary and number of words known in each language while the total vocabulary of the two languages has been reported to be comparable to that of monolinguals (e.g., Bialystok, 2009; Hoff, Core, Place, Rumiche, Senor, & Parra, 2012; Core, Hoff, Rumiche, & Señor, 2013; Poulin-Dubois, Bialystok, Blaye, Polonia, & Yott, 2013). Increasing word knowledge during the second year of life has been associated with specialized electrophysiological activity. When monolingual infants were presented with known and unknown words, the amplitudes of two ERP components, the N200 and N375, were larger for known than for unknown words (Mills, Coffey-Corina, & Neville, 1993, 1997; Conboy & Mills, 2006). The N200 and N375 components were not, however, found for for backwardly presented words in 20-month-old English-learning infants (Mills et al., 1993) while in younger infants (13- to 17-months) no significant difference between unknown and backwardly presented words was found in a non-referential task (Mills et al., 1997). In another study, conducted in 18-month-olds, German-speaking infants were presented with monosyllabic pseudowords either with a phonotactically legal or illegal consonant onset structure (Steber & Rossi, 2020). The results demonstrated a larger negativity for legal than for illegal words over the anterior and posterior scalp positions in a time window of 500 ms to 1000 ms. In a referential context, a (short-lived) larger negativity for pseudowords than for nonwords was obtained over the frontal scalp positions in 12-month-olds while in the 19-month-olds, a larger broadly distributed negativity was found (Friedrich & Friederici, 2005). The broadly distributed negativity was suggested to reflect a more mature mechanism of semantic integration, in response to phonotactically legal, but not to illegal words (Friedrich & Friederici, 2005). In our recent ERP study, conducted in monolingual 24 month old toddlers, we investigated whether vocabulary knowledge contributes to the brain signals, especially the N200 and the late negativity, in response to pseudowords and nonwords (Aygün & Rämä, 2022). Based on earlier behavioral results (Graf Estes et al., 2011; May & Werker, 2014), we expected that monolingual toddlers with higher vocabulary skills would exhibit a larger difference in the amplitudes between the word types indicating a greater sensitivity to word nativeness and meaning. The results demonstrated that frontally distributed N200 and late negativity were modulated by word type and vocabulary skills. The responses were more pronounced for pseudowords than for nonwords while no difference was found between known words and pseudowords. Vocabulary knowledge affected toddlers' reactivity to different word types: as expected only toddlers with larger vocabularies exhibited a gradient pattern of signal magnitude in response to different word types, suggesting that vocabulary knowledge contributes to the processing of native-like and non-native-like words in a non-referential task both at the level of word recognition (modulation of the N200) and lexical search (modulation of the late negativity).

Vocabulary knowledge and language dominance contribute to the brain signals also in bilingual infants. Conboy and Mills (2006) measured the event-related potentials (ERPs) in response to words in each of the 19- to 22-month-old bilinguals' languages: children were presented with English and Spanish known and unknown words during a listening task. Children with higher conceptual vocabulary skills exhibited greater N200–400 and N400–600 amplitudes for known than for unknown words for both languages while children with lower vocabulary skills showed similar effects only for the dominant language. For the non-dominant language, the word familiarity effect was found in a later time window (from 600 to 900 ms) in children with lower vocabulary skills. Bilingual children of two to four years have shown to activate lexical-semantic representations, as indexed by the N400 component, similarly to their monolingual peers in their dominant language (Kuipers & Thierry, 2013, 2015; Sirri & Rämä, 2019) while non-dominant language was observed to activate different, more frontally distributed, neural resources in a within-language semantic priming task (Sirri & Rämä, 2019). There is also evidence that 18-

month-old bilingual infants activate lexical-semantic representations slower than their monolingual peers even in their dominant language (Sirri & Rämä, 2015; Rämä, Sirri & Goyet, 2018).

In the present study, our aim was to study whether dual language exposure contributes to the magnitudes of N200 and late negativity in response to pseudowords and nonwords in a non-referential listening task. Bilingual infants are generally exposed to a greater amount of phonotactic and lexical variation in their linguistic input than monolingual infants. Consequently, bilingual infants are shown to be behaviourally more flexible in accepting non-native sounds as novel labels for novel objects (Graf Estes & Hay, 2015; Singh, 2018; Singh & Tan, 2021) than monolingually raised infants (Graf Estes et al., 2011; May & Werker, 2014; Hay et al., 2015). Based on behavioural evidence, we expected that the patterns of brain signals in response to pseudowords and nonwords are similar in bilingual language learners. We also investigated whether vocabulary knowledge and the amount of language input in bilingual toddlers affect the magnitudes of ERPs.

2. Material and methods

2.1. Participants

The final participant sample included 46 (21 girls) 24-month-old children. The sample was divided into two groups: balanced bilinguals (n= 24, 12 girls, mean age 24 months) and exposed bilinguals (n= 22, 11 girls, mean age 24 months). All children came from families in the Parisian region. They were recruited through a database of parents who previously volunteered to participate in child development studies. All children were born full term and none of them suffered from hearing or language impairment. Also, there was no atypical development of language in the families. The mean number of maternal education years was 17 (range from 11 to 24 years). Parents gave written informed consent before participation. Forty-one other participants were tested but their data was rejected due to noisy electroencephalogram (EEG) recording (n = 20), due to technical problems while recording (n = 4), refusal to put on the EEG cap (n = 15), the child not knowing one of the words used in the experiment (n = 2).

Parents filled the Language Exposure Questionnaire (Bosh & Sebastián-Gálles, 1997) and estimated the amount of their child's total exposure to each language. Participants who received at least 30% exposure to Another Language were included in the Balanced Bilingual Group (mean exposure for French was 59% and for another language 41%). Of the 24 participants in this group, 16 were mostly exposed to French (55 to 70% of exposure time) and eight were equally (50%) exposed to both languages. Children in the Balanced Bilingual Group were raised in a family where the mother spoke French and the father Another Language (n = 3), the father spoke French and the mother Another Language (n = 7), or both parents spoke French and one parent also Another Language (n = 7). In six families, the child learned French in a day care and Another Language at home (in three of these families, both parents spoke some French at home also), and in one family, a mother raising the child alone spoke both languages. Participants who received less than 30% exposure (but more than 15%) to Another Language were included in the Exposed Bilingual Group. They were all exposed to French 75% to 85% of their language exposure time (mean exposure for French was 80% and for another language 20%). Children in the Exposed Bilingual Group were raised in a family where the mother spoke French and the father Another Language (n = 3), both parents spoke French and one parent also Another Language (n = 12, in 9 families the father spoke Another Language), both parents spoke French and Another Language (n = 2), or both parents spoke French and Grandfather Another Language (n = 1), or the child learned Another Language in a day care (n = 2). In two families, a mother raising the child alone spoke both languages. Children in both Language Groups were exposed to a large variety of different languages (altogether 21 different languages) such as Chinese (13 % of participants), English (11 %), Spanish and Arabic (9 % each), and German, Portugal, Russian, and Coreen (7 % each). The rest of the languages (e.g., Polish, Vietnam, Wolof, and Danish) were exposed to 2% to 4 % of participants.

The French translation of the MacArthur-Bates Communicative Development Inventory for Words and Sentences (CDI) was used to measure comprehensive and productive vocabulary size (Fenson et al., 1993).The parents were asked to fill the inventory either in the laboratory or at home during the two weeks following the study. Parents were given the French translation of the CDI but they were instructed to also include words that their child understood or said in their Another Language. The conceptual vocabulary score was calculated. Three families in both Language Groups did not return the questionnaire. The study was conducted in conformity with the declaration of Helsinki and approved by the Ethics Committee of the University of Paris Descartes.

2.2. Stimuli

The audiostimuli consisted of three types of CVCV or CCVCV words: (a) familiar French words (ballon / balɔ̃ / (ball), cheveux / ʃəvø / (hair), maison / mɛzɔ̃ / (house), bateau / bato / (boat)), (b) pseudowords (lechon / ləʃɔ̃, vabeux / vabø, meautai / motɛ, bonsa / bɔ̃za, and (c) nonwords (vchonbe / vʃɔ̃bə, chbeula / ʃbøla, bmeausai / bmozɛ, zbaiton / zbɛtɔ̃. Words were selected from three databases: Cross Linguistic Lexical Norms (cdi-clex.org), Stanford Word bank (wordbank.standford.edu) and from our own BabyLab database. Before the experiment, the parents were sent a questionnaire and asked to evaluate if their child understood and/or produced the (familiar) words used in our experiment (among nine other words).

Pseudowords and nonwords were constructed by swapping phoneme positions between two word pairs: ballon/balɔ̃ and cheveux/ʃəvø, and maison/ mɛzɔ̃ and bateau/bato). As an example, pseudoword /lechon/ was constructed from the words /ballon/ and /cheveux/ by combining the third phoneme of ballon/balɔ̃, the second phoneme of cheveux/ʃəvø, the first phoneme of cheveux/ʃəvø and the fourth phoneme of ballon/balɔ̃. Three other pseudowords and also CCVCV nonwords were constructed in a similar manner but an additional consonant was added to CCVCC words to create an illegal onset consonant cluster in French (Dell, 1995). There was no meaning in any of the pseudo- or nonwords. Bi-phoneme (token) frequencies were retrieved from the database Lexique (New, Pallier, Brysbaert, & Ferrand, 2004). The duration of words varied between 487 ms and 690 ms (mean duration 578 ms, SD = 69 ms). Mean durations of familiar, pseudowords, and nonwords were 561 ms, 526 ms, and 646 ms, respectively.

The words were recorded with the TASCAM Linear PCM Recorder (DR-07MKII). The speaker was a female native French phonetician, and she pronounced the words written in the phonetic alphabet. She was asked to pronounce the words slowly, clearly and as neutral as possible. The stimuli were normalized with Praat software (version 6.0.28).

2.3. Procedure

Before the testing, parents received a picture book that explained in a child-directed manner what happens during their laboratory visit (e.g., EEG capping, testing session). This book was meant to help both parents and children to be prepared for the testing session. After arriving at the laboratory, the children were allowed to play in the laboratory environment, and they were also familiarized with the EEG cap. During the experiment the child sat on the lap of a parent in a dimly lit room at 70 cm from a computer screen and two loudspeakers from which the sound was delivered. Parents were instructed not to communicate with the child during the experiment. Children were allowed to watch a silent cartoon on the screen throughout the experiment or to play with small toys positioned on the table in front of them during the experiment. Each word (12 words) was presented 60 times during the experiment. Each word type (familiar words, pseudowords and nonwords) included four examples, thus, each child heard each word type 240 times and the total number of stimuli was 720. The presentation order was pseudo-randomized (with consecutive sets of 12 trials) to ensure an even distribution of each word type during the experiment. The same word was never repeated more than twice. The mean stimulus onset asynchrony (SOA) was 1000 ms with a jitter ranging from 950 to 1050 ms. The experiment lasted about 12 minutes.

2.4. EEG recording and pre-processing

Continuous electroencephalogram (EEG) was recorded (band-pass was 0.1 – 100 Hz, sampling rate was 250 Hz) from 128 electrodes using a Geodesic Sensor Net (GSN, NetStation EGIS V2.0). Impedances were kept below 50 kΩ. EEG was filtered (0.3–30 Hz), segmented (900 ms, beginning 100 ms before target word onset), and ocular artifacts were removed with an ocular artifact removal (OAR) algorithm (Gratton, Coles, & Donchin, 1983). The 100-ms pre-stimulus period determined the baseline for amplitude measures. The epochs including eye-movement artifacts, using the electrodes above and below the eyes, as well as motion artifacts exceeding ± 180 lV in any channel were excluded. The epochs with more than 30% contaminated channels were also rejected. Individual bad channels were replaced using spherical spline interpolation.

The data was divided into three equal bins according to the number of repetitions of each word type. Each bin consisted of twenty repetitions of each word, thus 80 repetitions of each word type, and lasted about four minutes. The ERPs were analyzed for early, middle and late bins. To obtain ERPs, the epochs were averaged separately for each subject, word type (known word, pseudoword, nonword), and phase (early, middle, late). The averaged waveforms were re-referenced to the average of mastoids and baseline corrected. The average waveforms were grand-averaged across all participants. The mean number of accepted EEG epochs was 42 (range: 13–76), 42 (range: 11–74), and 41 (range: 10–74) for the known words, pseudowords, and nonwords, respectively. The mean number of accepted EEG epochs was 44 (range: 11–74), 43 (range: 17–

74), and 37 (range: 13–76) for the early, middle, and late bin, respectively. The mean number of accepted trials was not significantly different among the word types (one-way ANOVA: $F(2, 137) = 0.050$, $p = 0.952$). The difference in the number of trials between the bins was significant (one-way ANOVA: $F(2, 137) = 5.38$, $p = 0.006$). The number of trials was smaller in the late bin compared with the early ($p < 0.05$) and the middle ($p < 0.05$) bin.

2.5. Data and statistics analyses

Based on previous literature (e.g., Mills et al., 1993, 1997; Friedrich & Friederici, 2005; Kooijman, Hagoort, & Cutler, 2005; Bosseler, Clarke, Tavabi, Larson, Hippe, Taulu, & Kuhl, 2020) and our recent study in monolingual toddlers (Aygün & Rämä, 2022), the following three waveforms were identified from our data: early positivity (time window of 100-250 ms), N200 (time window of 250-500 ms) and late negativity (time window of 500-800 ms). Mean amplitudes were measured over the time-windows post stimulus, relative to a -100 to 0 ms prestimulus baseline period.

Repeated measures analysis of variance (ANOVA) included Word Type (known word, native pseudoword, non-native pseudoword), Phase (early, middle, late), Recording Area (frontal, parietal) and Hemisphere (left, right) as within-subject and Productive and Comprehensive Vocabulary Group (separately) as between-subject factors. The mean amplitudes extracted from 16 electrodes over the frontal and the parietal recording areas were included in the statistical analyses. The frontal and the parietal recording sites included the following electrode positions: 12, 13, 18, 19, 20, 24, 28, and 29 (frontal left), 4, 5, 10, 111, 112, 117, 118, and 124 (frontal right), 52, 53, 59, 60, 61, 65, 66, and 67 (left parietal), and 77, 78, 84, 85, 86, 90, 91, and 92 (right parietal). According to the 10–10 international electrode position system, the electrode placements 24 and 124 in the frontal area are approximately located around F3 and F4 positions, and placements 52 and 92 in the parietal area around P3 and P4 positions. The statistical analyses were conducted with SPSS (IBM SPP statistics, version 24) and the Greenhouse-Geisser correction was applied for non-sphericity when appropriate.

