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Représentation des mots et des non-mots
en mémoire visuelle à court terme :
Évidence provenant de l'électrophysiologie humaine.

par

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Mémoire présenté à la Faculté des études supérieures

en vue de l'obtention du grade de Maître ès sciences (M. Sc.)

en psychologie

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(Membres du jury)

**Université de Montréal
Faculté des études supérieures**

Ce mémoire intitulé :

**Représentation des mots et des non-mots
en mémoire visuelle à court terme :
Évidence provenant de l'électrophysiologie humaine.**

**présenté par
David Predovan**

a été évalué par un jury composé des personnes suivantes :

**Martin Arguin, Ph. D., Président du jury
Pierre Jolicoeur, Ph. D., Directeur de recherche
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Mémoire accepté le :

SOMMAIRE

La présente étude vise à mieux comprendre comment les mots et les non-mots sont mémorisés en mémoire visuelle à court terme (MVCT). Des mesures électrophysiologiques ont été utilisées pour étudier la contribution du statut lexical sur le maintien d'une série de lettres en MVCT. La composante SPCN (sustained posterior contralateral negativity), un marqueur électrophysiologique qui reflète le maintien de l'information en MVCT a été mesuré lors de la mémorisation de mots, de non-mots (prononçable ou imprononçable) ainsi que de lettres dispersées à l'écran. Une composante SPCN d'amplitude réduite a été mesurée pour la condition mot en comparaison à la condition non-mot (et ce indépendamment de leur prononçabilité), indiquant que le statut lexical influence le maintien de l'information en MVCT.

Pour des fins exploratoires, une comparaison entre la condition non-mot et lettres dispersés a également été effectuée. Sur la base de recherches antérieures, la composante SPCN ne devrait pas être affectée par la taille de la région à encoder. Étonnamment, des différences d'amplitudes significatives entre la composante SPCN pour les non-mots et lettres dispersés ont été trouvées, ce qui suggère que des mécanismes d'encodage spéciaux semblent recrutés lorsque la série de lettres à mémoriser a une forme semblable à celle d'un mot.

Mots clés : Accès lexical, composante SPCN

SUMMARY

Electrophysiological measures were used to investigate the contribution of lexical status on the maintenance of letter strings in visual short-term memory (VSTM). The sustained posterior contralateral negativity (SPCN), an electrophysiological marker of storage in VSTM, was measured for words and nonwords as well as scrambled letters. A smaller SPCN was found for words than for nonwords (independently of their pronounceability), indicating that lexical status influences storage in VSTM. One possibility is that words produce a smaller SPCN because they can be recoded to a form that does not require a low-level representation in VSTM.

For exploratory purpose, a comparison between the nonwords and the scrambled nonwords was also made. Based on previous research, the SPCN component should not be affected by the size of the region enclosing to-be-encoded objects. Surprisingly, significant differences between the SPCN for nonwords and scrambled letters conditions were found, suggesting that special encoding mechanisms may be recruited to encode word-like letter strings.

Keywords : Lexical Access, SPCN component

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LISTE DES ABRÉVIATIONS

MVCT	Mémoire visuelle à court terme
SPCN	Sustained posterior contralateral negativity

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Introduction générale

L'accès lexical

Le lexique mental est un système de représentations mentales locales (Coltheart, 2004) qui rend possible la reconnaissance d'un mot par un traitement à la fois ascendant et descendant de ces modules.

Le traitement de bas en haut, commencerait par un processus prélexical qui traiterait les stimuli selon leurs ressemblances à la forme canonique d'un mot. Par exemple en conformité à des règles orthographiques dans le cas d'un stimulus présenté visuellement (Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999). À ce stade, le mot pourrait être différencié d'autres stimuli non verbaux. Lors d'une expérience utilisant la tomographie par émission de positrons, Petersen, Fox, Snyder, et Raichle (1990) ont observé que le cortex visuel extrastrié médian gauche était activé pendant le traitement passif de mots et de pseudomots en comparaison à une série de lettres ou de symboles imprononçables. Ils ont aussi observé que seuls les mots activaient les aires frontales gauches qui sont reliées aux traitements sémantiques des mots. Les mots seraient donc traités à un niveau supérieur et bénéficieraient de ce que l'on appelle l'accès lexical.

Au niveau de l'électrophysiologie humaine, les mots ont aussi leurs propres marqueurs. Ainsi, dans une tâche basée sur le paradigme de Reicher-Wheeler, Martin, Nazir, Thierry, Paulignan, et Démonet (2006) ont mesuré une

amplitude plus élevée de la composante N170 lorsque la lettre à mémoriser faisait partie d'un mot que lorsqu'elle faisait partie d'une série de lettres qui n'était pas prononçable. D'autres effets d'expertise reliés à la composante N170 ont été retrouvés dans la perception de mots (Eulitz, Eulitz, Maess, Cohen, Pantev, et Elbert, 2000) versus des stimuli non verbaux. Cette négativité serait associée à l'activité présente dans le gyrus fusiforme gauche communément appelé Visual Word Form Area (McCandliss, Cohen, & Dehaene, 2003) bien que cette dénomination ne fait pas consensus. (Price & Devlin, 2003). Enfin, la composante N170 est étroitement reliée à la composante N1 qui est une composante connue pour refléter les processus reliés à la discrimination (Vogel et Luck, 2000).

L'accès lexical a souvent été pensé comme étant un stade tardif qui succède au traitement prélexical. En raison, d'une résolution temporelle plus fine l'électrophysiologie humaine permet de mieux comprendre comment interagissent le traitement prélexical et l'accès lexical. Ainsi, des enregistrements électroencéphalographiques lors d'une tâche de décision lexicale montrent que l'accès lexical modifie précocement l'activité cérébrale (Sereno, Rayner, et Posner, 1998). La tâche consistait à appuyer une touche si la série de lettres présentées formait un mot. Dans le cas d'un mot, la fréquence d'emploi de celui-ci dans le langage courant et sa régularité de prononciation (i.e : hour vs tour & your) étaient contrôlés. Ces deux paramètres ont été choisis, car ils sont reliés à l'accès lexical. Comme attendu des différences d'amplitude de la composante N1

entre la condition mot et non-mot ont été rapportées. Il est également intéressant de constater que les deux paramètres mentionnés modulaient eux aussi la composante, laissant place à une nouvelle interprétation des interactions entre les deux processus.

Plusieurs études montrent que l'accès lexical semble être un processus automatique qui est effectué indépendamment de la tâche. Dans une expérience utilisant la technique de la TEP, Price, Wise, et Frackowiak (1996) ont montré qu'une tâche qui ne nécessitait pas de traitement lexical ou sémantique des stimuli présentés, activait tout de même certaines régions reliées à l'accès lexical. Une autre expérience utilisant cette fois si l'électroencéphalographie avec des stimuli auditifs a aussi montré des effets liés à l'accès lexical des stimuli même si ceux-ci n'étaient pas pertinents à la tâche (Muller-Gass, Roye, Kirmse, Saupe, Jacobsen, et Schröger, 2007).

L'intégration sémantique est souvent associée à la composante N400 (Kutas et Hillyard, 1980). À la lecture d'une phrase où la présence d'un mot apparaît conflictuelle à la signification de celle-ci, il est possible de mesurer une composante négative apparaissant environ 400 ms après la présentation de ce mot. On observe aussi cette composante dans un paradigme d'amorce sémantique. Étant une des composantes les plus étudiées sur le langage et se produisant relativement tard dans le décours temporel, on peut croire qu'elle ait monopolisée les vues sur le statut apparemment tardif de l'accès lexical.

Récemment, Penolazzi, Hauk, et Pulvermuëller (2006) dans une tâche similaire à celle mentionnée plus haut (présence d'un mot incongru dans une phrase) ont montré en contrôlant plusieurs facteurs dont la taille des mots que l'accès lexical se faisait beaucoup plus rapidement que prévu, soit 200 ms avant la composante N400.

L'accès lexical se produisant rapidement, il est possible de mesurer ses effets sur d'autres composantes. En effet, Dell'Acqua, Pesciarelli, Jolicoeur, Eimer, & Peressotti (2007) ont montré que la composante N2pc qui est associée au déploiement de l'attention dans l'espace est affectée par le statut lexical des stimuli présentés. Lors d'une tâche de décision lexicale où un mot était présenté dans chaque hémichamp et où l'on demandait au sujet de porter attention au stimulus en rouge, le déploiement de l'attention était moins marqué (une composante d'amplitude réduite) lorsque les deux mots partageaient la même sémantique. On peut penser que l'activation des sens de chaque stimulus a engendré une forme d'intégration sémantique initiale qui a nuit au déplacement de l'attention subséquent vers la cible.

