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An ERP investigation of the modulation of subliminal priming by exogenous cues

Yousri Marzouki^{a,*}, Katherine J. Midgley^{a,b}, Phillip J. Holcomb^b, and Jonathan Grainger^{a,c}

^aAix-Marseille University, Marseille, France

^bTufts University, Medford, MA, USA

^cCNRS, France

Abstract

Marzouki, Grainger, and Theeuwes demonstrated that masked repetition priming of letter identification is affected by the allocation of spatial attention to the prime location by an exogenous cue. Behavioral priming effects were obtained only when the exogenous cue was valid (prime at the same location as the cue). The present ERP study provides a further investigation of such exogenous influences on masked priming. Results showed a significant modulation of the amplitude of the P3 ERP component generated by centrally located target letters as a function of repetition priming and cue validity. The amplitude difference between repetition and unrelated primes was found to be enhanced in the presence of a valid exogenous cue. The electrophysiological data therefore confirm the influence of exogenous cues on the processing of subliminally presented prime stimuli, and show that such effects can be obtained in the absence of eye movements. The results further point to a relatively late influence of prime stimuli on target processing when these stimuli occupy distinct locations.

Keywords

Subliminal priming; Exogenous cueing; P3

1. Introduction

The process of identifying an isolated letter or printed word can be modified by the prior subliminal presentation of the same stimulus relative to a different prime stimulus (masked repetition priming: e.g., Bowers et al., 1998; Forster and Davis, 1984; Hartmut and Kopp, 1998; Jacobs and Grainger, 1991; Segui and Grainger, 1990; Ziegler et al., 2000). Results from recent ERP studies suggest that these subliminal repetition priming effects involve early perceptual processes as well as later integration processes (e.g., Holcomb and Grainger, 2006; Petit et al., 2006). Furthermore, recent behavioral work has shown that the amplitude of masked repetition priming effects can be modified by attentional cueing (Besner et al., 2005; Fabre et al., 2007; Marzouki et al., 2007; Naccache et al., 2002).

Most relevant for the present study, Marzouki et al. (2007) demonstrated that masked repetition priming of letter identification is affected by the allocation of spatial attention to the prime location by an exogenous cue. Target letters were always presented at a central location (on

fixation) and primes appeared randomly to the left or to the right of fixation. Priming only occurred when the exogenous cue appeared at the same peripheral location as the upcoming prime stimulus. Moreover, Marzouki et al. demonstrated that participants could not discriminate letter from pseudo-letter primes above chance in a post-experiment visibility test, strongly suggesting that participants were not aware of prime stimuli during the experiment.

The results of Marzouki et al. (2007) suggest that the presence of a valid exogenous cue facilitates processing of stimuli that are immediately presented at the cued location, even if these stimuli are not consciously processed. This implies that the very earliest perceptual processes are enhanced by attentional cueing, in line with the neurophysiological evidence obtained from monkey studies (e.g., Lee et al., 2007; Luck et al., 1997; Reynolds et al., 1999). This enhanced processing of subliminal prime stimuli has an observable influence on the processing of upcoming target stimuli to which participants are requested to respond. However, since prime and target stimuli appeared at different locations in the Marzouki et al. study (peripherally located primes, centrally located targets), priming effects are likely to be driven by location-invariant representations of prime and target stimuli and are therefore likely to arise relatively late during target processing (see Marzouki et al., in press, for a model of such priming effects). A key question guiding the present research is therefore exactly when such influences from peripherally located primes arise during the processing of centrally located targets. RT measures do not provide this information, hence the use of ERPs in the present work. Furthermore, eye movements were not recorded in Marzouki et al.'s behavioral study, hence it was impossible to evaluate the possible influence of fast saccades to the prime location on presentation of a valid exogenous cue. Some of the cueing effects could therefore have been due to improved visual acuity during prime processing following a valid cue.

ERPs have been successfully used to investigate the effects of exogenous attention in several prior studies. These studies found an enhancement of the P1 component during target processing following a valid exogenous cue (Fu et al., 2001; Hopfinger and Mangun, 1998; Hopfinger and Ries, 2005; Hopfinger and West, 2006). This influence of exogenous cues on the P1 component, peaking at around 100 ms post-target onset, is further evidence that exogenous cueing affects early perceptual processing of target stimuli likely performed by extrastriate visual cortex (Luck, 2005). However, the aim of the present study was not to directly investigate effects of exogenous cues on ERPs to stimuli appearing at the cued location. In the present study, subliminal prime stimuli could appear at a validly cued location or not, and we indirectly investigated the influence of exogenous cues on the processing of subliminal prime stimuli by examining the subsequent influence of such processing on ERPs generated by centrally located targets. The same logic was used by Kiefer and Brendel (2006) to investigate influences of temporal attention on masked semantic priming. These authors found that N400 priming effects only emerged when attention was directed to the moment in time when masked prime stimuli appeared.