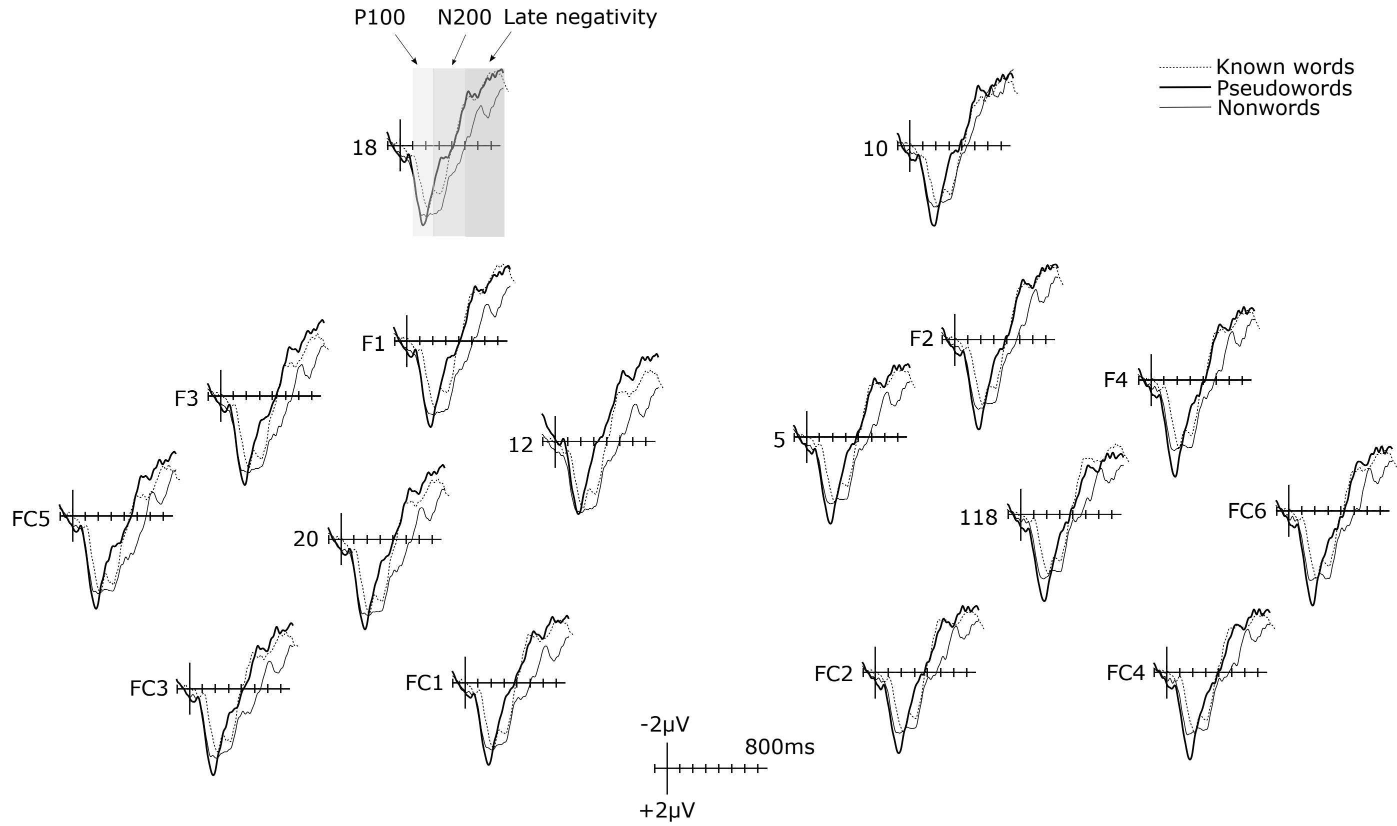

Fig. 1. The grand-average ERPs to known words (dashed lines), pseudowords (thick lines), and nonwords (thin lines) over the frontal recording sites in all participants. Vertical lines indicate word onset. The light, medium, and dark grey boxes indicate the time windows for Positivity (100–250 ms), N200 (250–500 ms), and late negativity (500–800 ms) amplitude analyses, respectively. The x-axis of the scale is from -100 ms to 800 ms with respect to word onset.

3. Results

3.1. The effect of Language Exposure Group on the vocabulary skills and the ERPs

Children in the Exposed Bilingual Group produced more words (mean 285 words, SD = 180) than children in the Balanced Bilingual Group (mean 176 words, SD = 141). The difference was statistically significant (1-ANOVA: $F(1,39) = 4.65$, $p = 0.037$). The amount of input in French significantly correlated with the number of produced words ($r = 0.354$, $p = 0.025$). No significant difference was found for the comprehensive skills (mean 508 words, SD = 192 for the Exposed Bilingual Group, mean 417 words, SD = 149 for the Balanced Bilingual Group) between the two Bilingual Groups (1-ANOVA: $F(1,39) = 2.82$, $p = 0.101$). There was also no correlation between the amount of input in French and the number of comprehended words ($r = 0.183$, $p = 0.259$).

When vocabulary data (Aygün & Rämä, 2022) of the monolingual group (comprehension mean 496 words, SD = 143, production mean 274 words, SD = 190) was included in the ANOVA, there was no main effect of Language Group on the number of comprehended and produced words (comprehension: $F(2, 62) = 1.95$, $p = 0.151$; production: $F(2, 62) = 2.55$, $p = 0.086$).

In the first analysis of the ERP data, the Language Exposure Group (Exposed *versus* Balanced Bilingual Group) was included as a between subject variable. The main effects of Language Exposure Group was not significant on the amplitudes of the P100 ($F(1,44) = 0.499$, $p = 0.507$, $\eta^2 = 0.010$), N200 ($F(1,44) = 0.034$, $p = 0.855$, $\eta^2 = 0.001$), and late negativity ($F(1,44) = 0.609$, $p = 0.439$, $\eta^2 = 0.014$). Also, no significant interactions between Word Type and Language Group were found for any of the components. As follows, all participants were included in the same statistical analyses, and the main effects of Word Type, Phase, Recording Area, and Hemisphere were calculated. Vocabulary Group (normal-to-high *versus* normal-to-low comprehenders and producers (separately) based on a medial split) was included as a between subject variable in the further analyses.

3.2. The effects of Word Type and Hemisphere

P100

There was a main effect of Hemisphere on the amplitudes of the P100 ($F(1,45) = 11.35$, $p = 0.002$, $\eta^2 = 0.201$) while no main effect of Word Type ($F(2, 90) = 2.64$, $p = 0.077$, $\eta^2 = 0.055$) was found. The amplitudes of the P100 were more positive over the left than the right hemisphere. No other main effects or interactions were found.

N200

The main effect of Word Type ($F(2,90) = 7.06$, $p = 0.002$, $\eta^2 = 0.136$) and the interaction between Word Type and Recording Area ($F(2,90) = 9.27$, $p = 0.001$, $\eta^2 = 0.171$) were significant on the amplitudes of the N200. The main effect of Word Type was observed over the frontal ($F(2,90) = 10.72$, $p = 0.001$, $\eta^2 = 0.192$) but not over the parietal ($F(2,90) = 1.26$, $p = 0.287$, $\eta^2 = 0.027$) recording sites (Fig. 1 and 2 A). The amplitudes were significantly more negative for known words than for nonwords ($t(45) = -4.30$, $p = 0.001$, $d' = 0.634$) over the frontal recording sites. The difference between pseudowords and nonwords was also significant ($t(45) = -3.66$, $p = 0.001$, d'

= 0.540) while no difference was found between known words and pseudowords ($t(45) = -0.747$, $p = 0.459$, $d' = 0.109$). The main effect of the Hemisphere ($F(1,45) = 9.39$, $p = 0.004$, $\eta^2 = 0.173$) was significant on the amplitudes of the N200. The amplitudes were more negative over the right than the left hemisphere, regardless of word type. No other main effects or interactions were found.

When we re-examined the N200 component with Productive and Comprehensive Vocabulary Groups as between subject variables over the frontal recording sites, the main effect of Word Type remained significant (Comprehension: $F(2,76) = 15.24$, $p = 0.001$, $\eta^2 = 0.286$; Production: $F(2,76) = 14.09$, $p = 0.001$, $\eta^2 = 0.271$), but no main effects of Comprehensive ($F(1,38) = 0.324$, $p = 0.572$, $\eta2 = 0.008$) or Productive ($F(1,38) = 0.275$, $p = 0.603$, $\eta2 = 0.007$) Vocabulary Groups were found.

The interaction between Word Type and Comprehensive Vocabulary Group was significant ($F(2,76) = 3.36$, $p = 0.040$, $\eta^2 = 0.081$). In normal-to-low word comprehenders, the differences between amplitudes for known words and nonwords ($t(19) = -4.99$, $p = 0.001$, $d' = 1.084$) and pseudowords and nonwords ($t(19) = -4.77$, $p = 0.001$, $d' = 1.030$) were significant (Fig. 2 C). The difference between known words and pseudowords was not significant ($t(19) = 0.371$, $p = 0.751$, $d' = 0.070$). In the normal-to-high word comprehenders, the difference between amplitudes for known words and nonwords was significant ($t(19) = -3.05$, $p = 0.007$, $d' = 0.706$). The difference in amplitudes between known words and pseudowords was approaching a significance ($t(19) = -2.00$, $p = 0.060$, $d' = 0.422$). No difference in the amplitudes between pseudowords and nonwords was observed in the normal-to-high comprehenders ($t(19) = -0.958$, $p = 0.350$, $d' = 0.261$). Independent sample t-test indicated that the difference in amplitudes for pseudowords between high- and low comprehenders was approaching a significance ($t(38) = 1.75$, $p = 0.088$). We also calculated correlations between vocabulary scores and differences in amplitudes between two word types (known words *minus* pseudowords, known words *minus* nonwords, and pseudowords *minus* nonwords). The results showed that the number of comprehended words correlated with the difference in amplitudes between pseudowords and nonwords ($r = 0.371$, $p = 0.018$). The bigger the vocabulary was, the smaller the difference in amplitudes between pseudowords and nonwords was. No other correlations were found.

Even though the main effect of the Language Exposure Group was not significant on the amplitudes of the N200, we ascertained that the main effects of Word Type over the frontal areas were significant in both language groups (Exposed Bilingual Group: $F(2,42) = 4.63$, $p = 0.015$, η^2

= 0.181; Balanced Bilingual Group: $F(2,46) = 5.92$, $p = 0.005$, $\eta^2 = 0.205$). The main effect of the Hemisphere over the frontal areas was found only in the Balanced Bilingual Group ($F(1,23) = 5.08$, $p = 0.034$, $\eta^2 = 0.181$). The effect was approaching in the Exposed Bilingual Group ($F(1,21) = 3.97$, $p = 0.060$, $\eta^2 = 0.159$). The amplitudes were more negative over the right than the left hemisphere, regardless of word type.

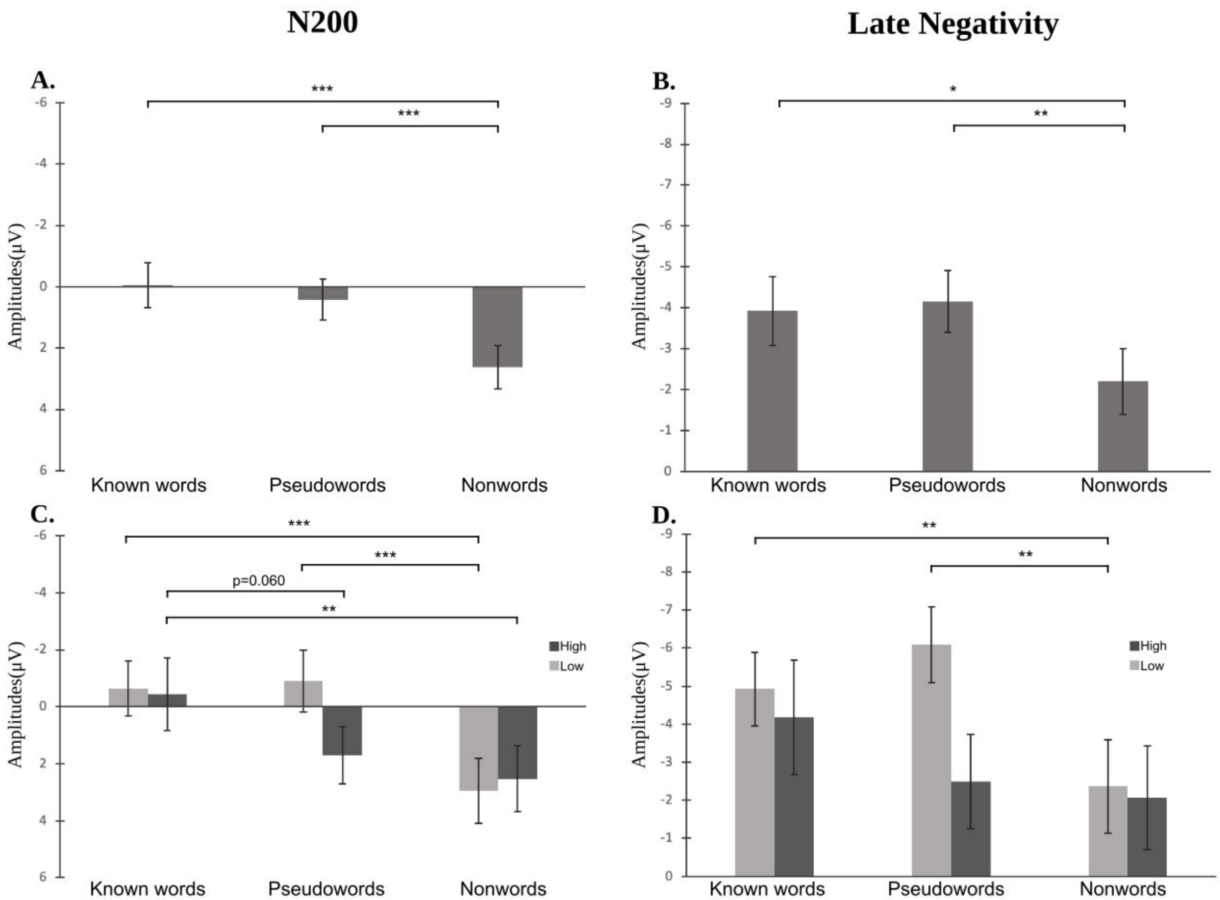

Fig. 2. A. Mean amplitudes for the N200 over the frontal recording sites for known words, pseudowords and nonwords in all participants. **B.** Mean amplitudes for the late negativity over the frontal recording sites for known words, pseudowords and nonwords in all participants. **C.** Mean amplitudes for the N200 over the frontal recording sites for known words, pseudowords and nonwords in the normal-to-low (light grey bars) and normal-to-high (dark grey bars) word comprehenders. **D.** Mean amplitudes for the late negativity over the frontal recording sites for known words, pseudowords and nonwords in the normal-to-low (light grey bars) and normal-to-

high (dark grey bars) word comprehenders. Vertical bars indicate SEMs * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Late negativity

The main effect of Word Type was not significant on the amplitudes of the late negativity ($F(2,90) = 2.30$, $p = 0.106$, $\eta^2 = 0.049$) but the interaction between Word Type and Recording Area ($F(2,90) = 5.87$, $p = 0.004$, $\eta^2 = 0.115$) reached a significance. The main effect of Word Type was observed over the frontal ($F(2,90) = 4.36$, $p = 0.016$, $\eta^2 = 0.088$) but not over the parietal ($F(2,90) = 0.289$, $p = 0.745$, $\eta^2 = 0.006$) recording sites (Fig. 1 and 2 B). The amplitudes were significantly more negative for known words than for nonwords ($t(45) = -2.31$, $p = 0.026$, d' = 0.634) over the frontal recording sites. The difference between pseudowords and nonwords was also significant ($t(45) = -2.75$, $p = 0.008$, d' = 0.540) while no difference was found between known words and pseudowords ($t(45) = 0.318$, $p = 0.752$, d' = 0.110). The main effect of the Hemisphere ($F(1,45) = 6.80$, $p = 0.012$, $\eta^2 = 0.131$) was significant on the amplitudes of the late negativity. The amplitudes were more negative over the right than the left hemisphere, regardless of word type. No other main effects or interactions were found.