Influence du statut lexical et mémoire visuelle à court terme

Sachant que le statut lexical d'une série de lettres peut influencer le processus qui permet le déploiement de l'attention dans l'espace, la présente étude examine l'influence du statut lexical sur d'autres processus qui succèdent

à ce processus, plus particulièrement la mémorisation d'une série de lettres en mémoire visuelle à court terme (MVCT).

Lorsqu'une tâche d'attention spatiale nécessite le rapport d'une cible parmi des distracteurs, on mesure 200 ms après la présentation des stimuli, un potentiel évoqué négatif sur les électrodes postérieures du scalp. Fait intéressant la négativité maximale est souvent observée de façon contralatérale à l'emplacement du stimulus (la composante N2pc). On mesure la N2pc en calculant la différence de voltage des paires d'électrodes postérieures ipsilatérales et contralatérales à la présentation du stimulus à rapporter. La N2pc refléterait des processus liés à la localisation des cibles (Woodman et Luck, 1999) et au rejet des stimuli non pertinents à la tâche (un rôle de filtre) (Luck et Hillyard, 1994), (Eimer, 1996).

En continuité avec la N2PC, une autre composante apparaît de 100 à 300 ms plus tard soit la SPCN (sustained posterior contralateral negativity). Bien que l'on puisse voir la SPCN comme faisant partie intégrante de la N2pc, nous préférons par souci de clarté dissocier au moins conceptuellement les deux composantes. La SPCN refléterait des processus permettant la consolidation de la cible en MVCT en vue d'un éventuel rapport. Plus la charge mnésique est importante, plus l'amplitude de la SPCN sera négative.

Désigné aussi sous le nom de contralateral delay activity (CDA) (Vogel, McCollough, et Machizawa (2005) et de contralateral negative slow wave (CNSW) (Klaver, Talsma, Wijers, Heinze, et Mulder, 1999)) elle a été étudiée lors d'une tâche de mémoire visuelle avec des figures géométriques (Vogel et Machizawa, 2004), ainsi qu'une tâche reliée à l'attentional blink (AB) (Jolicoeur, Sessa, Dell'Acqua, et Robitaille, 2006ab ; Dell'Acqua, Sessa, Jolicoeur, et Robitaille, 2006). Ces études semblent confirmer son rôle, car l'amplitude de la SPCN plafonne lorsque le nombre d'items à retenir s'approche de la limite de la MVCT. Aussi, la différence de voltage latéralisée se maintient tout au long de la période de rétention. Enfin, lorsque le stimulus n'est pas rapporté l'amplitude de la SPCN qui lui est associée diminue significativement.

La présente étude tire avantage de la composante SPCN qui rend possible la quantification d'information en MVCT. Étant une mesure très fine, il sera donc plus facile de déterminer l'influence possible du statut lexical d'une série de lettres mémorisées en MVCT. À notre connaissance, aucune étude sur la SPCN n'a été faite avec des stimuli linguistiques (mots). Cette étude permettra donc de mieux comprendre le rôle de la MVCT dans les processus de lecture.

Hypothèse de recherche

L'hypothèse défendue est que la mémorisation d'un mot représente une charge moins importante à maintenir dans la mémoire visuelle à court terme que celle d'un non-mot et que cette différence peut être observée en calculant une différence significative de l'amplitude de la composante SPCN entre les deux conditions. Plus précisément, si l'accès lexical influence la charge à maintenir en MVCT, l'amplitude de la composante SPCN associée aux mots devrait être significativement moins ample que celle associée aux non-mots. Enfin, sans prendre position et pour des fins exploratoires, une condition présentant des non-mots dont les lettres ne sont pas alignées horizontalement (condition non-mots brouillés) sera aussi utilisée pour vérifier si la densité des stimuli présentés peut avoir des conséquences sur la SPCN.

Contribution à l'article

L'idée originale et l'adaptation du protocole expérimental reviennent à Pierre Jolicoeur, Martin Arguin et Frédéric Gosselin. Des modifications subséquentes y ont été apportées par David Predovan et Pierre Jolicoeur. La création des stimuli a été fait par David Predovan. Une partie de la cueillette des données a été fait par David Predovan. L'analyse des données a été fait en grande partie par David Predovan, suivant les suggestions de David Prime. L'ensemble des graphiques a été créé par David Predovan. Enfin, David Predovan a écrit une première ébauche du texte qui a par la suite été corrigé et amélioré par l'ensemble des coauteurs et révisé par la suite par l'auteur principal. Tous les coauteurs consentent à ce que cet article fasse partie du présent mémoire, comme l'atteste le formulaire suivant.

On the representation of words and nonwords in visual short-term memory: Evidence from human electrophysiology

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Key word : Lexical status and VSTM

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Abstract

Electrophysiological measures were used to investigate the contribution of lexical status on the maintenance of letter strings in visual short-term memory (VSTM). The sustained posterior contralateral negativity (SPCN), an electrophysiological marker of storage in VSTM, was measured for words and nonwords as well as scrambled letters. A smaller SPCN was found for words than for nonwords (independently of their pronounceability), indicating that lexical status influences storage in VSTM. One possibility is that words produce a smaller SPCN because they can be recoded to a form that does not require a low-level representation in VSTM. For exploratory purpose, a comparison between the nonwords and the scrambled nonwords was also made. Based on previous research, the SPCN component should not be affected by the size of the region enclosing to-be-encoded objects. Surprisingly, significant differences between the SPCN for nonwords and scrambled letters conditions were found, suggesting that special encoding mechanisms may be recruited to encode word-like letter strings.

Introduction

There are reasons to believe that the lexical status of a letter string would interact with the degree to which visual short-term memory (VSTM) may be engaged during the retention of such strings. For example, Cowan (1996) postulated that access to a long-term memory code should facilitate the retention of word stimuli in working memory. We expected that a similar effect might be found when examining the role of VSTM (rather than a more abstract form of memory), but, to our knowledge, no one has used so far a measure of brain activity specifically related to VSTM to examine the influence of lexical status. In the present study we utilized event-related potentials (ERPs) to examine this issue.

Recently, an ERP component, which we refer to as SPCN (sustained posterior contralateral negativity; Jolicoeur, Dell'Acqua, Sessa, & Robitaille, 2006a), has been suggested to reflect information storage in VSTM. The SPCN is observed following the visual encoding of a stimulus presented off the vertical midline, either in the left or right visual hemifield. In order to deconfound memory encoding from low-level stimulus differences, the target stimuli in one visual field are presented with an equivalent set of distractor stimuli in the other visual hemifield. Klaver, Talsma, Wijers, Heinze, and Mulder (1999) argued that the SPCN (or contralateral negative slow wave) reflects activity related to encoding and retention in VSTM, a view that has recently received empirical support from the work of Vogel and colleagues (Vogel & Machizawa, 2004; McCollough,

Machizawa, & Vogel, 2007). In the work of Vogel and colleagues, a centrally displayed arrow stimulus cued participants to encode the stimuli appearing in either the left or right visual hemifield. A target display consisting of simple visual stimuli (e.g., colored squares) was then presented for 100 ms. After a retention interval of 900 ms, another set of stimuli was presented and participants decided whether or not the second set was the same as the first in the encoded hemifield. Starting about 300 ms following the presentation of the target display, the ERP was more negative at posterior electrodes contralateral to the cued visual field (e.g., the voltage was more negative at electrode PO8 than at PO7 for stimuli encoded from the left visual field). This lateralized voltage difference was sustained during the entire retention interval. Importantly, the amplitude of the voltage difference increased as the number of target items increased, reaching a maximum when the number of stimuli to be encoded equaled or exceeded the estimated capacity of VSTM (on a subject-by-subject basis; Vogel & Machizawa, 2004). Furthermore, the voltage difference was smaller on incorrect response trials relative to correct trials, suggesting that this activity contributes to accurate performance (see also Dell'Acqua, Sessa, Jolicoeur, & Robitaille, 2006; Jolicoeur et al., 2006a, 2006b; Robitaille, Jolicoeur, Dell'Acqua, & Sessa, 2007, for strong associations between behavioral accuracy and the amplitude of the SPCN in the context of the attentional blink paradigm).