By applying this logic to the domain of spatial attention, the aims of the present study were a) to demonstrate an influence of exogenous cueing on the processing of subliminal stimuli in the absence of eye movements, and b) to examine the timing of transfer of information from prime to target stimuli when these occupy distinct spatial locations.

2. Results

As can be seen in Fig. 1, the ERPs time-locked to target letters produced an early negative peak at about 90 ms (N1) which was followed by a larger positivity peaking around 180 ms (P2), a small negative-going peak at about 220 ms (N2) and finally a large positivity between 300 and 500 ms (P3). It can also be seen in Fig. 1 that there were no effects of peak latency of the P3 component in this study (this was the case for all electrode sites).

2.1. 100-200 ms and 200-300 ms

There were no significant effects in these time windows.

2.2. 300-400 ms

There was a marginally significant three-way interaction between Cue Validity×Prime Relatedness×Electrodes at Midline electrodes: $F(4, 72)=2.29$, $MSE=1.44$, $p=.06$. Follow-up analyses revealed that the critical Cue Validity×Prime Relatedness interaction was reliable at Fz: $F(1, 18)=4.75$, $MSE=1.28$, $p<.05$ with a significant priming effect in the valid cue condition, $F(1, 18)=5.70$, $MSE=1.57$, $p<.05$, but not in the invalid cue condition, $F<1$; and at Cz: $F(1, 18)=6.40$, $MSE=1.34$, $p<.05$ with a significant priming effect in the valid cue condition, $F(1, 18)=14.84$, $MSE=0.84$, $p<.002$ and not in the invalid cue condition $F<1$ (see Fig. 2). There was a significant two-way interaction between Cue Validity and Prime Relatedness in Column 1: $F(1, 18)=5.23$, $MSE=6.04$, $p<.05$. This reflected the presence of a significant repetition priming effect in the valid condition, $F(1, 18)=9.54$, $MSE=6.08$, $p<.01$, that was not significant in the invalid condition, $F<1$. The two-way interaction between Prime Relatedness and Cue Validity was marginally significant at Column 2: $F(1, 18)=3.27$, $MSE=5.38$, $p=.08$. The effect of Prime Relatedness with valid cues was significant at this column, $F(1, 18)=6.15$, $MSE=5.87$, $p<.05$, but was not significant with invalid cues, $F<1$. There were no significant effects at Column 3.

2.3. 400-500 ms

In this time window there was a significant interaction between Prime Relatedness and Electrodes at Column 1: $F(5, 90)=2.48$, $MSE=0.47$, $p<.05$ and Column 2: $F(7, 126)=2.11$, $MSE=0.67$, $p<.05$. The related prime condition generated more negative-going waveforms than the unrelated prime condition, independently of cue validity.

3. Discussion

The present study investigated attentional influences on subliminal priming effects with isolated letters using ERP recordings. The results are clear-cut. We found that ERP amplitude was significantly affected by subliminal repetition priming, but only in the presence of a valid spatial cue. Since all trials involving an eye movement were rejected before analysis, this is the first demonstration of a modulation of subliminal priming effects by exogenous cues without possible contamination from cue-induced eye movements to the prime location on valid trials. This adds considerable support to the hypothesis that exogenous cues can modulate the processing of stimuli that are not consciously perceived.¹

The major goal of the present study was to use ERP recordings in order to examine the precise timing of subliminal priming effects on target letter processing when prime and target occupy distinct spatial locations. Our priming manipulation was found to affect the amplitude of central-posterior positivity between 300 and 400 ms with related primes producing more positive ERPs than unrelated primes in the valid cue condition. Given the latency range, spatial distribution, and polarity of the effects reported here, it seems likely that the current effect is on the classic P3 ERP component (also referred to as P300).

It is important to compare the timing of letter priming effects found in the present study with those of another masked letter priming study in which primes and targets occupied the same

¹An analysis of the results of the 14 participants that were at chance performance on the visibility test administered by Marzouki et al. (2007) showed a pattern that was very similar to the one found for the whole group. Most important, the critical interaction between Cue Validity and Prime Relatedness in the 300-400 ms epoch was significant across the head, $F(28, 364)=3.25$, $MSE=324.3$, $p<.0001$, in Column 3, $F(9, 117)=3.25$, $MSE=136.15$, $p<.005$ and Midline, $F(4, 52)=4.72$, $MSE=75.17$, $p<.005$.