When we re-examined the late negativity component with Productive and Comprehensive Vocabulary Groups as between subject variables over the frontal recording sites, the main effect of Word Type remained significant (Comprehension: $F(2,76) = 6.04$, $p = 0.004$, $\eta^2 = 0.137$; Production: $F(2,76) = 5.88$, $p = 0.004$, $\eta^2 = 0.134$), but no main effects of Comprehensive ($F(1,38) = 1.05$, $p = 0.313$, $\eta2 = 0.027$) or Productive ($F(1,38) = 0.007$, $p = 0.934$, $\eta2 = 0.001$) Vocabulary Groups were found. The interaction between Word Type and Comprehensive Vocabulary Group was approaching a significance ($F(2,76) = 2.99$, $p = 0.057$, $\eta^2 = 0.073$). In normal-to-low word comprehenders, the differences between amplitudes for known and nonwords ($t(19) = -3.20$, $p = 0.005$, d' = 0.717) and pseudowords and nonwords ($t(19) = -3.49$, $p = 0.002$, d' = 0.779) were significant (Fig. 2 D). The difference between words and pseudowords was not significant ($t(19) = 1.26$, $p = 0.224$, d' = 0.282). In the normal-to-high word comprehenders, none of the differences in amplitudes between the word types were significant. Independent sample t-test indicated that the difference in amplitudes for pseudowords between high- and low comprehenders was significant ($t(38) = 2.26$, $p = 0.030$).We also calculated correlations between vocabulary scores and differences in amplitudes between two word types (known words *minus* pseudowords, known words *minus* nonwords, and pseudowords *minus* nonwords). The results showed that the number of comprehended words correlated with the difference in amplitudes between pseudowords and nonwords ($r = 0.396$, $p = 0.011$). The bigger the vocabulary was, the smaller the difference in amplitudes between pseudowords and nonwords was. No other correlations were found.

Even though the main effect of the Language Exposure Group was not significant on the amplitudes of the N200, we ascertained that the main effects of Word Type over the frontal areas were significant in both language groups (Exposed Bilingual Group: $F(2,42) = 4.63$, $p = 0.015$, $\eta^2 = 0.181$; Balanced Bilingual Group: $F(2,46) = 5.92$, $p = 0.005$, $\eta^2 = 0.205$). The main effect of the Hemisphere was not found when the groups were analyzed separately (Exposed Bilingual Group: ($F(1,21) = 2.54$, $p = 0.126$, $\eta^2 = 0.108$; Balanced Bilingual Group ($F(1,23) = 1.82$, $p = 0.190$, $\eta^2 = 0.073$).

3.3. The effect of Language Group: Bilinguals versus Monolinguals

When we re-examined the N200 and late negativity component with Language Group (Balanced Bilingual Group, Exposed Bilingual Group, and Monolinguals Group (data from Aygün & Rämä, 2022) as a between subject variable over the frontal recording sites, the main effect of Word Type remained significant (N200: $F(2,132) = 23.11$, $p = 0.001$, $\eta^2 = 0.259$; Late negativity: $F(2,132) = 8.00$, $p = 0.001$, $\eta^2 = 0.108$), but no main effect of Language Group (N200: $F(1,66) = 0.039$, $p = 0.961$, $\eta2 = 0.001$; Late negativity: $F(1,66) = 0.220$, $p = 0.803$, $\eta^2 = 0.007$) or interaction between Word Type and Language Group (N200: $F(4,132) = 0.302$, $p = 0.876$, $\eta2 = 0.009$; Late negativity: $F(2, 132) = 0.906$, $p = 0.460$, $\eta^2 = 0.027$) were found. The main effect of Hemisphere was significant on the N200 ($F(1,66) = 8.66$, $p = 0.004$, $\eta2 = 0.116$) but there was no interaction between Language Group and Hemisphere (N200: $F(2,66) = 0.650$, $p = 0.525$, $\eta2 = 0.019$). The amplitudes were more negative over the right than the left hemisphere, regardless of word type and Language Group.

4. Discussion

In the present study, we aimed at investigating whether vocabulary knowledge and the amount of another language input in bilingual toddlers affect the magnitudes of brain signals in response to known words, pseudowords, and nonwords in a non-referential task. Based on earlier behavioral evidence, we expected that the patterns of brain signals in response to pseudowords and nonwords are similar in bilingual language learners. The results, however, showed that, similarly to monolingual toddlers, the amplitudes of N200 and late negativity were significantly more pronounced for pseudowords than for nonwords. This finding suggests a similar reduced activation of the lexical networks for nonwords in bilingual toddlers as earlier found in the monolingual German- and French-learning infants and toddlers (Friedrich & Friederici, 2005; Steber & Rossi, 2020; Aygün & Rämä, 2022).

Earlier behavioral evidence shows that bilingual infants accept non-native lexical items as novel labels in word learning tasks until the age of 22 to 24 months in contrast to their monolingual peers who fail accepting non-native items already at the age of 17 to 19 months (Graf Estes & Hay, 2015; Singh & Tan, 2021). Difference in interpretative flexibility - whether an unknown word represents a potential word candidate or not - is suggested to be dependent on perceptual and/or attentional processing differences in monolingual and bilingual infants (Graf Estes & Hay, 2015). More precisely, bilingual infants experience a greater variability in acoustic-phonetic environment and, thus, they might need more time and experience to determine, for example, which phoneme combinations differentiate words from nonwords. Another possibility, according to the authors, is that bilingual infants learn early in life to switch attention between two language-relevant linguistic features, and this ability extends to increased sensitivity even for nonwords in word learning tasks. Our results, however, demonstrated that there was no difference in the magnitude of brain signals in response to pseudowords and nonwords in monolingual and bilingual toddlers. Both groups of participants exhibited a different brain signal in response to nonwords than for pseudowords, suggesting that nonwords were interpreted as non-potential lexical candidates, or at least, they did not activate similar neural resources than known words or pseudowords.

There are several possibilities to explain our findings. In previously mentioned behavioral studies, the bilingual participants were exposed to English and Mandarin Chinese (Singh & Tan, 2021) or English and another language from a variable group of languages (Graf Estes & Hay, 2015). More importantly, the exposure to English varied between 25% and 75% indicating that for some toddlers English was the dominant language while for the others the non-dominant language. In our study, all participants were dominantly exposed to French, and their other language exposure varied between 15% to 50%. Earlier evidence regarding lexical-semantic activation shows that bilingual toddlers activated similar networks as their monolingual peers when processing lexical-semantic relations in their dominant language (French) while processing of non-dominant language (Spanish) activated a different network (Sirri & Rämä, 2019). Also, younger bilingual infants show a preference for phonotactically legal phoneme combinations of their dominant language (Sebastián-Gallés & Bosch, 2002). Thus, bilingual participants' language dominance in the current study might explain similar neural responses in two language groups. We are aware that in studies investigating bilingual language acquisition, the amount of language exposure to another language is typically at least 25% to 30% of the total language input, and the so-called "exposed bilingual group" included in the current study is usually neglected. Our results showed, however, that there was no difference in the magnitudes of ERPs between these two groups of bilinguals. In addition to language dominance, the choice of task in the current study might also have influenced the findings. Sensitivity to non-native contrasts has been suggested to be dependent on the task in a recent study: infants were shown to be more sensitive to non-native sounds in word learning than in a non-referential habituation task (Singh & Tan, 2021). Whether dominantly French-learning bilingual 24 month old toddlers are sensitive to non-native nonwords in a word learning context remains to be investigated in future studies. Also, it remains to be investigated whether younger bilingual infants exhibit a different pattern of brain signatures in response to pseudowords and nonwords.

The amount of comprehensive vocabulary, however, interacted with the magnitudes of the brain signals. Bilingual toddlers with higher comprehension skills responded equally to pseudowords and nonwords, while bilingual toddlers with lower vocabulary knowledge exhibited a differential signal in response to these two word types. Correlation analysis confirmed these findings showing that the bigger the vocabulary was, the smaller the difference in amplitudes between pseudowords and nonwords was. This finding suggests that our initial expectation about similar responsiveness to pseudowords and nonwords applies only to those bilingual participants with higher vocabulary skills. We also showed that there was a significant positive correlation between the amount of input in French and the number of produced words, and thus, the participants with higher vocabulary skills were most likely to be part of the Exposed group who received more daily input in French. Interestingly, the effects of vocabulary skills on the magnitudes of brain signals were different in the monolinguals, that is, monolingual toddlers with a higher productive vocabulary knowledge exhibited a gradient pattern of activity in response to three word types while monolinguals with lower vocabulary skills responded equally (Aygün &

Rämä, 2022). In other words, bilingual toddlers with higher comprehensive vocabulary skills responded similarly than monolinguals with lower productive vocabulary skills. There is earlier evidence showing that monolingual infants who were exposed to a higher daily language input, as measured by Language Environment Analysis System (LENA), exhibited a full commitment to their native language while monolinguals with low language exhibited a similar neural pattern that was observed in bilingual infants with a high input in a specific language (Garcia-Sierra et al., 2016). The authors proposed that this finding was due to the fact that these two groups of infants received similar amounts of language specific input in their everyday lives. In the present study, the amount of language input was not measured. Better evaluation tools regarding linguistic environment (e.g., amount of speakers in everyday life, overheard speech) are needed to understand the interactions between the quantity and the quality of language specific input, vocabulary knowledge, and neural signatures associated with processing of native and non-native speech both in monolingually and bilingually raised infants and toddlers. Moreover, in the current study, in bilingual participants, the interaction between ERPs and vocabulary was found for comprehension, while for monolingual participants for production. This suggests that productive and comprehensive vocabulary measures might be more suitable to evaluate monolingual and bilingual vocabulary development, respectively.

The amplitudes of the N200 and the late negativity were more pronounced over the right than the left hemisphere, irrespective of word type, in the bilingual participants. When two Bilingual Exposure Groups were analyzed separately, a significantly more pronounced magnitude of the N200 over the right hemisphere was observed only in the Balanced Bilingual Group. In an earlier study by Conboy and Mills (2006), the difference in ERPs in response to known words and unknown words in the dominant language were more pronounced over the right than the left hemisphere in the bilingual participants with higher vocabulary skills. In contrast, in monolingual participants, age and increasing language skills have shown to shift the asymmetrical lateralization towards left-hemispheric distribution (Mills et al., 1993, 1997). There is recent evidence showing that brain activity, as measured by magnetoencephalography, in the right frontal cortex in response to familiar words in infants was correlated with later vocabulary growth at 18, 21, 24, and 27 months (Bosseler et al., 2020). Our results further suggest that dual language experience is associated with a greater right hemisphere involvement during language processing, at least in those toddlers exposed to another language more than 30% of their language input.

There are certain limitations in the present study. The phonotactic status of the consonant clusters in the other language of the participants was not evaluated, and thus, there is a possibility that illegal phonotactic structures were legal at least in some of the participants' other languages. There are also at least two limitations regarding the vocabulary measures. The participants were exposed to various languages. Linguistic distance between language pairs has shown to affect the vocabulary skills: the closer the languages are in phonology and morphology, the higher the vocabulary (Floccia et al., 2018). Thus, there is a possibility that vocabulary skills were influenced not only by environmental factors, such as amount of linguistic input, but also by language pairs the child was exposed to. Moreover, the vocabulary score was measured by the French translation of the CDI but the parents were instructed to also include words that their child understood or said in their another language. Thus, the vocabulary score of bilingual participants represented a conceptual vocabulary rather than a vocabulary in French, but it was not measured by two different language inventories.

To sum up, the amplitudes of N200 and late negativity were more pronounced for pseudowords than for nonwords suggesting a similar reduced activation of the lexical networks for nonwords in bilingual toddlers as earlier found in the monolingual infants and toddlers. The amount of comprehensive vocabulary, however, interacted with the magnitudes of the brain signals. Toddlers with higher comprehension skills responded equally to pseudowords and nonwords, while bilingual toddlers with lower vocabulary knowledge exhibited a differential signal in response to these two word types, suggesting that similar responsiveness to pseudowords and nonwords applies only to those bilingual participants with higher language input and vocabulary skills.

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Study III

Selective attention and lexical processing: An event-related potential (ERP) study in preschool-age French speakers

Oytun Aygun [1], Kimmo Alho [1,2], & Pia Rämä [1, 3]

[1] Université de Paris, Paris, France

[2]Department of Psychology and Logopedics, University of Helsinki, Helsinki, Finland

[3] Université de Paris, INCC UMR 8002, CNRS, F-75006 Paris, France

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Abstract

We investigated the influence of selective attention on processing of known words and novel lexical items (i.e., pseudowords) during the course of an event-related potential (ERP) experiment in French-speaking preschool children. Monolingually raised 4-year-olds were exposed to spoken words in an attentive and an unattentive condition. In the attentive condition, the children were instructed to find a target word in a stream of spoken words, while in the unattentive condition, they were asked to ignore the spoken words and find a target image in a stream of images on a computer display. ERPs in response to known words were similar in both conditions, suggesting that the 4-year-olds processed these words similarly when they were to be attended and when they were to be ignored. In contrast, ERPs to novel words were modulated by attention and exposure time: the slow negative ERP response elicited by the novel words was increased for attended novel words during the second part of the experiment. The results suggest that only in the attentive condition children start to treat pseudowords differently resulting in a stronger N400-kind of negative ERP response.

Introduction

Attention is a complex mental function that involves alertness, orienting and selection processes (Pascual-Leone, 1987; Pashler, 1999; Petersen & Posner, 2012; for a review, see Näätänen, 1992). Alertness is the general state of readiness to process information, whereas orienting refers to directing attentional resources to certain stimuli. Selective attention, in turn, refers to the mechanism of focusing on target stimuli while suppressing irrelevant information (for reviews, see Hillyard et al., 1995; Näätänen 1975, 1992; Stevens & Bavelier, 2012). Attention skills in the beginning of formal education are one of the strongest predictors of school achievement (Duncan et al., 2007). For example, the ability to pay attention to selected information at the age of 4 was found to predict even the probability of graduating from college (McClelland et al., 2013). Selective attention was also linked to language development in preschool and school aged children (e.g., Bosse & Valdois, 2009; Obrzut et al., 1997). Moreover, attentional problems are present in many developmental psychopathologies, such as attention deficit hyperactivity disorder (ADHD) (e.g., Christakou et al., 2013; Gumenyuk et al., 2005; Lubke et al., 2009; Oja et al., 2016), autism (e.g., Noterdaeme et al., 2001; Sikora et al., 2012) and specific language disorders (e.g., Noterdaeme et al., 2001), further showing the importance of attention for healthy development.