Previous studies that have investigated the relationship between VSTM and the SPCN have used very simple stimuli, such as colored squares and oriented bars. Here, we study how VSTM involvement might vary for stimuli such

as words, for which we have pre-existing LTM representations, compared to groups of random letters (forming nonwords). Our approach is to measure the SPCN component elicited when subjects encode and remember letter strings that form either a word or a nonword. We hypothesize that lexical status of the words should reduce the load in VSTM in comparison to the nonword condition, because of the availability of a supplementary form of representation (in LTM), and that this reduction will be represented by a significant attenuation of the SPCN component in the word condition. Perhaps such stimuli can be encoded directly from a form of iconic memory to a very abstract level that may not require the protracted storage of words in VSTM, or may require it to a reduced extent compared to different visual stimulation (e.g., via immediate phonological recoding, Holcomb & Grainger, 2006, 2007; or recoding to an abstract representation in semantic memory; see the Discussion for alternative hypotheses concerning this issue). There is good evidence that representations in LTM interact with processing at earlier levels (letters, features) to produce effects such as the word superiority effect (Cattell, 1886; McClelland & Rumelhart, 1981), or the letter superiority effect (Reingold & Jolicoeur, 1993).

Our expectation that lexical status of stimuli may affect early visual representations in VSTM is predicated on a subfield of the neurophysiological literature, mainly based on electroencephalographic (EEG) and magnetoencephalographic (MEG) recordings, showing that lexical access, under particular conditions, may be extremely rapid. For example, Sereno, Rayner, and Posner (1998) presented participants with high-frequency or low-frequency

regular and irregular English words. ERPs time-locked to these words during performance in a lexical decision task differed as a function of condition with effects of word frequency that started as early as 132 ms post-target and continued into the N1 time range (~ 170 ms). These effects suggest that lexical access took place within this time range on a significant number of trials. Pulvermüller, Assadollahi, and Elbert (2001) recorded MEG activity while participants performed a lexical decision task on distinct sets of words that varied in strength of semantic association. Differences in the event-related magnetic fields across the different sets of words were apparent as early as 150 ms following word onset, with the magnetic field responses being particularly pronounced for words characterized by strong semantic association. These findings also suggest fast semantic access, consistent with Sereno, Rayner, and Posner's findings (see also Hauk, Davis, Ford, Pulvermüller, & Marslen-Wilson, 2006; and Pulvermüller, 2001, for similar conclusions). Note that semantic effects on event-related magnetic fields in the Pulvermüller studies were strongest at sensors over left infero-temporal brain regions (see also Pulvermüller, Shtyrov, & Ilmoniemi, 2005).

It should be mentioned that this prediction may appear not entirely congruent with the different view that one reliable indicator of lexical/semantic processing of words would be reflected in the centro-parietal N400 component, that usually onsets at about 350 ms post-stimulus, and it is not, contrary to the SPCN, characterized by a scalp distribution contralateral to the eliciting stimuli (e.g., Heil, Rolke, & Pecchinenda, 2004; Rolke, Heil, Streb, & Hennighausen,

2001; Vogel, Luck, & Shapiro, 1998). However, as noted by Dell'Acqua, Pesciarelli, Jolicoeur, Eimer, and Peressotti (2007), Holcomb (1993) and Pesciarelli, Kutas, Dell'Acqua, Peressotti, Job, and Urbach (2007), it is likely that N400 activity may reflect semantic integration of sequential verbal stimuli, rather than semantic/lexical access per se. N400 activity modulations are normally found when the eliciting stimulus is semantically evaluated following the prior activation of a context, either via the presentation of a prime stimulus (e.g., Holcomb & Grainger, 2006), or via the inclusion of the word stimulus in a sentence, as done originally in seminal work on the N400 (e.g., Kutas & Hillyard, 1980).

Based on evidence suggesting a rapid access of lexical information from words (and also from pictures; see Thorpe, Fize, & Marlot, 1996) presented in isolation, scope of the present work was to fill the gap due to the lack of electrophysiological evidence of an interaction between lexical access mechanisms and mechanisms responsible for the encoding and maintenance of representations in VSTM. In addition to a comparison of strings of three letters that formed a word or a nonword, we also presented nonwords in which letters were misaligned horizontally (scrambled letters condition) to determine if the spatial layout of letter stimuli can have consequences for the SPCN. McCollough, Machizawa, and Vogel (2007) showed that the SPCN for colored squares is unaffected by the size of the region in which the squares were presented, suggesting that the spatial layout of simple stimuli does not influence the SPCN. We thought it was important to verify this supposition for letters, however,

because of our extensive reading experience that may have produced specialized mechanisms for dealing with compact horizontal letter strings. Operations such as chunking of groups of letters, leading to representations of pairs or triads of letters (e.g., "the") could reduce the need for the retention of the visual features of the stimuli themselves. In short, specialized encoding mechanisms built up over many years of practice may affect the nature of subsequent representations in VSTM.

Method

Participants

Sixty two native French speakers (ages 18–29 years, mean = 22.5 and sd = 3) participated in this experiment. All participants were naïve volunteers and were paid \$20 Canadian dollars. All participants reported normal or corrected-to-normal vision and no history of neurological problems. Thirty individuals participated in the pronounceable nonword condition and 32 individuals participated in the nonpronounceable nonword condition. Seven participants from the pronounceable nonword condition and 8 participants from the nonpronounceable nonword condition were excluded from data analysis because an excessive number of trials were rejected mainly due to a tendency to shift their gaze towards the attended hemifield but also due to EEG artifacts. On average, subjects who were retained for detailed analyses moved their eyes less than $.15^\circ$ of visual angle in the direction of the target.

Task and design

The experimental task required participants to encode and retain the identity of three visually presented letters. The target letters were equally likely to be presented in the left or right visual field. A retention period of 850 ms ensured that the task could not easily be carried out on the basis of a very low-level form of memory such as visible persistence (Coltheart, 1980). After the retention interval the participants performed a two alternative forced choice identification test on the identity of one of the letters. A 2x3 between-within design was employed. The within participant manipulation varied the lexical status of the target letters. In the *word* condition the three target letters were grouped into a horizontal string that formed a French word. In the *nonword* condition the target letters were grouped into a horizontal string that did not form a valid word. In the *scrambled letters* condition the letters were not aligned horizontally and did not form a word. The between participant manipulation varied the pronounceability of the letters in the nonword condition. In the *pronounceable* condition, to which about half the participants were submitted, the nonwords had a pronounceable sequence of consonants and vowels that closely matched the proportions of strings with particular sequence structure in the word condition (i.e., CVC, VCC, CCV, etc.). In the *unpronounceable* condition the nonwords were random consonant strings.

Stimuli

The visual field cue was a centrally presented 0.2° grey arrow pointing towards the left or right. Target displays consisted of three letters presented on each side of the vertical meridian (6 letters total). The letter stimuli were 0.7° tall capital letters (A-Z) presented in grey on a black background. In the word and nonword conditions the letter strings were centered 2.4° to the left and right of fixation on the horizontal meridian. The horizontal center-to-center distance between each letter was 1.3° . In the scrambled condition the letters had the same horizontal arrangement as in the other two conditions but each letter was randomly displaced, upwards or downwards, by 0.95° or 1.90° . The test displays had the same spatial arrangements as the target displays, except that one letter in each visual field was probed by two test letters positioned directly above and below its former location (Figure 1). The horizontal position of the test letters was always different in the left and right visual fields. The other letters were replaced by grey oval outlines. One of the two test letters matched the identity of the letter at the probed position in the target display. In the word condition both test letters formed valid words in conjunction with the other letters in the target display. For example, in English, if the target letters had been SUN, the identity of the first letter could be tested with the letters S and F, each of which forms a word. Furthermore, the distractor letter string in the opposite hemifield was always of the same type as the string in the attended hemifield (i.e., word, nonword, or scrambled letters).