central location. Petit et al. (2006) combined masked priming with ERP recordings and found a cascade of components that were sensitive to 1) prime-target feature overlap (around 150 ms post-target onset), 2) case-specific priming (around 200 ms post-target onset), and 3) case-independent priming (around 250 ms post-target onset). The fact that primes and targets occupied the same central location in the Petit et al. (2006) study allowed primes to affect early perceptual processing of target letters. There was no evidence for early repetition effects (i.e., before 300 ms post-target onset) in the present study. This is likely due to the fact that primes and targets occupied distinct spatial locations, hence suggesting that the early effects found by Petit et al. reflect integration of information across location-specific feature/letter representations. The results of the present study suggest that when primes and targets occupy distinct spatial locations, priming effects arise quite late during target processing, probably at the point in time when target letters have been categorized as such and the appropriate response is being prepared. According to this account, an alphabetic decision (letter vs. pseudo-letter classification) would be made on the basis of activity in abstract (shape and location invariant) letter representations of a phonological (i.e., the letter name) or conceptual nature, as argued by Marzouki et al. (in press).

Does this interpretation fit with current knowledge of the functional significance of the P3? Prior research has shown that the P3 is sensitive to manipulations of endogenous attention, typically obtained using the “oddball” paradigm (e.g., Mangun and Hillyard, 1995; Polich, 1996). The classic finding is that P3 amplitude increases as stimulus probability decreases, hence the most prominent P3 with “oddball” (low probability) stimuli. Since stimulus probability is defined relative to a given task that participants are instructed to perform, it is therefore inferred that the P3 reflects processing following stimulus categorization. However, there is still much debate as to exactly what processing the P3 does reflect. According to the influential “context updating” account of Donchin and Coles (1988), the P3 reflects a process whereby the contents of working memory are updated upon arrival of new information. One prominent alternative account emphasizes the role of decision-related processes linked to stimulus categorization and response generation in a given task (e.g., Verleger et al., 2005). It remains nevertheless possible that the P3 reflects multiple processes linked to working memory and task-specific response generation, and perhaps more.

Further evidence about the functional significance of the P3 can be found in the recent literature on P3 and the attentional blink (AB). Vogel et al. (1998) first reported suppression of the P3 component to unattended items in the AB paradigm (i.e., during the attentional blink). This was taken as evidence in favor of a failure to consolidate the unattended item in working memory (Dell’Acqua et al., 2003; Vogel and Luck, 2002). However, the recent study of Sessa et al. (2007) suggests that P3 amplitude is not so much determined by detection accuracy of target items in the AB paradigm (unattended items are less well detected and show a suppressed P3), but rather on the masking conditions of that item (i.e., whether or not the target is followed by another item). These authors found suppression of P3 when targets were followed by a masking item but were still detected at around 90% accuracy, and suggested that it might rather be response uncertainty that causes the lowering of P3 amplitude. The increased response uncertainty would be generated by the items surrounding the target, with no reduction in P3 amplitude when the trial sequence terminates with the target. This fits with prior findings from signal detection experiments showing that P3 amplitude increases as a function of the hit rate and confidence rating of detected stimuli (e.g., Kerkhof and Uhlenbroek, 1981). This response uncertainty explanation appears to be in a similar vein to Kok’s (2001) proposal that P3 amplitude depends on the ease with which a target stimulus can be categorized according to the demands of the task (event categorization), which in turn has antecedents in the “template matching” account of Squires et al. (1973). The general idea is that P3 amplitude increases as the match between incoming information and the task-defined response category increases.

The present results fit nicely with this general account of the P3, since targets preceded by related primes generated larger P3 amplitudes than targets preceded by unrelated primes. Appropriately primed targets would be easier to classify as letters as opposed to pseudo-letters in the present study, and especially when prime stimuli receive a prior processing boost from a valid spatial cue. Thus, it can be argued that the modulation of the P3 component found in the present study reflects the ease with which our participants classified clearly visible target stimuli as being letters or pseudo-letters. The fact that we did not observe priming effects in the behavioral data can be taken as a demonstration of the greater sensitivity of ERP measures, particularly with respect to rather subtle manipulations such as the combination of exogenous cueing and subliminal priming used in the present study.

In conclusion, the present study has demonstrated a clear influence of exogenous cueing on the processing of subliminally presented letters. Only in the presence of a valid spatial cue did prime letters influence subsequent target processing. This priming effect took the form of a modulation of P3 amplitude between 300 and 400 ms post-target onset, therefore suggesting a relative late influence of peripheral prime stimuli on the processing of centrally located targets.

4. Experimental procedures

4.1. Participants

Nineteen native French-speaking students (10 males, mean age=23 years), were paid to participate in the experiment. All participants were right-handed and reported having normal or corrected-to-normal vision. Fourteen participants had participated in the behavioral study of Marzouki et al. (2007) and had shown chance-level performance on a prime visibility test.