In the auditory modality, selective attention has often been investigated with event-related brain potentials (ERPs) in dichotic listening paradigms where two auditory streams of tones (e.g., Hillyard et al., 1973; Hink et al., 1978) or linguistic stimuli (e.g., Asbjørnsen & Hugdahl, 1995; Foundas et al., 2006; Mittag et al., 2013; Teder et al., 1993) are presented simultaneously to the left and right ear and the participant is asked to attend to one or the other (for a review, see Hugdahl et al., 2009). These ERP studies have unfolded the timing of auditory processes related to attention. The studies with non-linguistic stimuli found more negative ERPs for attended than for unattended tones around 60–110 ms after stimulus onset (e.g., Hillyard et al, 1973; Hink et al., 1978). Additionally, there was a later positive component around 250–400 ms after stimulus onset to target stimuli among the attended ones (e.g., Hillyard et al., 1973) presumably reflecting allocation of attentional resources to a specific task (Hoffman et al., 1985). When linguistic stimuli were used, the early enhanced negativity for attended probes was more posterior in distribution and longer in duration compared to non-linguistic stimuli (e.g., Coch et al., 2005). Perhaps it was caused, at least in part, by the processing negativity (PN), ERP response proposed (e.g., Näätänen, 1982) to explain the negative displacement (Nd) of ERPs to attended stimuli in relation to ERPs to unattended stimuli (e.g., Alho et al., 1994; Hansen & Hillyard, 1980; 1984; Näätänen et al., 1992). The PN is suggested to be an endogenous component related to attentional mechanisms that is different from the exogenous N1 component (for a review, see Näätänen, 1982). The Nd consists of an early and a late part: the early Nd (Nde) is typically peaking at 100– 200 ms from sound onset and is largest over the frontal-central scalp positions, whereas the late Nd (Ndl), peaking after 300 ms, has usually a more frontal distribution. The Nde has been suggested to be caused by an earlier PN component associated with selection of attended stimulus, while the Ndl has been suggested to be caused by a later PN component associated reflecting further processing of the attended sounds or the maintenance of a selective tuning of the auditory cortex with sensory support from the attended stimuli (e.g., Alho et al., 1989; Näätänen, 1990).

Selective attention has also been investigated using an intermodal paradigm: in this case, the participants are typically presented simultaneously with visual and auditory streams and asked to detect target stimuli in one sensory modality while non-targets are present in both modalities (e.g., Alho et al., 1994; Eimer & Schröger, 1998; Karns & Knight, 2009; Talsma & Woldorff, 2005; Woods et al., 1993). In such studies, the ERPs to the attended-ear tones were also negatively displaced in relation to the ERPs to the unattended-ear tones and the ERPs to the tones when the attention was in the visual modality (Alho et al., 1994; Mittag et al., 2013). Additionally, combining a dichotic listening task with a visual task reduced the Ndl to attended sounds whereas the Nde was unaffected (Ramirez et al., 2005; Singhal et al., 2002) suggesting that the uni- versus bimodality of attentional paradigms affects the further processing of attended sounds rather than their attentional selection for further processing. In a neuroimaging study, selective attention to one sensory modality in a bimodal auditory-visual task was shown to increase the activity in the corresponding cortical area while a decrease in activity was observed in the cortical area subserving the ignored modality, suggesting that cross-modal attentional effects are mediated by gating of the sensory input through modulation of sensory cortical areas (Johnson & Zatorre, 2005). There seem to be differences in the processing of task-irrelevant intramodal vs. cross-modal information. In unimodal tasks, task-irrelevant stimuli in the same modality as the target stimuli are processed more when the task involving the targets has a low perceptual load (Lavie & Tsal, 1994; Lavie et al., 2004), whereas the processing of task-irrelevant stimuli occurring in another modality is either independent of task load (Rees et al., 2001; Sandhu & Dyson, 2016) or increases with increasing perceptual load (Tellinghuisen & Nowak, 2003). The latter case is explained by a reduction in the ability to inhibit cross-modal distractors (auditory) when the (visual) task requires more attentional resources.

Multiple developmental studies using behavioural (e.g., Tipper et al., 1989; Wetzel et al., 2006; for reviews, see Hanania & Smith, 2010; Lane & Pearson, 1982) and ERP methods (e.g., Berman & Friedman, 1995; Wetzel et al., 2006; Wetzel & Schröger, 2007; for reviews, see Gomes et al., 2000; Ridderinkhof & van der Stelt, 2000) have shown that the ability to ignore task-irrelevant stimuli in unimodal attentional paradigms increases with age (throughout childhood). A few studies investigated the developmental changes in the brain responses during selective auditory attention using the dichotic listening paradigm in childhood and adolescence (e.g., Coch et al., 2005; Karns et al., 2015; Sanders et al., 2006; Stevens et al., 2006; 2009). These experiments demonstrated that with adequate cues and age-appropriate stimuli even preschool children are capable of selectively attending to one auditory stream while ignoring the other (e.g., Sanders et al., 2006) and that the ERPs in response to both linguistic (syllable *ba)* and non-linguistic (*buzz* created by scrambling the syllable *ba*) probes embedded in an attended story were enhanced (Coch et al., 2005; Karns et al., 2015; Sanders et al., 2006). Children from 3 to 5 years of age displayed an early positive response that continued from 100 ms to 300 ms in response to attended non-linguistic probes, while the positive attention effect in children from 6 to 8 years of age was shorter, expanding from 100 to 200 ms (Sanders et al., 2006). For linguistic probes, both an early positive and a later negative attention effect was obtained in both age groups**.**

The development of intermodal selective attention, on the other hand, has been less investigated compared to unimodal attention. There are only a few behavioral developmental studies investigating children's abilities to selectively attend in cross-modal attention tasks (e.g., Hanauer & Brooks, 2003; 2005; Hirst et al., 2019; Thomas et al., 2017). These studies have shown that, similarly to unimodal paradigms, the ability to ignore task-irrelevant cross-modal stimuli increases with age throughout childhood (Hanauer & Brooks, 2003; 2005; Hirst et al., 2019). Environmental factors can also contribute to this ability: musically-trained children and adolescents outperformed those without musical training in a visual categorization task with non-linguistic auditory distractors (Putkinen et al., 2021). The ERP studies investigating the brain signatures of intermodal selective attention in developing populations are even more scarce. In a longitudinal study with ERP measurements at the age of 6 and 8 years, typically developing and boys and boys with ADHD attended to non-linguistic auditory (clicks) or visual stimuli (flashes) while ignoring stimuli in the other modality (Satterfield et al., 1990). In neurotypical children, the Nde was found at the age of 8 but not at the age of 6, while in children with ADHD, the Nde was not observed at either age. The Ndl was observed at both ages in neurotypical children, while it was present at the age of 8, but not at the age of 6, in children with ADHD.

In the current study, we investigated the effect of attention on the processing of linguistic stimuli in preschool children in an intermodal selective attention task. Our aim was to determine whether attention results in an increase in the brain signals for words and pseudowords (i.e., meaningless words that obey the phonetic, prosodic, and phonotactic rules of a given language). In a previous study on preschool children, attention allocation was shown to modulate an early positivity and a later negativity in ERPs to linguistic probes (single syllable) in an intramodal task (Karns et al., 2015; Sanders et al., 2006). However, to our knowledge, processing of known words and pseudowords has not been investigated in preschool children using an intermodal selective attention task. Earlier evidence from adults shows that the brain signatures for pseudowords become more pronounced with attention allocation (Garagnani et al., 2008; Shtyrov et al., 2010). Moreover, it was shown in adults (e.g., Bakker et al., 2015; Bentin et al., 1999; Chwilla et al., 1995; Holcomb & Neville, 1990; Rossi et al., 2013), school age children (Abel et al., 2018, 2020) and toddlers (Friedrich & Friederici, 2005) that pseudowords evoke a larger N400 response, associated with lexical-semantic processing, than real words suggesting that neural activation is increased for more demanding lexical search. In the current experiment, monolingual 4-year-olds were presented with simultaneous and independent streams of spoken words and pictures and they were asked, in separate conditions, to press a button upon detecting a target in the auditory stream or in the visual stream. We investigated the ERP modulations in response to known words and pseudowords, in attended and unattended conditions during the course of the experiment. We expected that auditory attention to linguistic stimuli (both known words and pseudowords) would generate an early broad positivity and a later negativity similarly to previous studies with young children (Coch et al., 2005; Sanders et al., 2006; Karns et al., 2015). We also expected preschool children to show more negative ERP responses to pseudowords than to known words, indicating an ease of lexical access for already known words.

2. Material and methods

2.1. Participants

The final participant sample included twenty-three (15 girls) 4-year-old children (mean: 49 months 12 days, SD: 2 months, min: 45 months 18 days, max: 51 months 22 days). All children came from monolingual French-speaking families in the Paris Region. They were recruited through a database of parents who previously volunteered to participate in child development studies. All children were born full term and none of them suffered from hearing or language impairment. Also, according to their parents, there was no atypical development of language in the families. The mean number of maternal education years was 16 (range from 9 to 20 years; SD: 2 years). Parents gave a written informed consent before participation. Fifteen other participants were tested but their data were rejected due to noisy electroencephalogram (EEG) recording (n = 12), due to technical problems while recording (n = 2), or refusal to put on the EEG cap (n = 1). The study was conducted in conformity with the declaration of Helsinki and approved by the Ethics Committee of the Paris Descartes University.

2.2. Stimuli

The auditory stimuli consisted of two types of bisyllabic words: (a) four real French words (ballon /balɔ̃/ (ball), cheveux /ʃəvø/ (hair), maison /mɛzɔ̃/ (house), bateau /bato/ (boat)) and (b) four pseudowords (lechon /ləʃɔ̃/, vabeux /vabø/, meautai /motɛ/, bonsa /bɔ̃za/) (Table 1). The auditory stimuli were grouped in two random lists (list A and B), each list consisting of two realand two pseudowords, each occurring equiprobably. Pseudowords were constructed by swapping phoneme positions between two word pairs: ballon*/balɔ̃/* - chevaux/*ʃəvø*/ and maison/*mɛzɔ̃*/ - bateau/*bato*/. As an example, pseudoword "lechon/ləʃɔ̃/" was constructed from the words "ballon/balɔ̃/" and "cheveux/ʃəvø/" by combining the third phoneme of "ballon/ba**l**ɔ̃/", the second phoneme of "cheveux/ʃ**ə**vø/", the first phoneme of "chevaux/**ʃ**əvø/", and the fourth phoneme of "ballon/bal**ɔ̃**/". There were three different recordings of each word, randomly chosen each time when the word was presented. None of the pseudowords had any meaning in French. Average phoneme frequencies and word durations are shown in Table 1. The target word was the word "chat" (cat in French). Additionally, in the Training Task, two familiar words, that is, "manteaux" (coat) and "raisin" (grape), and two pseudowords, that is, "lumo" and "ponve", were used. The words were recorded with TASCAM Linear PCM Recorder (DR-07MKII). The speaker was a female native French phonetician. She pronounced the words written in the phonetic alphabet slowly, clearly and as neutral as possible. The stimuli were normalized to 70 dB SPL with Praat software (version 6.0.28).

Table 1 : Average Biphoneme Frequency, Word Frequency and Duration of the Stimuli

		AvbiF	WordF	Duration (ms)		AvbiF	WordF	Duration (ms)
	Known Words				**Pseudowords**			
List A	*ballon /balɔ̃/*	6469	27	506	*lechon /ləʃɔ̃/*	786	0	487
	cheveux /ʃəvø/	2907	116	657	*vabeux /vabø/*	3600	0	533
	mean	**4688**	**72**	**582**	***mean***	**2193**	**0**	**510**
List B	*bateau /bato/*	4209	107	585	*meautai /motɛ/*	5449	0	523
	maison /mɛzɔ̃/	6371	570	496	*bonsa /bɔ̃za/*	1285	0	561
	mean	**5290**	**339**	**541**	***mean***	**3367**	**0**	**542**
	mean total	**4568**	**80**	**582**	**mean total**	**2662**	**0**	**523**

Table 1. Average bi-phoneme frequency (AvbiF), word frequency (WordF) and word duration (in ms). Bi-phoneme (token) frequencies were retrieved from the database Lexique 3.83 (New et al., 2001, http://www.lexique.org/).

The visual stimuli (presented at the center of the screen, 12.5 × 6.8 visual degrees) consisted of colored images of eight different animals, half of them were familiar (duck, horse, elephant, bird) and the other half were less familiar (amarillo, comodo dragon, anteater, platypus). The eight images were also grouped in two pseudorandom lists (list A and list B), each list consisting of two familiar and two less familiar animals. The target image was a picture of a cat. Each image was displayed until the next image appeared. All images were found from Google Images (www.google.com/imghp) and had no copyright restrictions.

2.3. Procedure

Before the testing, parents received a picture book that explained in a child-directed manner what will happen during the laboratory visit (e.g., EEG capping, testing session). This book was meant to help both children and parents to be prepared for the testing session. After arriving at the laboratory, the child was allowed to play in the laboratory environment, and was familiarized with the EEG cap. During the experiment the child sat alone on a chair in a dimly lit room at 70 cm from a computer screen and between two loudspeakers which were 40 cm away from each other and from which the sound was delivered. The accompanying parent was seated on a separate chair about one meter behind the child.

There were two tasks during the experimental session, an auditory task and a visual task, performed consecutively with a short break in between. During both tasks, the participants were presented with parallel auditory and visual stimulus streams. The order of tasks was counterbalanced between the participants: 12 children started the experimental session with the visual task, and 11 of them with the auditory task. All children completed both tasks during the experimental session.

In the auditory task, the participant was instructed to press a response button upon detecting the target word “chat” (“cat” in French) and in the visual task they were instructed to press the button to the image of a cat. If the participant pressed the button within five seconds of hearing or seeing the target, a smiley was displayed on the screen for a second. Before each task there was a short training session for about 30 s. The task was explained to the participant in a child-friendly manner before the training session. The training session was repeated until the participant understood the task (and successfully pressed the button on target at least 3 consecutive times).

The order of tasks and the lists used in each task was counterbalanced so that the participant heard different words and saw different images during the auditory and visual tasks. The presentation order of words/pseudowords was pseudo-randomized to ensure an even distribution of each word type with the rule that the same (pseudo)word was never repeated consecutively. Each (pseudo)word was presented 90 times during each task, thus the total number of auditory stimuli was 360 per task (except for the target words) and 720 during the whole experimental session. The stimulus-onset asynchrony varied between 850 ms and 1650 ms for both the auditory and the visual stimuli. The target appeared randomly 20 times in each task. Targets were not presented in the unattended modality. The whole experiment lasted about 20 minutes. Brief breaks were taken if needed (e.g., if the child was moving , or pressing the button too frequently).

2.4. EEG recording and pre-processing

Continuous electroencephalogram (EEG) was recorded (band-pass 0.1–100 Hz, sampling rate 250 Hz) from 128 electrodes using a Geodesic Sensor Net (GSN, NetStation EGIS V2.0). Impedances were kept below 50 kΩ. The data was filtered off-line (0.3–30 Hz) and segmented into 700 ms epochs starting 100 ms before word onset. The 0 μV baseline was determined as the mean amplitude over the 100 ms prestimulus period. Eye movement artefacts were removed with ocular artefact removal (OAR) tool (Gratton et al., 1983). The epochs including artefacts (eye-movements, blinks, or motion artefacts) exceeding ±150 μV were excluded. The epochs with more than 30% of the channels contaminated were also rejected. Individual bad channels were replaced using spherical spline interpolation.