Figure1 about here

Experimental procedure

The trial sequence is illustrated in Figure 1. Participants viewed the experimental stimuli displayed on a computer monitor from a distance of 57 cm and a chin rest was used to stabilize the head. Each trial began with the presentation of a central fixation cross that remained on screen throughout the trial. Participants were instructed to maintain their gaze at fixation during a trial, and to blink only between trials. An arrow cue indicating the visual field of the to-be-remembered letters replaced the fixation cross for 200 ms. After a further 800 ms delay, the target display was presented for 150 ms followed by a blank screen with the fixation cross. One second after the onset of the target display, the test display was presented. Participants were required to indicate which of the two test letters in the to-be-remembered visual field matched the letter in the target display. To select the letter, participants had to respond by pushing predetermined keys on the keyboard (standard Qwerty natural keyboard). Half of the subjects responded with the right hand (key 'j' to select top letter and 'n' to select bottom letter) and the other half responded with the left hand (keys 'g' and 'b'). Accuracy feedback was provided immediately after the response, in the form of a plus sign for correct responses or a minus sign for errors. Participants initiated the next trial by pressing the space bar.

The experimental session consisted of 18 practice trials and 720 experimental trials (240 trials per condition) divided into two blocks of 360 trials. Participants were required to rest between blocks and could rest at any time during the experiment. The experimental session lasted approximately one and a half hours.

Electrophysiological recording and analysis

The electroencephalogram (EEG) was recorded with active Ag/AgCl electrodes (Biosemi Active Two) mounted on an elastic cap at standard 10–10 scalp sites (Fp1, Fpz, Fp2, AF7, AF3, AFz, AF4, AF8, F7, F5, F3, F1, Fz, F2, F4, F6, F8, FT7, FC5, FC3, FC1, FCz, FC2, FC4, FC6, FT8, T7, C5, C3, C1, Cz, C2, C4, C6, T8, TP7, CP5, CP3, CP1, CPz, CP2, CP4, CP6, TP8, P9, P7, P5, P3, P1, Pz, P2, P4, P6, P8, P10, PO7, PO3, POz, PO4, PO8, O1, OZ, O2, Iz, M1, and M2). Eye position was monitored by both the horizontal and vertical electro-oculogram (EOG). The vertical EOG was recorded as the voltage between Fp1 and an electrode placed below the left eye. The horizontal EOG was recorded as the voltage between electrodes placed lateral to the external canthi. Amplified EEG and EOG channels were low-pass filtered at 67 Hz and digitized at 256 Hz. After acquisition the EEG channels were referenced to the average of the left and right mastoids and high-pass filtered at 0.01 Hz (half power cut-off).

Trials containing blinks, eye movements, and EEG artifacts were removed prior to ERP averaging by applying automated artifact detection routines.

Participants who had less than 60% of trials remaining in one or more conditions after artifact rejection were excluded from further analysis. Separate ERP averages were calculated from EEG epochs time-locked to the presentation of the target display for each experimental condition and visual field of the target items. The resulting ERP averages were low-pass filtered at 6 Hz and baseline corrected relative to mean voltage of the 200 ms pre-stimulus interval. In order to isolate the SPCN activity, ERP waveforms from electrodes ipsilateral to the target items were subtracted from those from contralateral electrodes and the resulting difference waves for each visual field were averaged. For purposes of statistical analysis, pooled SPCN waves were formed in order to improve the signal-to-noise ratio of the data. The pooled SPCN waves were derived from electrode pairs PO7/PO8, O1/O2, and P7/P8. These electrode locations were chosen because they correspond to the location of the maxima of the SPCN topography (Figure 4B). The SPCN amplitude for each condition was quantified as the mean voltage of the pooled SPCN wave in the 400 ms to 1000 ms latency range.

Results and discussion

Behavior

Mean percent correct and mean SPCN amplitude measures were submitted to separate 2 x 3 between-within analyses of variance (ANOVAs) with factors of Group (pronounceable nonword, unpronounceable nonword) and Lexical Status (word, nonword, scrambled). The Geisser-Greenhouse correction

procedure was used for repeated-measures involving more than one degree of freedom.

Mean accuracy rates for the word, nonword, and scrambled conditions were respectively 95%, 94%, and 89% for the pronounceable nonword group and 94%, 88%, and 83% for the unpronounceable nonword group. The ANOVA of accuracy rates revealed a significant main effect of Lexical Status, $F(2, 90) = 78.6$, $p < 0.001$, $\epsilon = 0.67$, $\eta_p^2 = 0.64$. In addition, both the main effect of Group (mean accuracy of 93% for the pronounceable group vs. 88% for the unpronounceable group), $F(1, 45) = 6.8$, $p < 0.02$, $\eta_p^2 = 0.13$, and the interaction effect, $F(2, 90) = 5.9$, $p < 0.02$, $\epsilon = 0.67$, $\eta_p^2 = 0.12$, were significant.

Figures 2 about here

ERP

Figure 2 shows grand average waveforms, collapsed across both groups, separately for stimuli encoded from the left and right visual fields at all electrode sites. The word condition is shown in Panel A, the nonword condition in Panel B and the nonword scrambled condition in Panel C. The SPCN can be seen as a relative negative shift in the ERP wave at electrode sites contralateral to the visual field of the target. As expected the SPCN difference is largest at lateral

occipital sites (see also the topographic maps in Figure 4, Panel B). Furthermore, the SPCN difference can be seen in all three conditions for stimuli encoded from both visual fields.

Figure 3 shows the pooled response at three posterior electrode sites for stimuli encoded from the left visual field or right visual field for left-sided and right-sided electrodes, for each stimulus type (words, nonwords, and scrambled letters). As is evident in the figure, there was no evidence of left-right asymmetries in the SPCN waveforms for any of the stimulus types.

Figure 4, Panel A, shows the SPCN subtraction waves (contralateral - ipsilateral) pooled over electrode pairs PO7/PO8, O1/O2, and P7/P8 for each group and condition. Figure 4, Panel B, shows the scalp distributions of the SPCN for each type of letter string, averaging over the two groups. These scalp distributions are based on the SPCN subtraction waves at each lateralized electrode pair (zero voltage assumed at midline electrodes) and they exhibit the same relatively focused voltage peak at posterior electrodes (e.g., Brisson & Jolicoeur, 2007). The distributions were quite similar in general topography, suggesting that the same component was elicited in the three string type conditions, but with different amplitudes.

The SPCN amplitudes were subjected to an ANOVA of the same type as used for the accuracy results. SPCN amplitude was highest for the scrambled condition, intermediate for the nonword condition, and smallest for the word condition, producing a significant main effect of Lexical Status, $F(2, 90) = 33.9$, $p < 0.001$, $\epsilon = 0.80$, $\eta_p^2 = 0.19$. In contrast to the accuracy results, neither the main

effect of Group, $F(1, 45) = 0.84, p > 0.36, \eta_p^2 = 0.02$, nor the interaction effect, $F(2, 90) = 1.0, p > 0.35, \epsilon = 0.80, \eta_p^2 = 0.02$, approached significance. The lack of any Group effects indicates that the pronounceability of the nonwords did not affect the amplitude of the SPCN.

Figures 3 and 4 about here

In order to explore further the effect of Lexical Status on the amplitude of the SPCN, 2 x 2 between-within ANOVAs were performed for each pairing of the Lexical Status variable. Analysis of the difference between the word and nonword conditions revealed that the words elicited a significantly smaller SPCN than nonwords, $F(1, 45) = 9.8, p < 0.01, \eta_p^2 = 0.18$. Neither the main effect of Group nor the interaction effect approached significance, both p 's > 0.62 , indicating that the pronounceability of the nonwords had no effect on the difference in SPCN amplitude between words and nonwords.

Analyses of the difference in SPCN amplitude between the scrambled and the other two conditions revealed that the scrambled condition elicited a significantly larger SPCN than either the word condition, $F(1, 45) = 48.2, p < 0.001, \eta_p^2 = 0.52$, or the nonword condition, $F(1, 45) = 28.1, p < 0.001, \eta_p^2 = 0.38$.

Neither the main effect of Group nor the interaction effect approached significance in either ANOVA, all p 's > 0.25.

An inspection of Figure 4, Panel A, reveals that the SPCN appears to onset at a shorter latency in the scrambled condition than in the other two conditions. In order to analyze this effect, SPCN onset was measured using a fractional area latency measure (Kiesel, Miller, Jolicoeur, & Brisson, 2008) on jackknife-subsample average waveforms (Ulrich & Miller, 2001). The SPCN onset for each condition was defined as the point in time that the area under the SPCN wave reached 20% of the total area in the interval between the start of the negative portion of the curve and 500 ms (this interval corresponds to the rising portion of the SPCN wave). Analysis of the onset latencies revealed a significant main effect of Lexical Status, $F(2, 90) = 5.5$, $p < 0.01$. Neither the main effect of Group, $F(1, 45) = 1.3$, $p > 0.26$, nor the interaction effect, $F < 1$, approached significance. Subsequent analyses revealed that the SPCN onset earlier in the scrambled condition (332 ms) than either the word (398 ms), $F(1, 45) = 7.3$, $p < 0.01$, or the nonword (380 ms), $F(1, 45) = 13.4$, $p < 0.001$, conditions. The difference in SPCN onset between the word and nonword conditions was not significant, $F < 1$.

The present results were clearcut in demonstrating that the lexical status of a letter string modulated activity in VSTM during the retention interval of a VSTM task. When the target string formed a word, the amplitude of the SPCN was reduced relative to when the target string did not form a word. At the functional level, one viable explanation for this effect is that the storage of target

letters that form words is facilitated by a lexically-driven grouping or chunking mechanism that reduces the information load in VSTM (e.g., Martin, Nazir, Thierry, Paulignan, & Demonet, 2006). In this view, the availability of an alternative memory code, already stored in LTM, would reduce the need to rely on an earlier, lower level, visual representation of the letters by, for instance, providing supplementary top-down activation support to word representations in VSTM. A second possibility is that horizontal letter strings may make contact with specialized letter detectors that are tuned for horizontally-aligned sets of letters (e.g., Dufau, Grainger, & Holcomb, 2008; Grainger, Granier, Farioli, Van Assche, & van Heuven, 2006). The output of these detectors may reduce the need to maintain a low-level visual representation in VSTM, which are in turn reflected in the smaller SPCN for words than for nonwords, observed in the present empirical context. At the neurophysiological level, it is natural to hypothesize that the present selective attenuation of an SPCN response to words vs. nonwords may arise from the short-range bidirectional connections between the extrastriate portion of the visual cortex, the lower part of the parietal lobes (which are held to be primary sources of SPCN activity) and regions in the surroundings of the left lingual and fusiform gyri, these latter regions known to be involved in early visual processing of word-like stimuli (e.g., Nobre, Allison & McCarthy, 1994; Puce, Allison, Asgari, & McCarthy, 1996).

At first blush, the absence of an effect of pronounceability seems surprising, especially in light of the behavioral literature suggesting that some form of phonological processing involvement, even when pictures are displayed,

may occur rapidly and automatically (e.g., Morsella & Miozzo, 2002). One possibility is certainly the lack of power in detecting such phonological effects in terms of an impact of the manipulation of pronounceability on the SPCN amplitude, despite the large sample of subjects tested in each of the present experimental conditions. However, if this were not lack of power, a different possibility is that VSTM mechanisms are not subject to the influence mediated by phonological recoding, and this may not be surprising given the long studied sensitivity of this memory sub-system to spatial, and not verbal, information about objects. Evidence concerning the neurophysiology of word processing may help to corroborate this view. Contrary to the topographical proximity and massive interconnection of cortical regions in the human brain devoted to early orthographic processing and the hypothesized substrate of SPCN activity, regions devoted to the assembly of phonological codes (i.e., primarily, cortical regions in the left inferior frontal cortex; e.g., Mado Proverbio, Vecchi, & Zani, 2004) seem to entertain short-range connections with regions in the left temporal lobe and, however, a restricted band-width re-entrant circuitry to the occipito-parietal areas under scrutiny in the present context.

One note of caution is in order, however, concerning the proposed model for the effects found in our study. We are interpreting the lexical-status effects on SPCN as evidence for interactions between lexical status and VSTM. An alternative interpretation could be formulated on the basis of results suggesting that other ERP components, such as the "recognition potential" (RP) are also sensitive to the difference between words and nonwords (e.g., Martin-Loeches,

Hinojosa, Gomez-Jarabo, & Rubia, 1999; Rudell & Hua, 1997). The RP is usually observed as an occipito-parietal negativity peaking in a time window of 200–250 ms following the presentation of words at fixation. The RP to word stimuli is particularly pronounced over left posterior occipito-parietal regions (e.g., at P7), probably originating from the left portion of basal extrastriate cortex labeled visual word form area (VWFA; Cohen, Dehaene, Naccache, Lehéricy, Dehaene-Lambertz, Hénaff, & Michel, 2000). Could the SPCN results we report in this article be a reflection of the RP component? This possibility appears to be remote in light of the known functional properties of the RP and the timecourse of that component. Similar to the MEG activity reported by Pulvermüller et al. (2001), the RP tends to be larger as the semantic richness of word stimuli is increased (e.g., Hinojosa, Martin-Loeches, Munoz, Casado, and Pozo, 2004; Martin-Loeches, Hinojosa, Gomez-Jarabo, & Rubia, 2001), with the degree of semantic association (or semantic redundancy) of specific word stimuli positively correlated with the negativity in the RP time-range. This appears incompatible with the present results, given that lexical activation (words relative to nonwords) in the present case produced a decrease in SPCN amplitude, rather than an increase. Furthermore, the RP component has a timecourse that is relatively short compared with the sustained nature of the SPCN, and a topographical distribution (larger over left posterior recording sites) which is not consistent with the symmetrical distribution of SPCN activity we have documented. Although it is clear that there are other ERP components that are sensitive to the lexical status of letter strings, the present results appear to be a novel manifestation of

processing differences between words and nonwords that is specifically related to differences in VSTM processing efficiency (or load) for words and nonwords.

In contrast to the results obtained by McCollough et al. (2007) for simple geometric shapes, the amplitude of the SPCN was affected by the spatial configuration of the target letters in the present experiment. The amplitude of the SPCN was substantially larger in the scrambled condition than in either of the other two conditions, and particularly than in the nonword condition, despite the use of letter strings with identical left-to-right structure (e.g., consonant, consonant, vowel, as in SPI). The interpretation of this result and a direct comparison with the results obtained with horizontally aligned letter strings (words and nonwords) is particularly hard due to the marked dissimilarity in the spatial layout of aligned and scrambled letters. In particular, one of the regions held to contribute to SPCN activity (i.e., the intra-parietal sulcus, IPS) has been shown to increase in activity when scrambled objects are displayed relative to objects possessing a regular structure (Xu, 2008). In this perspective, the increment in SPCN activity with scrambled letters could be taken to reflect the likely increase in activation of neurons in IPS for scrambled letters vs. aligned letters. This, considering the verbal material used in the present study, is not incongruent with the idea that special encoding algorithms are used to process letter strings arrayed horizontally (i.e., via activation of letter detectors that are tuned for horizontally-aligned sets of letters). A second interpretation, which relates with the topographical distribution of neurons in the visual cortex, is that absolute spatial location differences across the distinct conditions implemented in

the present design had not nil effects on the amplitude of the SPCN. To clarify, it is possible that letters encoded from upper visual field positions (projecting in the lower portion of the occipital lobes) may have produced a smaller SPCN than letters encoded from lower visual field positions (projecting to the upper portion of the occipital lobes), and these effects may be non-linear, leading to a net increase in SPCN amplitude when positions off the midline are used. The horizontal letter strings were always on the horizontal midline, and thus caution is mandatory under these circumstances.

An intriguing aspect of the present results is that the SPCN elicited by scrambled letters onset earlier than the SPCN elicited by horizontally aligned letter strings. In general, one would expect ERP reflections of processing more difficult visual stimulation (as it appears the case for scrambled letters) to affect amplitude and latency parameters congruently. The present results instead showed an increase in SPCN activity for scrambled words which was accompanied by a shorter onset latency relative to the other two types of stimuli tested. One possibility is that these differences are not tied to SPCN per se, but rather arise from differences in the amplitude of the attention sensitive N2pc component that is typically observed in the latency range preceding the SPCN onset (e.g., Jolicoeur, Brisson, & Robitaille, 2008). On two thirds of trials, in the word and nonword conditions, the three target letters were presented at known and adjacent locations. In contrast, in the less frequent scrambled condition, the letters were presented at nonadjacent and unpredictable locations. Furthermore, when scrambled, the letters occupied adjacent locations, and were likely to fall in

the same receptive field of infero-parietal neurons (Jack, Patel, Astafiev, Snyder, Akbudak, Shulman, & Corbetta, 2007). This brings to the fore two possible cases. In one case, more attentional resources may have been demanded to orient attention to each of the target letters. Such an increase in attentional demands may have resulted in an increase in N2pc amplitude, which, in turn, would have given the impression of an earlier onset for the SPCN. In the second case, scrambled letters, by being processed as distinct objects and providing stronger activation of SPCN-eliciting neurons, caused also a consequent faster allocation of attention resources for the maintenance of the scrambled letters in VSTM. An additional and interesting perspective to look at the SPCN latency shift between scrambled vs. aligned letters emerges if one interprets the onset latency discrepancy for scrambled words compared with word-like stimuli not as an effect of onset anticipation for scrambled letters, but, viceversa, as a delay in onset latency for word-like stimuli. To note, this alternative perspective would not be incongruent with the view proposed above that the activation of letter detectors may be triggered upon the presentation of horizontally aligned letter strings, on the assumption that this additional stage may be time-consuming.