The data were divided into two equal bins according to the number of repetitions of each (pseudo)word. Each bin consisted of 45 repetitions of each (pseudo)wor (i.e., 90 words and 90 pseudowords) and lasted about 7 min. The ERPs were analysed separately for early and late bins. To obtain ERPs, EEG epochs were averaged separately for each participant, Word Type (word, pseudoword), Task Phase (early, late), and Task (auditory vs. visual). The averaged waveforms were re-referenced to the average of mastoids and baseline corrected. The averaged waveforms were grand-averaged across all participants. The mean number of accepted EEG epochs for early and late bins, respectively, was 49 (range: 25–71; SD = 15) and 41 (range: 15–71; SD = 12) in the attentive condition and 50 (range: 19–74; SD = 14) and 43 (range: 17–64; SD = 12) in the unattentive condition. The difference in mean number of accepted trials was significant between the bins (one-way analysis of variance, ANOVA: $F(1, 45) = 6.35$, $p = 0.015$) but not between the conditions ($F(1, 45) = 0.126$, $p = 0.725$).

2.5. Data and statistics analyses

Two-way repeated-measures analyses of variance (ANOVAs) were used to test the effects of Task (auditory, visual) and Task Phase (early, late) on the behavioral results (the proportion of hit responses, and the hit reaction times). Due to an experimental error, the behavioral data were not obtained from three participants. The mean amplitudes of ERPs were calculated separately over six consecutive 100-ms time windows from the word onset until 600 ms. A repeated-measures ANOVA conducted separately for each time window included within-subject factors Attention [attentive (auditory task), unattentive (visual task)], Word Type (word, pseudoword), Task Phase (early, late), Recording Area (frontal, parietal) and Laterality (left, midline, right) factors. The effects of Laterality and Recording Area will be reported only when they interact with the other factors. The mean amplitudes extracted from 18 electrodes over the frontal, central, and the parietal recording sites were included in the statistical analyses. The 54 channels with some of their equivalents according to the 10-10 international system of electrodes sites are as follows (Figure 2): 24, 27, 23, 19, 20, 28 in the left frontal, 16, 11, 12, 5, 6, 15 in the midline frontal, 124, 3, 4, 118, 117, 123 in the right frontal, 36, 41, 35, 30, 42, 37 in the left central, 7, 31, 55, 80, 106 in the midline central, 87, 93, 105, 104, 103, 110 in the right central, 52, 59, 60, 51, 66, 65 in the left parietal, 72, 71, 76, 77, 67, 62 in the midline parietal, and 92, 85, 91, 97, 84, 90 in the right parietal recording sites. The statistical analyses were conducted with SPSS (IBM SPP statistics, version 24) and the Greenhouse-Geisser correction was applied for non-sphericity when appropriate.

3. Results

3.1. Behavioral results: target accuracy and reaction times

The accuracy (the percentage of correct responses to the targets) was high in both tasks (visual and auditory) and task phases (early and late) (Fig. 1). According to a two-way ANOVA there were no significant main effects of Task ($F(1, 19) = 1.13$, $p = 0.302$) or Task Phase ($F(1, 19) = 1.48$, $p = 0.238$) or interaction of these factors ($F(1,19) = 0.874$, $p = 0.361$) on the accuracy in detecting targets. Also, there were no significant main effects of Task ($F(1, 19) = 2.01$, $p = 0.172$) or Task Phase ($F(1, 19) = 0.40$, $p = 0.534$) or interaction of these factors ($F(1,19) = 1.827$, $p = 0.192$) on the reaction times.

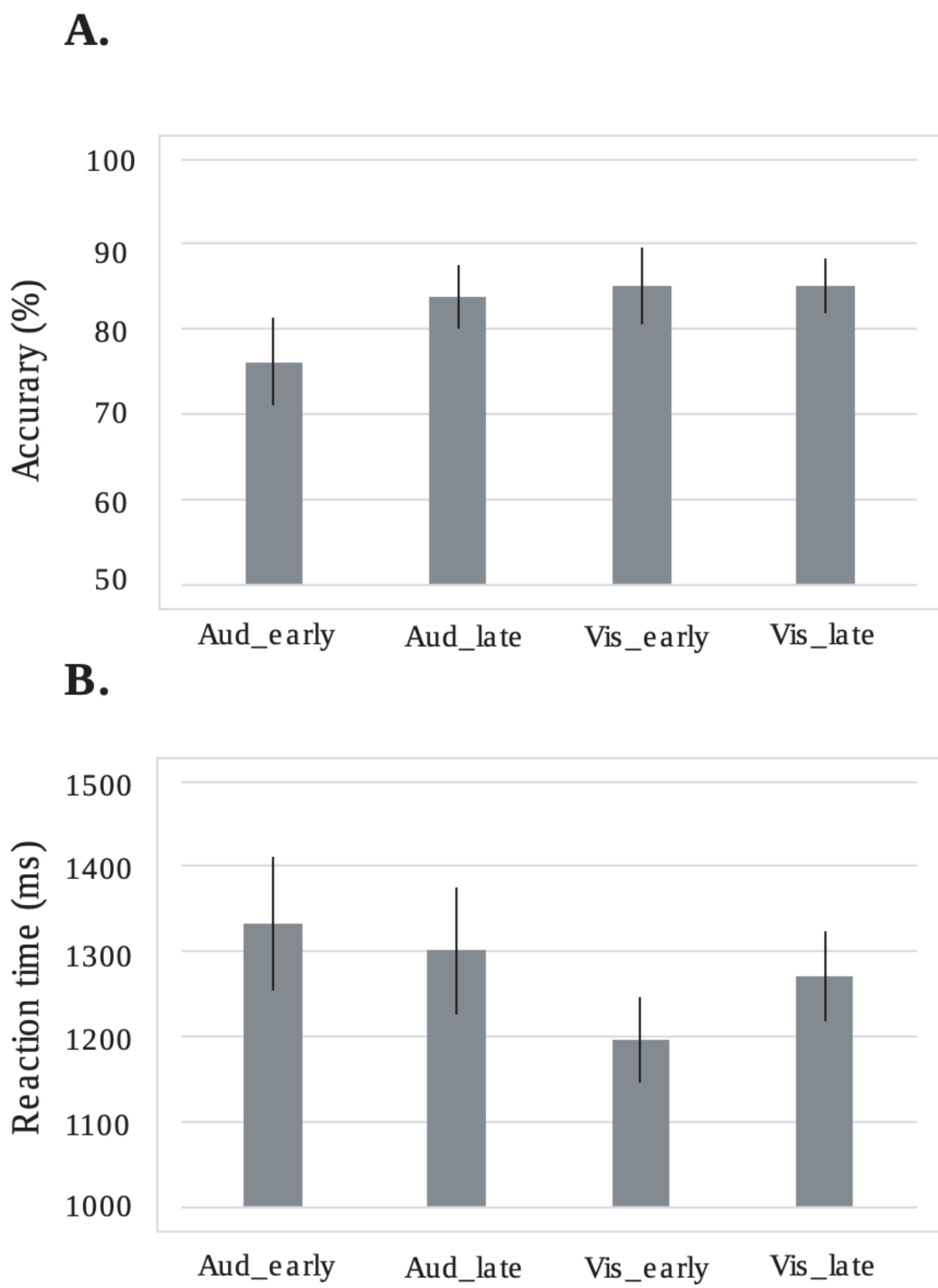

Figure 1. A. Percentages of correct responses (hits) to target words in the early and late phase of the auditory task (Aud_early and Aud_late, respectively) and visual task (Vis_early and Vis_late, respectively). **B.** The same for reaction times (RTs) to the correctly detected target words (in the attended stream). Vertical bars indicate SEMs.

3.2. ERP results

Across participants averaged ERPs to attended and unattended words and pseudowords during the early and late phase of each task are shown in Fig. 2. ERP amplitudes at consecutive 100-ms time windows between 100 and 600 ms from word/pseudoword onset are shown in Fig. 3. According to ANOVAs at each time window, the main effects of Word Type ($F(1, 22) = 0.01$–2.72, all $p > 0.05$ in all cases), Attention ($F(1, 22) = 0.21$–2.21, $p > 0.05$) or Task Phase ($F(1, 22) = 0.924$–3.63, $p > 0.05$) or interactions of these factors with the factors Recording Area or Laterality were not significant on the amplitudes at any time window.

However, interaction between Attention and Task Phase was significant in the time windows 0–100 ms ($F(1, 22) = 9.30$, $p = 0.006$, $\eta 2 = 0.297$), 100–200 ms ($F(1, 22) = 5.67$, $p = 0.026$, $\eta 2 = 0.205$) and almost significant at 200–300 ms ($F(1, 22) = 4.271$, $p = 0.051$, $\eta 2 = 0.163$). The amplitudes were more negative at the late phase than at the early phase in the attended condition at the three first time windows (0–100 ms: $t(22) = 2.78$, $p = 0.011$, $d' = 0.577$; 100–200 ms: $t(22) = 2.35$, $p = 0.028$, $d' = 0.488$; 200–300 ms: $t(22) = 2.44$, $p = 0.023$, $d' = 0.508$). Moreover, in the time window 300–400 ms, the interaction between Attention, Task Phase, and Laterality was close to significance ($F(1, 22) = 2.77$, $p = 0.082$, $\eta 2= 0.112$). According to subsequent t-tests performed separately for different recording areas, the amplitudes were more negative at the late phase than at the early phase in the attended condition over the midline recording sites ($t(22) = 2.25$, $p = 0.035$, $d' = 0.468$). In contrast, in the unattended condition, the amplitudes did not differ between the late and the early phase in any time window (for all time windows, $p > 0.05$).

Next, we conducted ANOVAs with factors Attention, Recording Area, and Laterality separately for the two task phases and word types. At 0–100 ms, the main effect of Attention was not significant either for words or pseudowords, either in the early or late phase. Moreover, the main effect of Attention was not significant for words in the early or late phase at any time window. However, the main effect of attention was significant for pseudowords in the late phase at 100–200 ms ($F(1, 22) = 5.346$, $p = 0.031$, $\eta 2 = 0.195$), 200–300 ms ($F(1, 22) = 9.261$, $p = 0.006$, $\eta 2 = 0.296$), 300–400 ms ($F(1, 22) = 4.414$, $p = 0.047$, $\eta 2 = 0.167$), 400–500 ms ($F(1, 22) = 6.669$, $p = 0.017$, $\eta 2 = 0.233$), and 500–600 ms ($F(1, 22) = 4.355$, $p = 0.049$, $\eta 2= 0.165$) ERPs to attended pseudowords being markedly more negative than ERPs to unattended pseudowords, as seen in Figures 2 and 4.

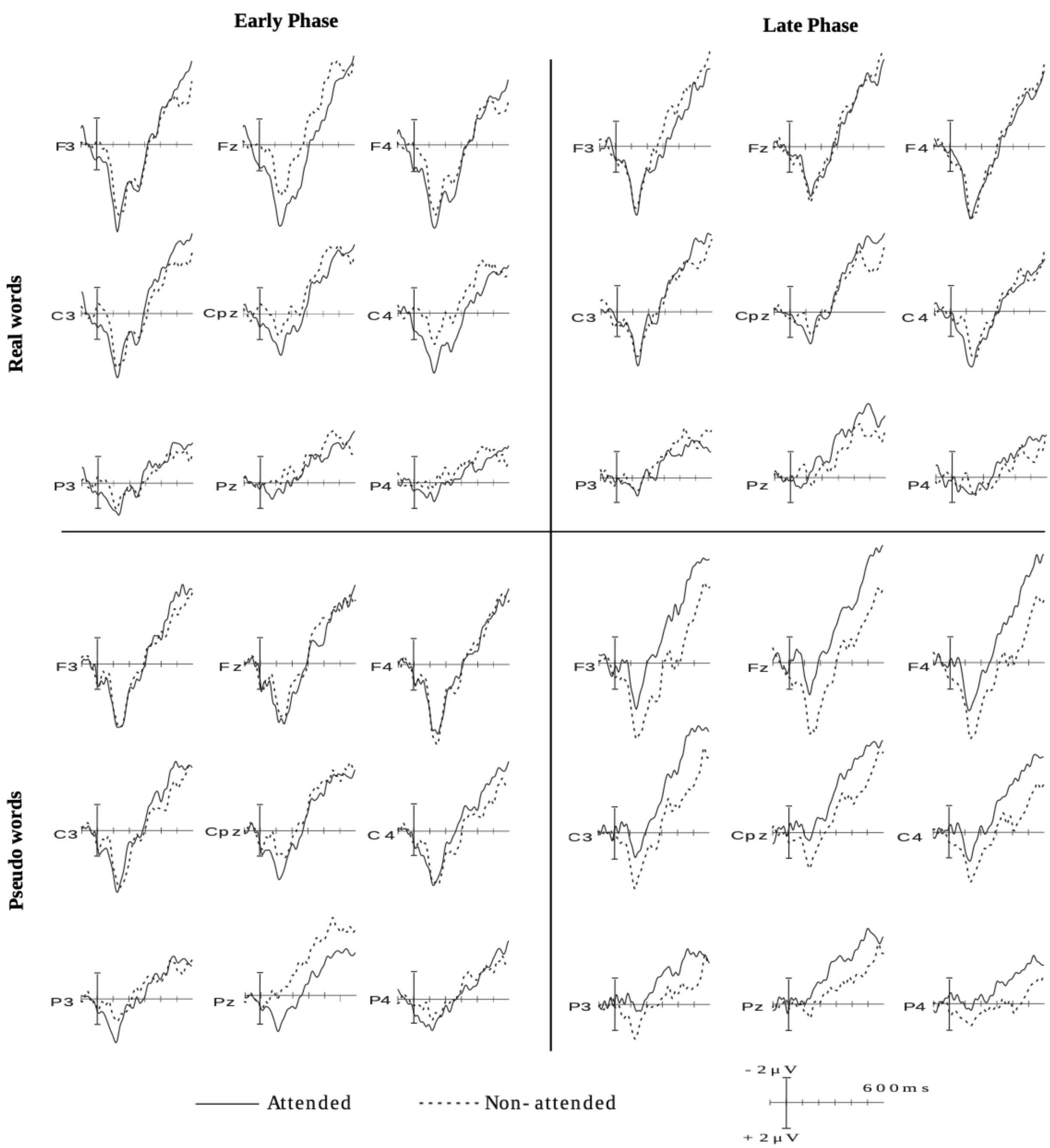

Figure 2. Grand average ERPs (23 subjects) at different scalp sites to spoken words and pseudowords when attended (solid lines) and unattended (dashed lines) during the early phase

(first 45 repetition of each stimuli) and late phase (second 45 repetition of each stimuli) of the relevant task (auditory task for attended, visual task for unattended) of the experiment.

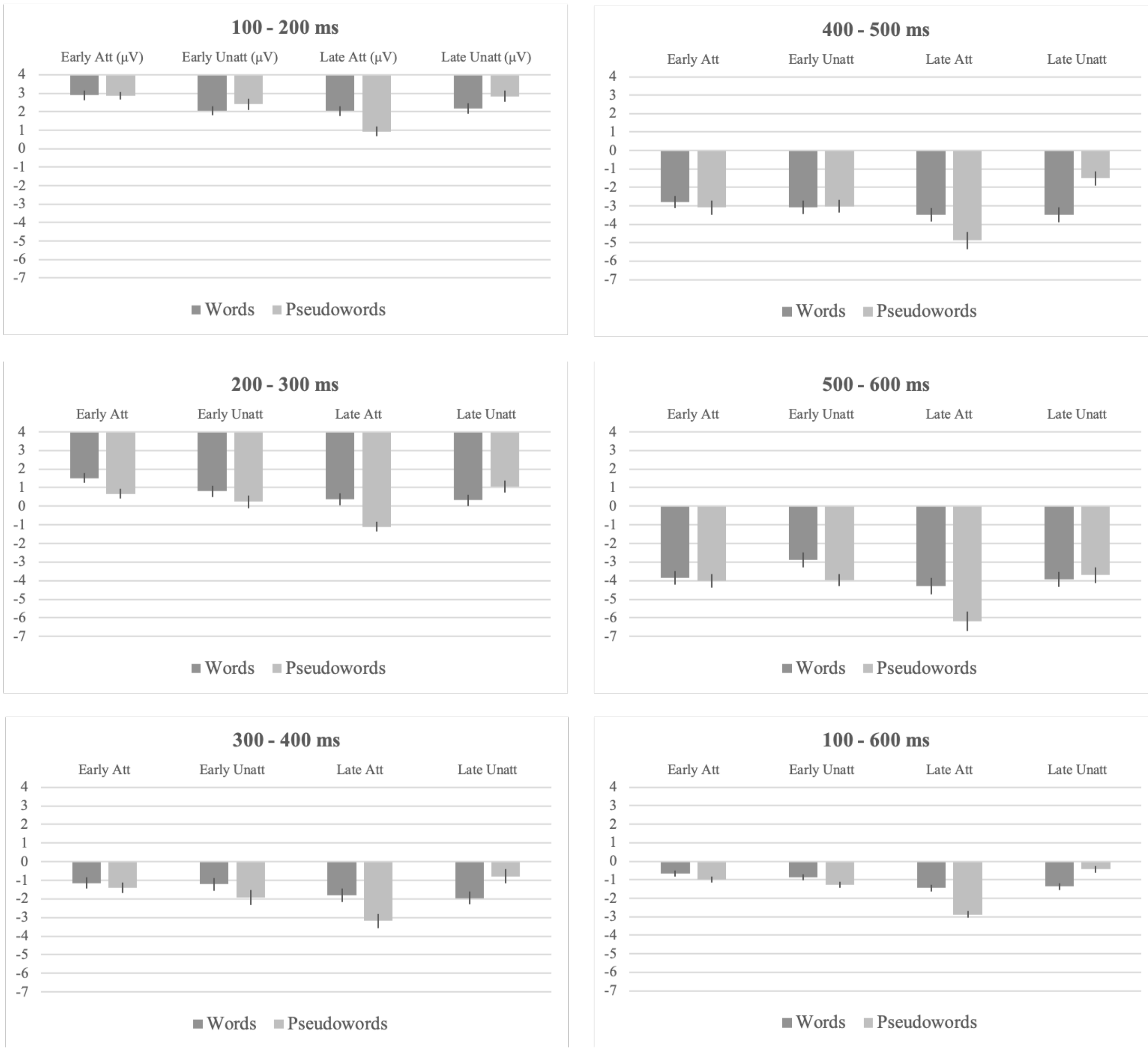

Figure 3. Amplitudes of ERPs to attended and unattended spoken words and pseudowords (dark vs. light bars, respectively) during the early phase (first 45 repetitions of each stimulus) and late phase (second 45 repetitions of each stimuli) of each task (Early Att: early task phase of the auditory task at consecutive 100 ms time windows between 100 and 600 ms from word/pseudoword onset. Early Unatt: early task phase of the visual task; Late Att: late task phase of the auditory task; Late Unatt: late task phase of task the visual task) averaged across participants.

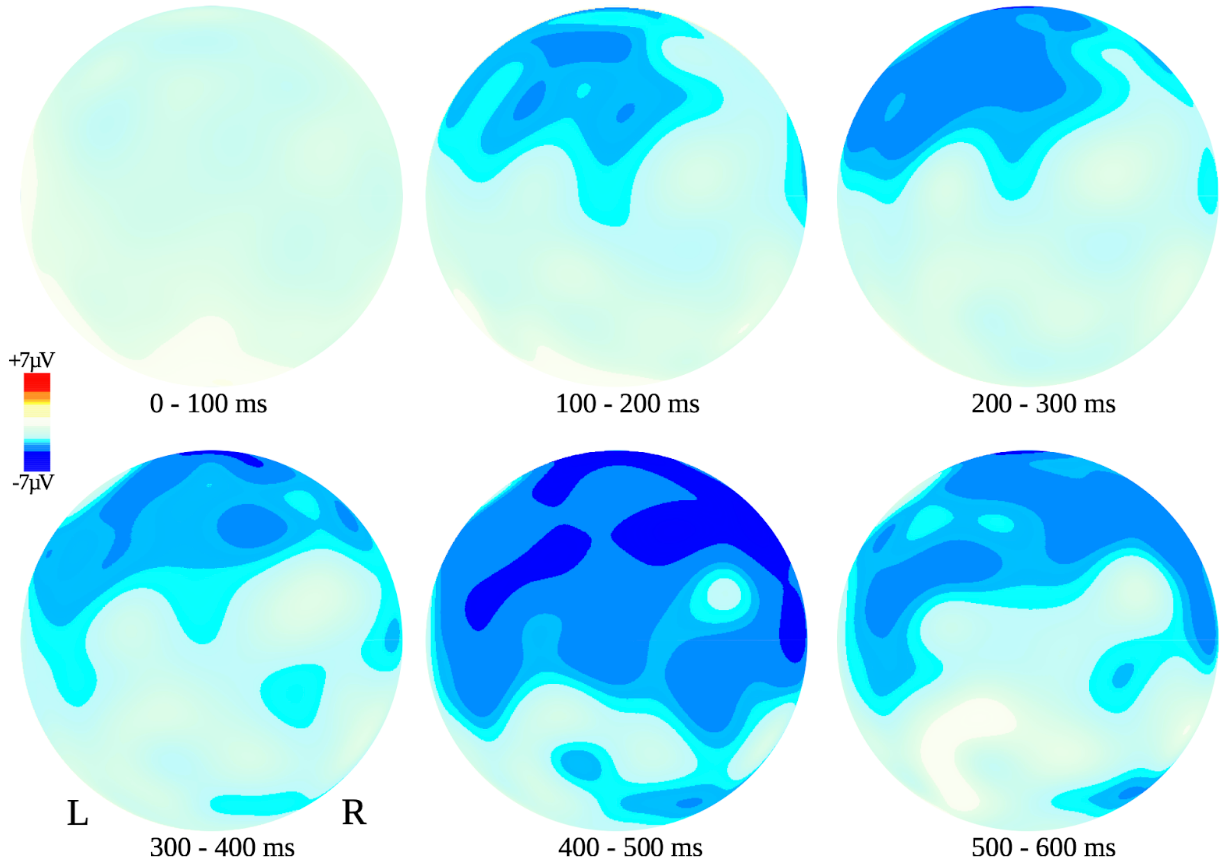

Figure 4. Isopotential maps showing the across-participants calculated scalp distributions of the negative difference between the ERPs to pseudowords in the attentive vs. unattentive conditions at 100 ms time windows between 0 and 600 ms after pseudoword onset. The head viewed from above, L = left, R = right.

Discussion

In the present study, we investigated the effects of selective attention on brain activity in response to spoken familiar words and pseudowords in preschool-age French-speaking children. No overall effect of attention was observed on the ERPs, suggesting that the participants processed the spoken inputs similarly in the attentive and unattentive conditions. However, further analysis demonstrated that the negativity elicited by the pseudowords was augmented during the late phase of the auditory attention condition, suggesting that both attention and repetitive exposure affected the processing of pseudowords. The ERPs in response to the familiar words, in turn, were similar in both attention conditions and exposure phases suggesting similar processing throughout the experiment.

In contrast to our findings, in previous ERP studies using an intramodal attention task, an early positive attention effect, starting around 100 ms, was present for both linguistic and non-linguistic auditory stimuli in preschool (3–5-year-olds) and school (6–8-year-olds) age children (Coch et al., 2005; Karns et al., 2015; Sanders et al., 2006). This effect was prolonged until 300 ms in preschoolers (Sanders et al., 2006). Additionally, a later negative effect for linguistic stimuli was observed in preschool-age children (Sanders et al., 2006), as well as in participants from school-age to adulthood (Karns et al., 2015). The occurrence of the later negativity for the syllable probes was suggested to be due to a more demanding task to attend selectively to linguistic probes compared to non-linguistic probes during story listening. In our study, instead of syllables or non-linguistic items, children were presented with two types of lexical items: familiar words and pseudowords, that followed the phonotactic regularities of native language. Both word types elicited a broad negativity but the main effect of attention was not significant. There are a few possible explanations for the lack of attention effect in the present study.

First, the early positive-polarity attention effect observed in the previous intramodal selective attention studies (Coch et al., 2005; Karns et al., 2015; Sanders et al., 2006) could reflect selection of the attended auditory stimuli on the basis of the feature (location) shared by them and separating them from the unattended stimuli, like the early processing negativity observed in adults in similar paradigms (e.g., Näätänen, 1982, 1990, 1992). Since in the present auditory attention condition, there were no auditory stimuli to be ignored, there was no need for such intramodal selective state possible resulting in the lack of early positive response to attended words or pseudowords.

Second, some studies have found a relatively high intermodal distractibility in preschool children. For example, 4-year-olds were more distracted by auditory distractors (spoken color names) while naming the color of visual stimuli than older (11-year-old) children and adults in a cross-modal Stroop task (Hanauer & Brooks, 2003). Moreover, a study on preschool- and school-age children found that the time needed to name visual objects in the presence of auditory speech distractions got shorter with increasing age (Jerger et al., 2013), suggesting that younger children might not be as good as older children in intermodal selective attention. Thus, it is possible that our preschool-age participants were not efficient in focusing their attention on the relevant input in the bimodal design.

Third, our task may have been too easy for the participants. According to the perceptual load model (Lavie, 1995; 2005; Lavie et al., 1994; 2004), task-irrelevant stimuli are processed more when the perceptual load in the current task is low as more resources are left available for processing the distractors. The high levels of correct responses in the current study (Figure 1) suggests that the children quite easily detected the targets in both modalities throughout the experiment. This suggests that the tasks, which contained 4 images and 4 words in each condition, represented low load for the participants. Moreover, previous studies have shown that while performing a low-load task in one modality, preschool-age children are easily distracted by linguistic stimuli in another modality (Jerger et al., 2013) and that preschool-age children performing a low-load task are less efficient in suppressing processing of linguistic distractors than older children (Hirst et al., 2019). Thus, in the current intermodal selective attention experiment with arguably a low perceptual load, the spoken words might have caught children's attention even during the visual attention condition, resulting in similar ERPs to the spoken words in both attention conditions.

Importantly, in the current experiment, the amplitudes of ERPs to pseudowords became more pronounced during the second half of the experiment in the attention condition. The performance of the participants did not differ between task phases or attention conditions indicating that the children could follow the instructions and perform the task in both auditory and visual conditions throughout the experiment. This suggests that the differential processing of the attended pseudowords in the later phase could be related more to the specific requirements to process the pseudowords than fatigue during the experiment. In line with previous findings in adults (e.g., Bakker et al., 2015; Bentin et al., 1999; Chwilla et al., 1995; Holcomb & Neville, 1990; Rossi et al., 2013) and children (Abel et al., 2018, 2020; Friedrich & Friederici, 2005), the higher N400-like response to pseudowords than to the familiar words in the current experiment likely reflects more demanding lexical search for the pseudowords that are not integrated to the lexicon. Our results suggest that in the first task phase, regardless of attention allocation, the pseudowords were treated similarly to the familiar words. Only after a certain repetition, during the second task phase, and with the allocation of attention, the N400-like response to them became more pronounced. Previously in school-age children, modulation of N400 amplitudes was observed dependent on the meaningfulness of words (Abel et al., 2018, 2020): When children could deduce the meaning of pseudowords from a carrier sentence, the N400 amplitude was attenuated and reached the same level as known words (which remain stable) after only a few repetitions. However, if the pseudoword's meaning was not understandable from the carrier sentence, the N400 levels stayed high (Abel et al., 2018). The steadiness of the ERPs to familiar words in the current experiment in both attention conditions and phases could be explained by the fact that they are among the first words learnt by French infants. Their lexical representations are thus expected to be highly stable in preschool aged children (see Abel et al., 2018; Partanen et al., 2017), consequently their processing could be highly automatized and independent of attentional resources and task load. The differential processing of word types in the current experiment suggests a distinctive role of attention over the lexico-semantic network for unknown words in young children. However, besides the necessary allocation of auditory attention, a certain amount of familiarization with novel words seems to be required for the brain responses to enhance in preschool children, at least in the absence of a semantic context. This finding is in line with the fact that word learning often requires multiple word repetitions which creates opportunities to store more information (e.g., Horst & Samuelson, 2008; Mather & Plunkett, 2009; McMurray et al., 2012), the processing of new words presented in an environment with dense auditory and visual stimulation may also require familiarization.

In sum, the present study investigated the effect of selective attention on auditory ERPs for known word and pseudoword processing throughout a short experiment in preschool children during a cross-modal task. The present results suggest that the processing of attended words depends on attention allocation, the lexical status and repetition. During the second half of the auditory attention condition, the spoken pseudowords were differentially processed in relation to spoken pseudowords that were to be ignored during visual attention. This suggests that in preschoolers, a certain amount of familiarization with words might be needed for the brain responses to enhance for novel words at least when there is no referent.

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General Discussion

Summary of the results

During the second year of life, infants increase the size of their lexicon rapidly, and there are several neural signals in response to word processing that have been associated with growing vocabulary knowledge. However, less is known about neural signatures in response to non-native words, and also, how vocabulary development in bilinguals affect neural signals in response to words. The present dissertation investigated word processing in monolingual and bilingual 24-month-olds, and in monolingual 4-year-olds, using the event-related potential (ERP) technique. In Studies I and II, monolingual and bilingual (learning French and another language) toddlers were presented with known words, phonotactically legal pseudowords, and phonotactically illegal nonwords in a non-referential listening task. The effects of vocabulary skills and the amount of exposure to another language on the processing of different word types were measured. In Study III, the effect of attention on the processing of known and unknown words was investigated using a cross-modal selective attention task in preschool children.

The results of Study I revealed that in monolingual 24-month-olds, the N200 and the late negativity were sensitive to the word type. The amplitudes of both components were similar between known words and pseudowords whereas the amplitudes of nonwords were less pronounced. The results of Study I also showed that the vocabulary skills of toddlers affected the amplitudes of the N200 and late negativity. The productive vocabulary skills and the differences in the N200 amplitudes evoked by known words and pseudowords were positively correlated: toddlers with higher productive vocabulary scores showed bigger differences in amplitudes. There was also an interaction between the productive vocabulary skills and the amplitudes of the late negativity. Toddlers with higher productive vocabulary showed a differential brain activity for the different word types whereas toddlers with lower vocabulary skills were not sensitive to the different word types. The results of Study I suggest that the vocabulary skills of toddlers contribute to the processing of different word types both at the level of word recognition and lexical search. Infants with higher vocabulary skills were shown to be more sensitive to word familiarity and phonotactic structure than their peers with lower vocabulary skills.