Conclusions

From the point of view of encoding and maintenance in VSTM, all letter strings are not equal. Letter strings forming words elicit a smaller SPCN than strings forming nonwords, suggesting strongly that maintaining word

representations taxes VSTM mechanisms to a less extent relative to nonwords representations. In addition, the spatial layout of letter strings may also affect ensuing retention loads in VSTM. Both effects are interesting and suggest that the SPCN component may provide a powerful new tool to study interactions between early sensory and memory systems (i.e., VSTM) and processes that interpret stimuli in the context of rich lexical and semantic representations in long-term memory engaged during reading. We expect that the present findings will lead to important discoveries concerning the representation of words and nonwords in individuals with and without reading difficulties.

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Figure captions

Figure 1. Sequence of events in each trial for the word, nonword and nonword scrambled conditions.

Figure 2. Panel A: Grand averaged waveforms, collapsed across groups, at all electrode sites for the word condition. Separate waveforms are shown for stimuli encoded from the left and right visual fields.

Panel B: Grand averaged waveforms, collapsed across groups, at all electrode sites for the nonword condition. Separate waveforms are shown for stimuli encoded from the left and right visual fields.

Panel C: Grand averaged waveforms, collapsed across groups, at all electrode sites from the nonword scrambled condition. Separate waveforms are shown for stimuli encoded from the left and right visual fields.

Figure 3. Pooled response at left-sided and right-sided posterior electrode sites for stimuli encoded from left visual field or right visual field, for each stimulus type (words, nonwords, and scrambled letters).

Figure 4. Top panel: Contralateral minus ipsilateral waveforms showing the SPCN for the pooled response at three posterior electrode sites for each type of stimulus (words, nonwords, and scrambled letters) for each group. Bottom panel: scalp distributions of the SPCN for each stimulus type (mean activity from 400–1000 ms post memory stimulus onset).

Figure 1. Sequence of events in each trial for the word, nonword and nonwordscrambled conditions.

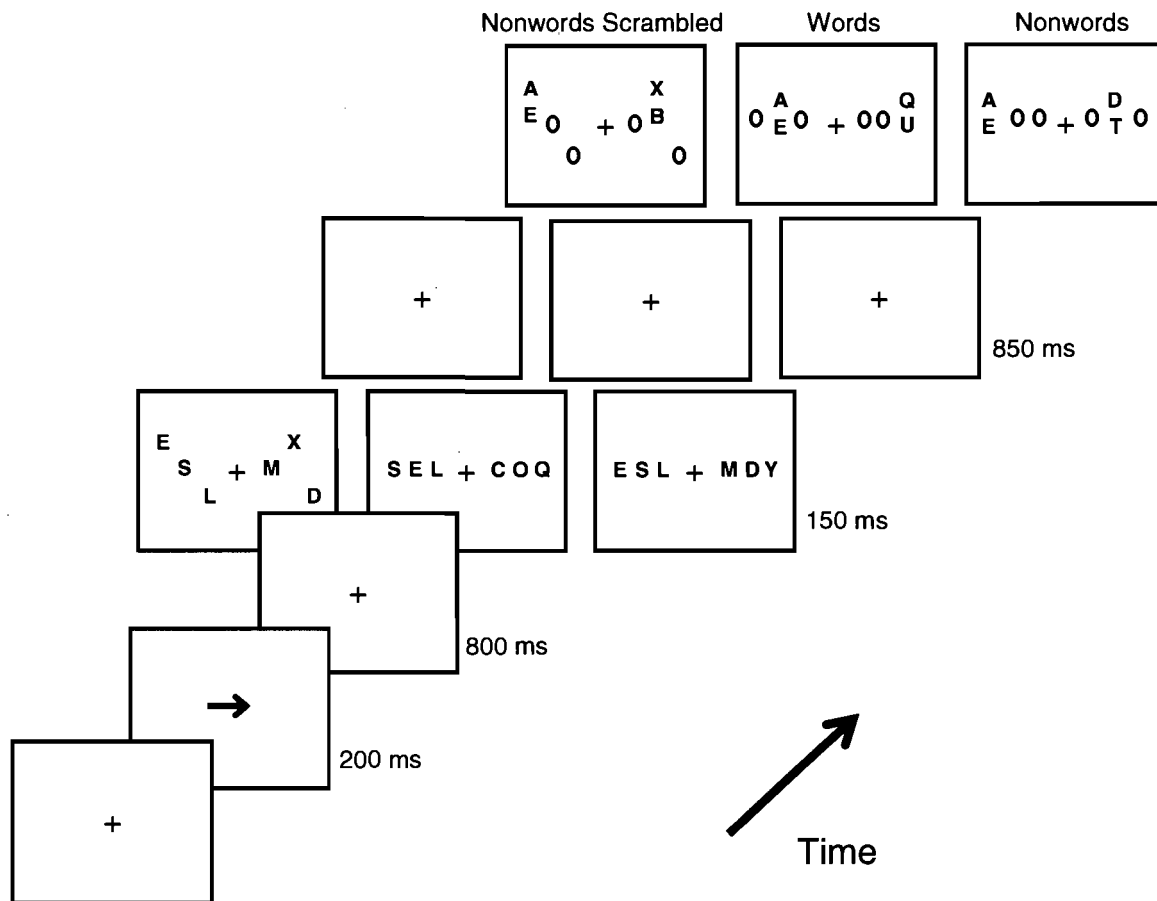


Figure 2. Panel A: Grand averaged waveforms, collapsed across groups, at all electrode sites for the word condition. Separate waveforms are shown for stimuli encoded from the left and right visual fields.