Study II investigated the effects of vocabulary skills and the amount of another language input of 24-month-olds bilingual toddlers on the processing of known words, pseudowords and nonwords, using the identical paradigm to Study I. Similar to monolinguals, in bilingual toddlers, the N200 and late negativity were more pronounced for pseudowords than for nonwords whereas no difference between known words and pseudowords was found. The relative amount of exposure to the other language (varying between 15%-50%) did not modulate the ERPs. However, comprehensive vocabulary skills had an effect on the amplitudes of the N200 and late negativity. Bilingual toddlers with higher vocabulary skills exhibited similar responses for pseudowords and nonwords. The bilingual toddlers with lower vocabulary skills on the other hand showed differential brain responses between pseudowords and nonwords. The results of Study II suggest that the relative amount of exposure to each language does not modulate the amplitudes of brain responses for words in toddlers, at least in their dominant language. Comprehensive vocabulary skills on the other hand modulate the brain responses to native and non-native unknown words also in bilingual toddlers. Bilingual toddlers with higher comprehensive vocabulary skills were revealed to be more flexible in processing novel lexical items with non-native phonotactic structure compared to bilingual toddlers with lower vocabulary skills and monolingual peers.

In Study III, monolingual 4-year-olds participated in an intermodal, audio-visual, selective attention task while ERPs were recorded for known words and (legal) pseudowords. The results of Study III revealed that the ERPs in response to known words were not modulated by attention allocation, suggesting that the processing of known words in young children is highly automatized. However, the allocation of (auditory) attention increased the ERPs (from 100 to 600 ms) for pseudowords during the course of the experiment: the ERPs were more pronounced in the second half of the experiment. The results of Study III suggest that selective attention and exposure time modulates the brain responses to novel words in young children.

Processing of phonotactically illegal nonwords does not depend on language experience

There are only a few ERP studies investigating the brain responses to illegal nonwords in monolingual toddlers and to our knowledge none in bilingual peers. The finding of Study I is in accordance with two previous studies in monolingual toddlers showing that nonwords elicit more attenuated brain responses than phonotactically legal pseudowords (Friedrich & Friederici, 2005; Steber & Rossi, 2020). Previously, nonwords elicited reduced amplitudes in a non-referential task (Steber & Rossi, 2020) and failed to evoke an N400 response in a picture-word task (Friedrich & Friederici, 2005) in 18- to 19-months-old toddlers. The authors suggested that, unlike phonotactically legal pseudowords, phonotactically illegal nonwords do not activate lexical semantic pathways. The result of Study I further suggests that nonwords do not activate lexical semantic pathways in French-learning 24-month-old toddlers during a non-referential task.

Previously, it was shown that bilingual infants exhibit a prolonged perceptual narrowing process for non-native sounds (e.g., Ferjan Ramırez et al., 2016; Garcia-Sierra et al., 2011; Petitto et al., 2012; Singh et al., 2017; see also Kuhl et al., 2008), and a higher flexibility to accept non-native words as object labels (e.g., Graf Estes & Hay, 2015; Liu & Kager, 2018; Singh, 2018; Tsui et al., 2019) compared to monolingually raised infants (Graf Estes et al., 2011; Hay et al., 2015; May & Werker, 2014). However, the bilingual toddlers in Study II showed a similar pattern of brain activation to monolingual peers (Study I) for different word types.

The similar pattern of brain responses between monolingual and bilingual toddlers could be, first, due to the relative amount of exposure to French and another language in bilingual participants. The amount of exposure to another language varied between 15% to 50% among participants in Study II, indicating that toddlers were either more or equally exposed to French compared to the other language. For infants and toddlers, who are at a period of language acquisition, bilingualism and language dominance is typically measured by relative language exposure (e.g., Byers-Heinlein, 2015; Birdsong, 2014; De Houwer, 1990). Therefore, the amount of exposure to French of bilingual toddlers in Study II suggests that French was the dominant or equally dominant language for all participants. Previous ERP studies in bilingual toddlers have shown evidence that the processing of the dominant language, but not the non-dominant language, was similar to monolingual peers in a non-referential task (Conboy & Mills, 2006) and in a lexical-semantic priming task (Sirri & Rämä, 2019). The results of Study II demonstrate that bilingual and monolingual toddlers have a comparable pattern of activity in response to different word types in their dominant language, suggesting that nonwords do not activate lexical semantic pathways also in bilingual toddlers during a non-referential task. Moreover, all bilingual toddlers, exposed between 15% to 25% or between 30% to 50% to another language, showed a similar pattern of brain activation to monolingual peers in Study I, suggesting that the level of exposure to the other language does not affect the processing of different word types in the dominant language.

Second, the choice of nonwords in Study I and II, could have also contributed to the similar pattern of activity for words in monolingual and bilingual toddlers. There is evidence that the degree of word typicality (i.e., whether or not a word conforms to phonetic and phonotactic properties of native-language) has an effect on the performance during word learning tasks both in monolingual and bilingual toddlers (see Tsui et al., 2019). The performance diminishes as words become more atypical, that is, containing more inconsistent sound patterns of the native language. The nonwords used in the current experiment were created by an addition of a consonant to create an onset consonant cluster that violates the phonotactic rules of French, and thus, they could be atypical enough for both mono- and bilingual toddlers to disregard them from being potential words. Moreover, nonwords with imported non-native sounds from foreign languages in some previous experiments (e.g., Liu & Kager, 2018; Singh, 2018) may not have the same status for bilinguals as nonwords with native phonemes but are phonotactically illegal phoneme combinations (see Graf-Estes et al., 2011). Previously, in monolingual infants, word learning performance was affected by phonotactic patterns of stimuli (legal versus illegal word-initial consonant sequences) (Graf-Estes et al., 2011). In bilingual infants, language dominance has been shown to affect the sensitivity to phonotactic properties during the first year of life (Sebastián-Gallés & Bosch, 2002): Catalan-dominant 10-month-olds were as sensitive as Catalan monolinguals to the phonotactic rules of Catalan, whereas Spanish dominant Catalan-Spanish bilingual infants were less sensitive. The bilingual toddlers in Study II could be highly sensitive to the phonotactic regularities of French (as they were French-dominant), and word processing could be restrained by the native phonotactic rules. The results of Study II suggest that at 24-months bilingual toddlers are committed to the sounds of native language as much as monolingual peers, and nonwords do not trigger lexical pathways during a non-referential task

Third, the non-referential nature of the task could also explain the similar ERPs between mono- and bilingual toddlers, as the nonwords were presented out of context. In word learning experiments, bilingual infants show a higher flexibility in accepting non-native sounds as novel labels for novel objects (Graf Estes & Hay, 2015; Singh, 2018; Singh & Tan, 2021). However, a meta-analysis showed that adding referential cues increased the flexibility of infants to accept more atypical words as object labels, regardless of language background (Tsui et al., 2019). Moreover, a recent study with monolingual and bilingual infants showed that the flexibility to treat non-native sounds depends on the referential nature of the specific task used. In this study, both monolingual (learning English) and bilingual (learning English and Mandarin) 14-month-olds failed to discriminate non-native sounds (from Hindi) in a non-referential design (Singh & Tan, 2021) while during a word learning task, in the presence of a referential object, 14-

month-old monolinguals as well as 14- and 19-month old bilinguals were sensitive to the non-native phonetic variations. None-the-less at 24-month-olds, bilingual infants did not show sensitivity to non-native sounds even during word-learning, suggesting a commitment to native sounds in bilingual toddlers also in referential tasks at this age. In behavioral word learning experiments, infants' fast mapping ability is employed to link a novel word to a novel object, whereas in Study II words were presented out of context, without matching to objects. As suggested by Singh and Tan (2021), linguistic sensitivities measured in non-referential and word learning tasks could be measuring non-identical mechanisms.

In sum, Study I and II presented evidence on the effects of language background on word processing, in a continuum from monolingual French learning to balanced bilingual toddlers. The results indicated that, regardless of language background, nonwords evoked smaller N200 and late negativity responses than pseudowords, suggesting that phonotactically illegal nonwords do not activate lexico-semantic mechanisms in a non-referential task.

Vocabulary skills affect the processing of words differently in monolingual *versus* bilingual toddlers

Both monolingual and bilingual 24-month-olds in Study I and II showed similar brain responses to known and unknown words whereas the ERPs for nonwords were attenuated. Although both groups demonstrated an interaction between vocabulary skills and the brain responses to different word types, the effect of vocabulary skills on N200 and late negativity in monolingual *versus* bilingual toddlers was different. Monolingual toddlers with higher productive vocabulary showed a gradient pattern of activity in response to different word types, while those with lower vocabulary skills responded equally to all words. Bilingual toddlers with higher comprehension skills on the other hand elicited similar brain responses to pseudowords and nonwords, while those with lower vocabulary showed a differential signal in response to pseudowords and nonwords.

In accordance with previous studies (Freidrich, & Friederici, 2004; 2006; Mills et al., 1997), vocabulary skills modulated the magnitudes of ERPs in response to known and unknown words in monolingual toddlers. There was also a correlation between the number of words in the productive vocabulary and the N200 amplitude difference between known words and pseudowords. Monolingual toddlers with a higher productive vocabulary had a bigger difference in amplitudes than peers with a lower productive vocabulary. The "known words" that were chosen in Study I and II Study I were among the first acquired lexical items of French-learning infants. Moreover, prior to the experiment, the parents verified whether their toddlers understood them or not. Therefore, the lack of difference in the N200 amplitudes between known words and pseudowords is unlikely to be due to a failure to recognize the known words, even in toddlers with lower vocabulary scores. In the previous study by Mills and colleagues (1993, 1997), known words elicited more negative ERPs than unknown words in 20-month-olds in a non-referential task. However, in another study by Mills and co-workers (2005), when the stimuli were presented in an infant directed speech (IDS), familiar and novel words evoked similar ERPs. The authors suggested that the lack of differences between known words and unknown words could be due to attentional effects caused by the use of IDS (see also, Zangl & Mills, 2007). In Study I the stimuli were not presented in IDS, although the speaker was asked to read them in a slow and clear manner. Therefore, the amplitude differences between known words and pseudowords are likely to be related to vocabulary skills of participants in Study I, instead of IDS related effects. Although all toddlers knew the experimental words, the strength of word representations and the age of acquisition might have differed in low and high producers, which in turn, could explain the correlation between productive vocabulary and the N200 amplitude difference between known words and pseudowords.

Similarly, the late negativity was modulated by an interaction between vocabulary group and word type. Monolingual toddlers with higher productive vocabulary skills exhibited a gradient pattern of activity for different word types whereas the toddlers with lower productive skills showed similar brain activation in response to all word types. A previous study using a picture-word congruence task found that 19-month-olds with high comprehension skills showed a bigger N400 incongruity effect than peers with low comprehension skills (Friedrich & Friederici, 2004). Moreover, when 19-month-olds were grouped retrospectively according to their language skills at 30-months, unlike 19-month olds with age adequate vocabulary skills, those with vocabulary skills below age norms did not show a differential processing of legal pseudowords and illegal nonwords (Friedrich & Friederici, 2006). Study I provided evidence that vocabulary skills have an effect on the ERPs for words also in a cross-sectional design as the vocabulary skills were evaluated at the same time of the ERP measures, at 24-months. The results of Study I further indicated that toddlers with higher vocabulary skills exhibit differential brain activation patterns for known words, phonotactically legal pseudowords and phonotactically illegal nonwords, suggesting that vocabulary knowledge contributes to word processing in both word recognition and lexical search levels.

The findings of Study II indicated that in bilingual toddlers, the amount of comprehensive vocabulary contributes to the brain responses to different word types. Bilingual toddlers with higher comprehension skills responded equally to pseudowords and nonwords, while bilingual toddlers with lower comprehension skills responded equally to known words and pseudowords. The results are partially parallel to previous behavioral findings showing that bilingual infants are more flexible in treating non-native word-forms both in perceptual tasks (e.g., Garcia-Sierra et al., 2011; Ferjan Ramırez et al., 2017; Petitto et al., 2012; see also Kuhl et al., 2008), and word-learning situations (e.g., Graf Estes & Hay, 2015; Liu & Kager, 2018; Singh, 2018). However, the findings of Study II suggest that only bilingual toddlers with higher vocabulary skills are more likely to treat novel words with non-native phonotactic structure (nonwords) similar to those with native phonotactic structure (pseudowords). Processing nonwords and pseudowords similarly may be an adaptive strategy during bilingual language acquisition, considering that the linguistic environment of bilingual infants has a higher level of phonetic and phonotactic variability. Previously it was shown that 17-month-old bilinguals could learn minimal pairs pronounced bilingually, whereas their monolingual peers failed to do so (Mattock et al., 2010), showing a higher flexibility to treat phonological variability in bilinguals during word learning. Additionally, toddlers with higher vocabulary skills in Study II may be more efficient in directing the limited cognitive resources onto processing novel word forms rather than differentially processing pseudowords and nonwords. Previously it was suggested that phonetic details during word learning may be less important for bilingual infants as they may be directing cognitive resources more into word learning (e.g., Fennell et al., 2007).

Interestingly, bilingual toddlers with higher comprehensive vocabulary skills in Study II, showed similar patterns of brain responses to monolinguals with lower productive vocabulary skills in Study I. Previously one study found similar patterns of neuronal activity between bilingual infants with a high language input and monolingual infants with a low language input (Garcia-Sierra et al., 2016). The authors suggested that the similar amount of language input in the tested language between the groups could explain the similar patterns. In other words, monolinguals with low language input had a comparable amount of language input in the tested language to bilinguals with high vocabulary skills. Previously in monolinguals vocabulary skills were linked to the amount of language input (Hart & Risley, 1995; Hoff, 2006; Huttenlocher et al., 1991). Similarly, in bilinguals, the amount of language input in one language was associated to the vocabulary skills in bilingual infants in that language (e.g., Barnes & Garcia, 2013; Floccia et al., 2018; Hoff, 2003; Hoff et al., 2014; Law & So, 2006). In the same direction, in Study II, the relative amount of French input positively correlated with the number of words produced. The toddlers in the Exposed group (exposed to French 75% to 85% of total language exposure time) produced more words than toddlers in the Balanced group (exposed to French 50% to 70% of total language exposure time). In Study II, the parents estimated the conceptual vocabulary size and relative amount of vocabulary input between the languages, while the amount of real language input in French was not measured. The amount of language exposure in bilinguals is divided in two languages resulting often in a reduced time of exposure in each of their languages (for a review, see Hoff & Core, 2013). It is possible that bilinguals with high vocabulary skills and monolinguals with low vocabulary skills had comparable input in French, as suggested by previous studies measuring real language input using the LENA system (Garcia-Sierra et al., 2016). The similar brain responses between bilinguals with high vocabulary skills and monolinguals with low vocabulary skills could thus be due to (a possibly) similar amount of language input in these groups with respect to only French input.

Attention affects the processing of pseudowords in young children

Processing of speech has been shown to be highly automatic in children (e.g., Uwer et al., 2002). Nevertheless, language skills correlate positively with attentional measures in infants and young children (e.g., Dixon & Shore, 1997; Dixon & Smith, 2000; Kannass & Oakes, 2008; Mundy et al., 2003; Yu & Smith, 2011), suggesting that the efficiency of word learning may be linked to the ability to selectively attend to relevant information in speech. Previously, only a few studies have explored the automatic allocation of attention to familiar and unfamiliar words in infants and toddlers (Kuipers & Thierry, 2013; 2015; Thierry et al., 2003; Vihman et al., 2007). The authors linked N200 amplitudes to attentional mechanisms and have shown that age, specific language tested and the language background affected differential N200 modulations for familiar and unfamiliar words. However, most studies with controlled attentional conditions on speech processing were carried out with preschool-aged children (Coch et al., 2005; Karns et al., 2015; Sanders et al., 2006; Stevens et al., 2009).

Arguably preschool and school aged children are able to more efficiently and reliably direct their attention than infants on demand during a selective attention task. Thus, Study III investigated the effects of voluntary allocation of attention on spoken words in preschool children.

In Study III there was no overall attention effect on the magnitudes of ERPs, which could be due to the use of an intermodal task, high distractibility of young children - especially by speech - or the easiness of the task. However, the results of Study III demonstrated that the effect of attention on word processing depends on the lexical status of the word as well as exposure time. The ERP responses to known words were similar throughout the experiment regardless of attention allocation, suggesting that the processing of known words is highly automatised. It is worth stating that as the known words in Study III were among the first learnt words by French infants, the mental representations for them might be particularly stable in pre-school children. The ERPs for novel lexical items, on the other hand, were modulated by attention and exposure time. In the attended condition, an increase in the slow negative ERP response for pseudowords was observed during the second half of the experiment. The results suggest that attention is affecting the brain responses to novel lexical items in young children. The negative processing difference (Nd) for the attended pseudowords in Study III could be due to the higher cognitive effort needed to process the pseudowords, as unlike known words, pseudowords are not yet integrated into the mental lexicon (see Bentin et al., 1985; Chwilla et al., 1995; Soares et al., 1991; see also Friedrich & Friederici, 2005). In school-aged children, brain responses were more negative for pseudowords whose meaning the children did not learn yet, suggesting that unknown words evoke higher N400 responses also in children (Abel et al., 2018). Thus the higher ERPs for pseudowords in Study III is likely to reflect the activation of lexical semantic search pathways in preschool aged children. However, the responses to pseudowords became more negative only in the second half of the experiment in Study III, demonstrating a modification of ERPs by word repetition. Thus perhaps, in young children, a certain familiarization with novel word forms is also needed along with the allocation of attention for the brain responses to enhance. In sum, the results of Study III demonstrated that paying attention to unknown words affects brain responses for them while for known words attention allocation does not affect word processing.

Limitations and Future Directions

This dissertation provided new evidence on the effects of vocabulary skills and language experience on neural signatures of word processing in monolingual and bilingual (Study I and II) toddlers. Additionally, Study III presented evidence that the brain responses for pseudowords become more pronounced by selective attention and exposure time in preschool children. Although this dissertation addressed many questions on lexical processing of different word types during mono- and bilingual language acquisition, the studies in the current dissertation have some limitations.

First, Study I and II showed that vocabulary skills affected the processing of different word types in monolingual and bilingual 24-month-olds. Combining the current study with a longitudinal design could predict a link between the brain signatures of different word types at 24-months (or an earlier age) and later language outcome. A recent longitudinal study demonstrated that the amplitudes of ERP components underlying lexical-semantic processing were reduced, along with distributional alterations, in toddlers with low expressive vocabularies and early signs of autism spectrum disorder (Cantiani, et al., 2021). The ERP amplitudes measured at 19-months correlated with communication measurements at 24-months, suggesting that toddlers at a risk for a neurodevelopmental disorder already had altered brain signatures a few months earlier. Further longitudinal studies are needed to follow the developmental outcomes of toddlers with low and high vocabulary skills to investigate the link between word processing at an early age and future linguistic skills. This approach could be beneficial for identifying toddlers at risk of language related development delays.

Second, there were also some limits due to the diversity of the other languages learnt (besides French) as well as the variability in linguistic environments of bilinguals. Study II included bilinguals learning French and another language among twenty-two different languages due to the diversity of families with different bilingual language pairs in Paris and the relative scarcity of bilingual toddlers with specific language pairs. In order to keep a uniform way of measurement, the parents were asked to include words known by infants in both languages although they were given only the French CDI, and the amount of known words estimated by parents this way was accepted as conceptual vocabulary of toddlers. Previously, while calculating the conceptual vocabulary, the parents were given the CDI in both languages, then words that the child knows in both languages were added up while the number of concepts occurring in both languages were subtracted (Core et al., 2013). In Study II, the variability of linguistic environments at home of bilinguals could have caused unreliable estimates by some parents who received only the French CDI. Moreover, some concepts in other languages may be lacking in the French CDI, as suggested by the differences in the words included in adaptations of CDI in different languages (see Dale, 2015). Thus using only the French CDI may have resulted in an underestimation of the vocabulary skills of some toddlers (depending on the language they are learning).

Another related confounding variable could be the variability of the language pairs between the bilingual toddlers tested. Previously the phonological overlap between the language pairs of bilingual toddlers was shown to have a positive effect on expressive vocabulary skills (Floccia et al., 2018). Other measures of linguistic distance, word order typology and morphology, had similar effects on comprehensive vocabulary, providing evidence that bilinguals learning different pairs of languages are not necessarily identical in language development. The effects of variable linguistic distance between the language pairs of bilingual toddlers tested in Study II remained undetected in this thesis and could perhaps have biased the distribution of toddlers learning specific language pairs differently in high and low vocabulary groups. Toddlers with different language pairs could also process pseudo-words and nonwords in a non-identical manner. Due to the vast variability of the other languages learnt by bilingual toddlers in Study II, the phonotactic status of the nonwords in all other languages was not checked (although this was initially attempted). Testing participants from specific bilingual pairs (e.g., only toddlers who are exposed to French and English) in the future could help disentangle the effects of various language-specific contributions. Selecting bilinguals from a restricted group of language pairs could be more conclusive, particularly regarding the processing of non-native words. In order to help to evaluate vocabulary skills of bilingual infants with such variable language backgrounds, future studies are needed to develop a tool to measure vocabulary in French similar to the UKBTAT (Floccia et al., 2018) which was specifically developed to measure vocabulary skills of toddlers learning English and another language. Unlike the CDI, programming tools are able to take into account variability in language input, such as linguistic distance, while estimating vocabulary skills of bilingual toddlers. These tools could allow a more reliable measuring of vocabulary skills for bilinguals learning various language pairs. Bilingual research would benefit from standardized measures in different languages that are easy to apply and take into account multiple language pairs.

Third, in all the studies presented in this dissertation, the ERPs were recorded throughout the experiments in order to investigate the changes in the brain reactions in time. Although attention and exposure time affected the ERPs for pseudowords in Study III, the brain signals did not change during the experiment in Study I and II for any word type. The lack of phase effect in Study I and II could be due to attentional fluctuations of toddlers throughout the experiments or a lack of attention to the auditory stimuli. Study III provided evidence for the role of attention on word processing in young children: attention increased the ERPs for pseudowords during the course of the experiment. However, the ages of participants in Study III were not identical to Study I and II. During Study III, the role of attention in 4-year-olds, instead of 2, was investigated mainly due to the difficulty to cue younger infants during a (controlled) selective attention task.

There is recent evidence showing that exposure to novel lexical items (pseudowords) increases neuronal responses during the course of a short passive-listening experiment (e.g., Partanen et al., 2017; Shtyrov, 2012). Similar modulation was not found for known words, suggesting that neural representations for known words are already robust. The authors have suggested on the other hand that the rapid modulations of ERPs for pseudowords represents a neural signature for lexical acquisition. Interestingly, the neuronal modulations for pseudowords were faster in school-age children than in adults, that is, less amount of pseudoword repetition was needed for the neuronal responses to enhance. In Study I and II, the brain responses did not change over the course of the experiment. The lack of phase effect could be due to stimulus differences with these studies: in previous studies, the ERPs were averaged from word disambiguation points (i.e. when the word is identified as a known or unknown item), while in the current studies the ERPs were averaged from word-onsets, not word disambiguation points. Nonwords were created with the addition of a consonant to word-onset, as this is a common way to create illegal word-forms in French (Dell, 1995). However, this made it not possible to average ERPs from word disambiguation points for all word types, known words, pseudowords and nonwords. For a follow-up study, we designed novel stimuli (known words and pseudowords, e.g., “gâteau” and “gâpeau”) whose disambiguation point was set at the onset of the second syllable. Monolingual 24-month-olds were tested in a passive listening task as the ERPs were recorded throughout the experiment. The preliminary analyses showed that during the course of the experiment, the brain signals increased in response to novel pseudowords while no modulation was observed for known words. Additionally, potential effects of vocabulary skills on neuronal modulations for pseudowords will be investigated. This study, and other similar ones, could provide further information about the neural mechanisms involved during lexical acquisition or familiarization with novel items in infants and toddlers.

Although half of the world population is raised multilingual, there is relatively a small amount of research on word processing during bilingual first language acquisition and even less for trilinguals. Neural correlates of lexical processing in trilinguals are little known. A group of trilingual 24-month-olds were tested in an identical experiment to Study I and II with the aim to explore the effects of exposure to a third language on the brain signatures for different word types. Although the data collection continues in this on-going project, this additional group of subjects with an exceptionally rich linguistic background will help understanding the effects of multilingual language exposure on word processing.

Finally, this dissertation contributed to the understanding of the effects of language background and vocabulary skills on the processing of different word types. During this work we have highlighted some of the neuronal signatures related to word processing in monolingual and bilingual toddlers. Moreover, this dissertation provided evidence to help understanding the role of selective attention on word processing in young children. However, future studies are needed to build up on the findings revealed in this dissertation to investigate further the neuronal correlates of language acquisition.

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Annex

CONSENTEMENT DE PARTICIPATION
pour une recherche sans bénéfice individuel direct

(Formulaire de consentement concernant les représentants légaux d'un sujet mineur)

Nous soussignés : ……
déclarons accepter que l'enfant ……………………………………………………………… dont nous avons la charge légale participe à la recherche intitulée : ………………………………………………………………………………………
……… menée par ……………………………………………………………………..…………………………………… sous la responsabilité de ……………………………………………………………………… Les informations recueillies font l'objet d'un traitement informatique destiné à étudier …………………….……………………………………………………………………………………………
………….……
dans les conditions précisées ci-dessous et pour laquelle le Comité d'Éthique de la Recherche (CER) a émis un avis favorable.

Nous avons bien reçu les informations concernant la recherche.

Il nous a été précisé que :

- Conformément à la loi Informatique et Libertés du 6 janvier 1978 (Loi n° 78-17), modifiée en juin 2018 pour le cadre juridique européen (RGPD-n°2016/679), nous bénéficions d'un droit d'accès, de transparence, de rectification, de limitation et d'effacement des informations qui nous concernent, que nous pouvons exercer en nous adressant à : incc-contact.labobb@services.cnrs.fr et à la Déléguée à la Protection des Données du CNRS : dpd.demandes@cnrs.fr

- Nous sommes libres d'accepter ou de refuser ainsi que d'arrêter à tout moment la participation de l'enfant dont nous avons la charge.

- Les données personnelles qui concernent l'enfant dont nous avons l'autorité parentale seront strictement conservées dans l'enceinte du laboratoire.

- La publication des résultats ne comportera aucun résultat individuel identifiant. Dans le cadre de la publication des résultats, les données anonymes de la recherche pourront être partagées avec les autres chercheurs du domaine.

- Nous pourrons à tout moment demander des informations aux responsables de la recherche.

- Nous pouvons être tenus au courant des résultats globaux de la recherche en consultant le site : https://baby.biomedicale.parisdescartes.fr/fr

- Cette recherche est sans bénéfice individuel direct pour les personnes qui y participent.

- Notre consentement ne décharge pas les organisateurs de la recherche de leurs responsabilités.

- Nous conservons tous nos droits garantis par la loi.

Nom et signature de l'investigateur Fait à Paris, le ……………………………….

Signature du ou des parent(s) responsable(s)

Accepteriez-vous d'être recontacté dans le futur par le Babylab ? OUI NON

Questionnaire de Bilingue Babylab INCC

élément sous droit, diffusion non autorisée

CDI : MacArthur communicative development inventories

élément sous droit, diffusion non autorisée

L’aventure du chercheur en herbe au Labo Bébé

Avant de te joindre à notre mission au Labo Bébé, lis donc avec ta Maman ou ton Papa le récit de l’aventure passionnante qui t’attend.

Prends un petit moment pour te reposer tranquillement avant de venir au Labo. Mange un petit morceau si tu as un peu faim pour prendre des forces, être prêt et joyeux.

Sache que ton Papa ou ta Maman seront là pour t’accompagner durant tout le temps passé au Labo. Ici tu es en totale sécurité.

Laisse-moi maintenant t’expliquer comment se déroulera ton aventure ici et ce que fait une chercheuse comme moi, Oytun, lorsque j’étudie le cerveau.

Nous avons un tas de jouets ici à l’accueil du Labo.

Tu peux jouer avec tous ceux qui te plaisent, super non? Ta Maman ou ton Papa jouerons aussi avec toi. Même moi j’ai bien envie de jouer avec toi.

Bon, je vais t'expliquer ce que tu vas faire comme petit chercheur ici.

Je te présente Monsieur le chat et Monsieur le robot.

Ce sont des assistants chercheurs ici au Labo.
Choisis-en un. Il sera notre compagnon de voyage aujourd'hui.

Il faut que tu m'aides à mesurer l'activité de leur cerveau. Tu vas voir c'est vraiment rigolo.
Bien, es-tu prêt?

Afin de mesurer l’activité de leur cerveau, nous devons utiliser un bonnet. Voilà à quoi ça ressemble. Quel look!

D’abord mesurons ensemble leur tête, comme ça.

Ensuite on mesurera la tête de chacun d’entre nous.

Maintenant il faut soigneusement mouiller le chapeau avec un petit peu d'eau. Pas de trop, juste comme il faut. L'eau va nous aider à mesurer plus précisément les signaux émis par le petit cerveau.

C'est un peu comme le bonnet que tu mets à la piscine finalement.

Ensuite, mettons le chapeau sur la tête de M. le Chat ou M. le Robot. Il faut que tu m'aides, tu es aussi un membre de l'équipe maintenant. C'est super!

Haha regarde les. Comme ils sont beaux avec ces bonnets.

Maintenant nous les amenons à la chambre d'expérience.
Ils regardent un dessin-animé super cool pendant l'expérience, quelle chance.

Ho, et ils écoutent des sons différents. En tant que bons chercheurs, il sont très calmes et joyeux dans cette petite chambre. L'expérience ne dure que quelques minutes.

Impressionnant! Tu es un vrai chercheur maintenant que l'expérience est finie. Il faut prendre une photo avec le chapeau avant de l'enlever.

Regarde un peu ! Quel style ! Ils mériteraient un diplôme!

Après cela, avec ton aide, nous allons enlever délicatement le bonnet de M. le Chat et M. le Robot. Cela se déroule très vite. Et nous leur donnerons un diplôme pour les féliciter de leur participation.

Holala, quel beau diplôme!

Voici donc la grande, la passionnante aventure de la recherche sur le cerveau au Labo Bébé!

C’est à ton tour de devenir un grand chercheur maintenant! Tu seras une formidable aide pour nos recherches. Tu peux maintenant participer à cette expérience et mettre ce super chapeau comme Monsieur le chat pour avoir ton propre diplôme de scientifique!

Nous attendons avec impatience ta visite pour vivre cette aventure, à très vite.