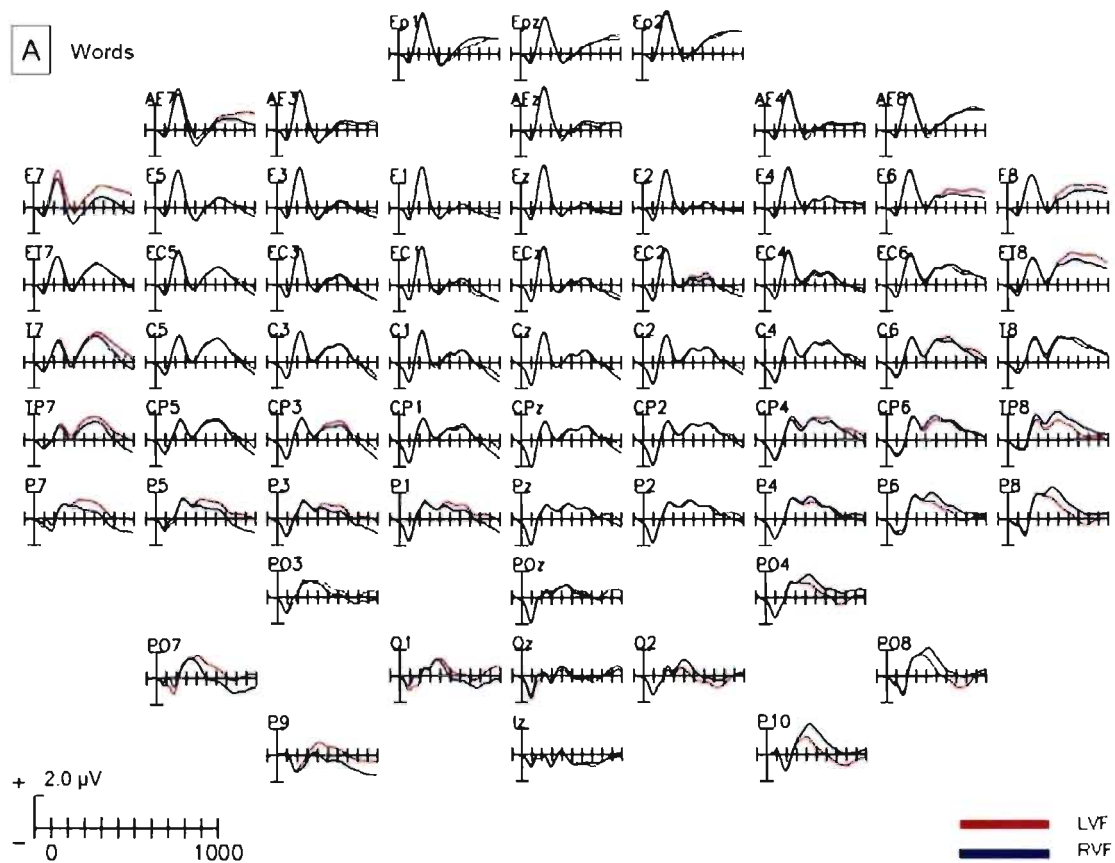


Figure 2. Panel B: Grand averaged waveforms, collapsed across groups, at all electrode sites for the nonword condition. Separate waveforms are shown for stimuli encoded from the left and right visual fields.

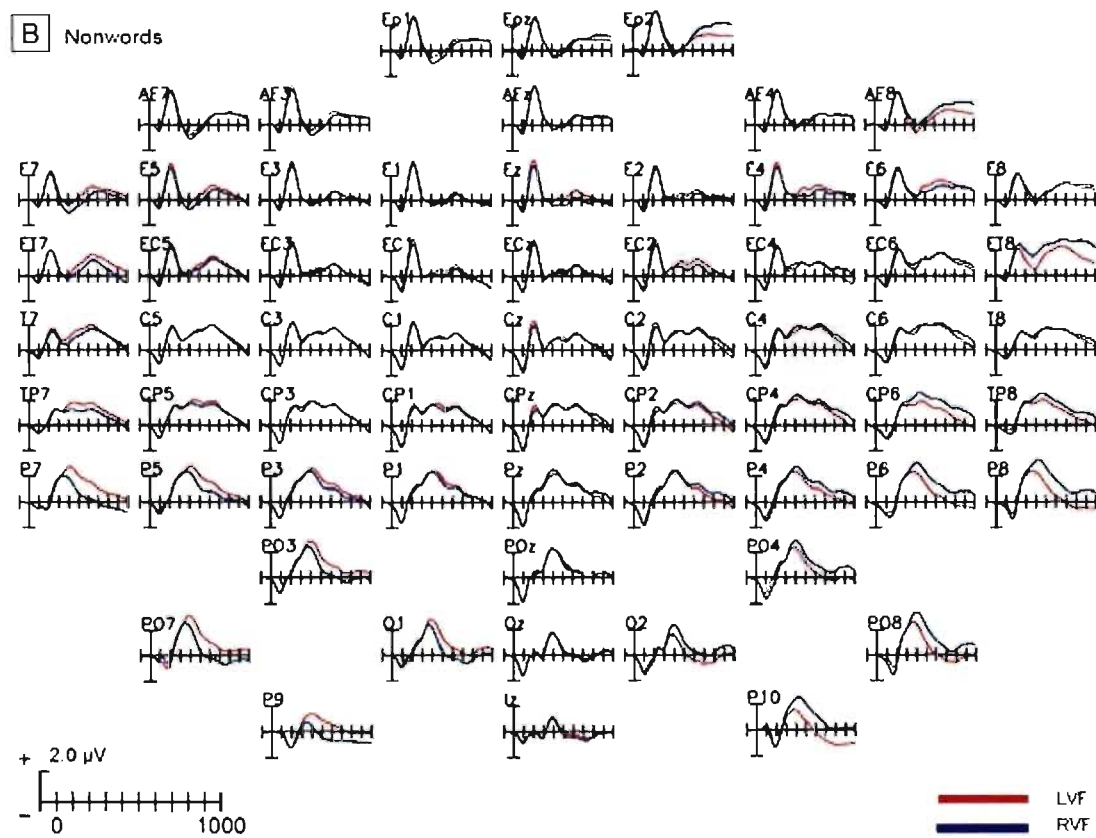


Figure 2. Panel C: Grand averaged waveforms, collapsed across groups, at all electrode sites from the nonword scrambled condition. Separate waveforms are shown for stimuli encoded from the left and right visual fields.

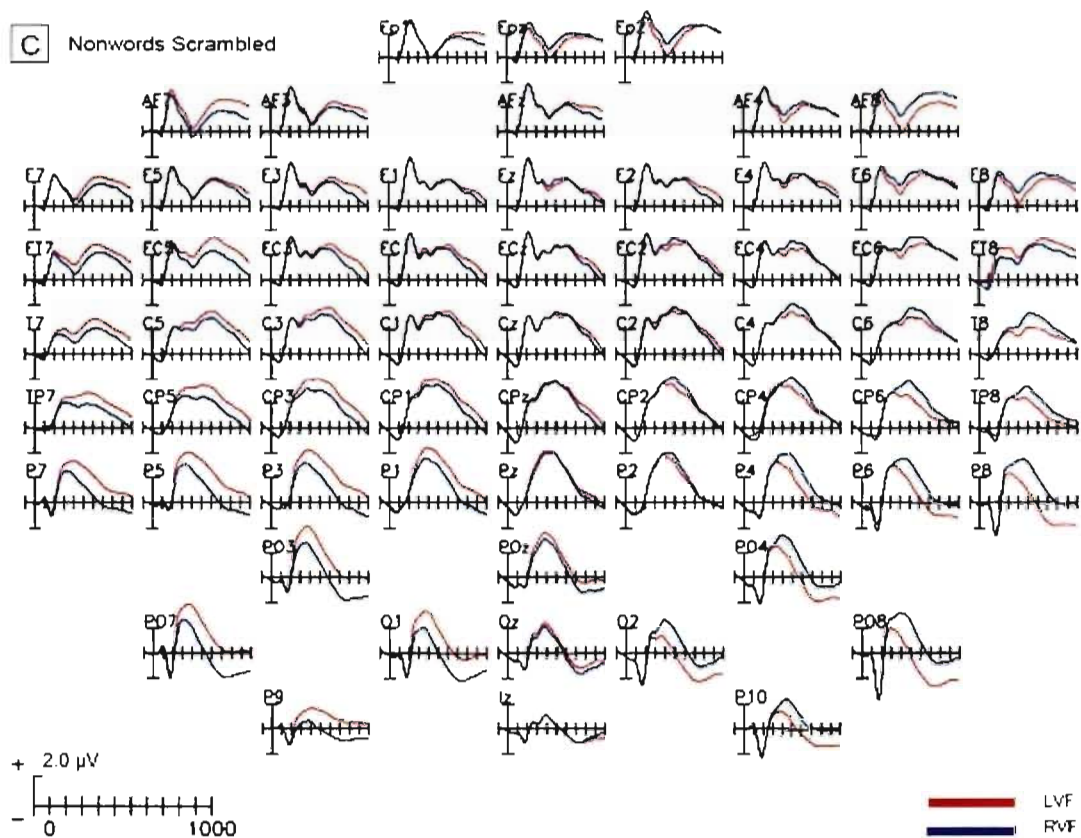


Figure 3. Pooled response at left-sided and right-sided posterior electrode sites for stimuli encoded from left visual field or right visual field, for each stimulus type (words, nonwords, and scrambled letters).

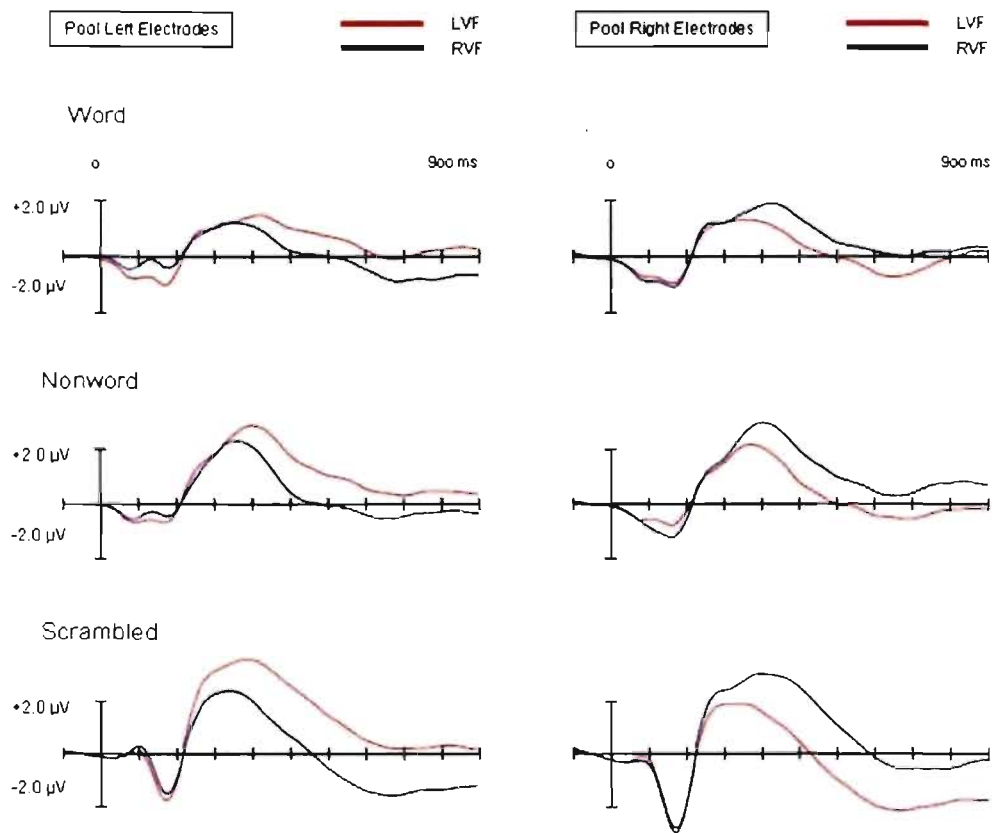
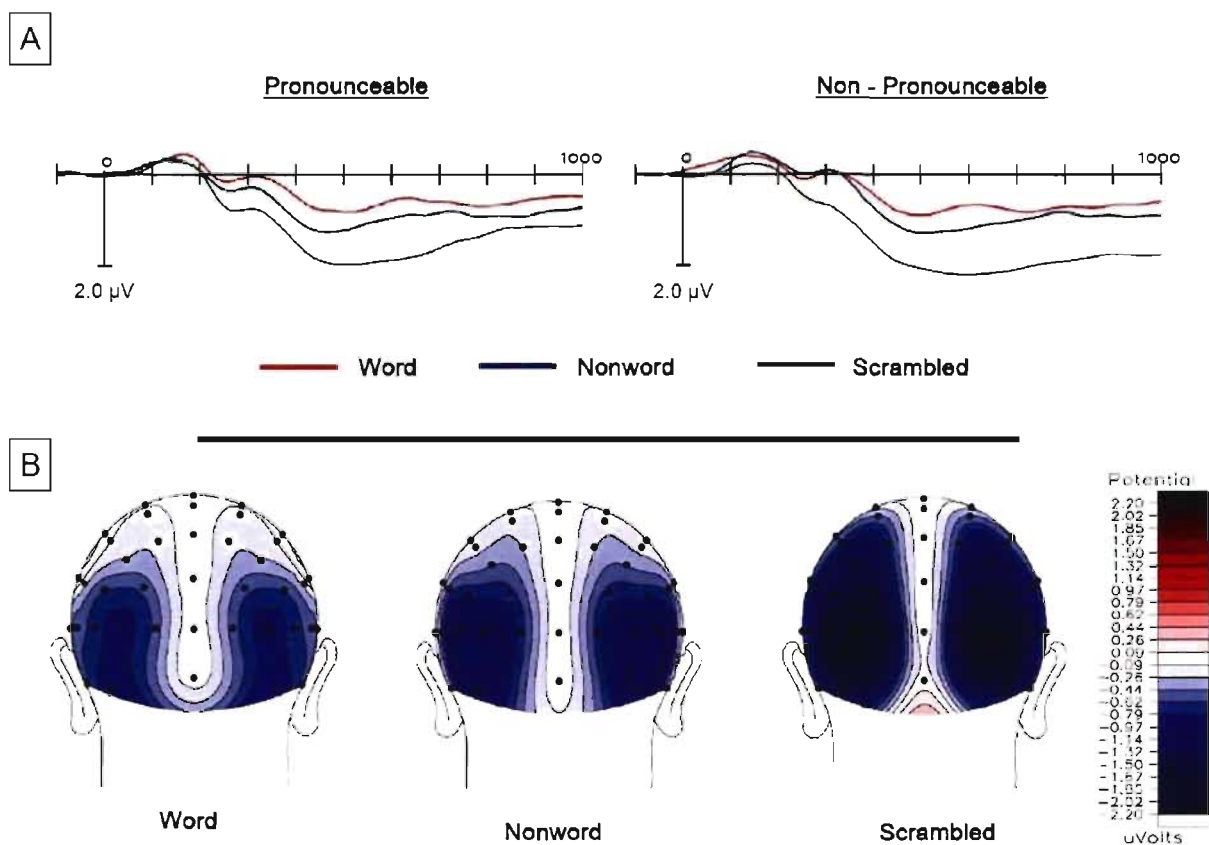


Figure 4. Top panel: Contralateral minus ipsilateral waveforms showing the SPCN for the pooled response at three posterior electrode sites for each type of stimulus (words, nonwords, and scrambled letters) for each group. Bottom panel: scalp distributions of the SPCN for each stimulus type (mean activity from 400–1000 ms post memory stimulus onset).



Discussion générale

Discussion générale

Une amplitude significativement réduite de la composante SPCN a été trouvée pour la condition mot en comparaison à la condition non-mot (et ce, indépendamment de leur prononçabilité), indiquant ainsi que l'accès lexical influence la façon dont l'information est encodée et maintenue dans la mémoire visuelle à court terme. Il est donc possible de penser que les mots représentent une charge moindre à maintenir en MVCT. Deux possibilités pour expliquer ceci peuvent être évoquées. Une possibilité est que les mots soient recodés sous une représentation alternative à celle de bas niveau (la représentation visuelle des lettres) en MVCT. Une autre possibilité est que les mots bénéficient davantage des mécanismes de chunking et de regroupement que les non-mots.

Au premier abord, une absence d'effet de prononçabilité pour les non-mots peut apparaître incongrue. Il se peut que l'effet ne soit pas apparent faute de puissance, et ce, malgré le grand nombre de sujets composant les groupes utilisés. Une autre possibilité est que la mémoire visuelle à court terme n'est pas influencée par le recodage phonologique, ce qui renforcerait notre conception de la composante SPCN comme étant une mesure fine de la quantité d'information présente en MVCT.

Mentionnons aussi que la composante SPCN reliée à la condition lettres dispersée débute plus tôt que celle reliée à la condition mot et non-mot. Il est

possible que la détection de chaque lettre nécessite davantage de ressources attentionnelles ou une allocation plus rapide des ressources. Une possibilité originale est que les mécanismes de chunking ou de regroupement qui bénéficient à la perception des mots et des non-mots prennent du temps à s'actionner, ce qui expliquerait le délai présent dans ces deux conditions.

Enfin, la différence d'amplitude de la composante SPCN entre la condition non-mot et lettres dispersées est surprenante. Ayant une composante d'amplitude réduite, les non-mots semblent représenter une charge plus faible en MVCT. Ainsi, le simple alignement horizontal d'une série de lettres semble faciliter le maintien de celle-ci en MVCT.

Conclusion générale

La présente étude appuie l'hypothèse que le statut lexical d'une série de lettres influence son encodage et son maintien dans la mémoire visuelle à court terme. De plus, le simple alignement d'une série de lettres permet à celle-ci d'être plus aisée à maintenir en MVCT. Enfin, de façon générale les présents résultats indiquent que l'utilisation de la composante SPCN dans l'étude de la représentation de stimuli linguistique en MVCT est appropriée. Nous espérons que la présente étude conduira à d'importantes découvertes concernant la représentation des mots et des non-mots chez des individus qui éprouvent ou non des difficultés de lecture.

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