4.2. Design and stimuli

Sixteen letters (all consonants) of the Roman alphabet served as targets along with sixteen pseudo-letters designed using Font Creator 4.0 software. Each target letter was primed either by the same letter (repetition prime) or a different letter (unrelated prime), defining the two levels of the factor Prime Relatedness. Target stimuli were always centrally located, and prime stimuli could appear in the right or the left visual field, defining the two levels of the factor Prime Position. Prior to prime presentation, a cue stimulus appeared either at the same location as the prime (valid cue, 50% of trials) or the opposite location (invalid cue, 50% of trials), defining the two levels of the factor Cue Validity. It is important to note that since targets appeared centrally, they never appeared at the cued location. Prime Relatedness (on 50% of trials prime was the same letter as the target) was crossed with Prime Position and Cue Validity in a $2 \times 2 \times 2$ factorial design. It should be noted that we also had pseudo-letters as targets. These pseudo-letter targets were distortions of the corresponding letters used as primes (see Fig. 3 for examples of pseudo-letter targets). Each participant was tested in each of the 8 experimental conditions with the 16 letters and 16 pseudoletters being repeated 8 times during the experiment.

4.3. Procedure

Stimuli were displayed on a computer screen in white on a black background in VGA mode (75 Hz refresh), with constant brightness and contrast of the display, using E-prime 1.1 software. The background luminance of the screen was approximately 0.1 cd/m^2 and the luminance of all stimuli was approximately 6.5 cd/m^2 . The procedure is described in Fig. 4. Each trial began with a central fixation point (an asterisk) for 300 ms. The fixation point was then replaced by a complex geometric form (a cross superimposed upon a filled circle) that constitutes the cue stimulus for 150 ms located at a distance of 3.21° of visual angle at a viewing distance of 80 cm either left or right of fixation.

The cue stimulus was replaced by a forward mask consisting of a white square with black crossed stripes which appeared both left and right of fixation at the same eccentricity as the cue for 12 ms. The prime stimulus followed the forward mask and appeared either left or right of fixation accompanied by the letter W in the opposite location. The letter W was not a target letter and was used as a filler letter to maintain a balance in visual complexity over left and right visual fields. Prime and W presentation lasted 45 ms and was replaced by the centrally located target stimulus and two peripherally located backward masks that remained on the screen until participants responded by indicating if the target was a letter or a pseudo-letter (alphabetic decision). The experiment was run inside a dimly lit room and was controlled using E-Prime 1.1 software. Participants responded by pressing one of two game-pad triggers with their index fingers: right button for letters and left button for pseudo-letters. Participants first performed a practice session with the complete set of 16 target letters and pseudo-letters, followed by 256 randomly ordered trials in each of the 2 blocks, giving a total of 512 trials per participant. The EEG signal (200 Hz sampling rate, bandpass of 0.01 to 40 Hz) was recorded from electrodes attached to the scalp with an elastic cap (see Fig. 5). We also used two electrodes to detect blinks and eye movements — one below the left eye and one to the right of the right eye. All trials contaminated by eye movements were rejected prior to averaging. Items rejected across participants varied from 0.0% to 16.0% with a mean of 3.1% ($SD=4.7\%$).

4.4. Data analysis

Participants performed the alphabetic decision task with a high level of accuracy (97.4% of Hits and 2.6% False Alarms; Mean $d' = 4.1$, $SD = 0.8$).² Averaged ERPs were formed off-line from trials free of artifact and time-locked to the onset of target letters. Averaged ERPs were quantified by calculating the mean amplitude values (relative to a 100 ms pre-target baseline) in four different time windows: 100-200 ms, 200-300 ms and 300-400 ms and 400-500 ms post-target onset. Separate sets of repeated measures ANOVAs were run on the data from each of the four time windows, with Cue Validity (valid vs. invalid), Prime Relatedness (related vs. unrelated), and Electrode Site as factors. In order to examine distributional effects in the ERPs, electrodes were grouped into columns (Column 1, Column 2, Column 3, Midline: see Fig. 5) and separate analyses performed per column with within-column electrode site as a factor.

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²There were no significant effects in an analysis of the behavioral data (RTs and percentage errors). This is likely due to the unusually large amount of variance in these data, perhaps as a result of the specific requirements of the present experiment—no eye movements or blinking until the blink sign appeared — and the smaller number of participants compared with the Marzouki et al. (2007) study. It can be noted that the absence of effects in the behavioral data is in line with the absence of any effects on P3 peak latency, given that this ERP measure generally correlates well with RTs (e.g., Dehaene et al., 1998; McCarthy and Donchin, 1981).

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Fig. 1. Grand-average event-related potential (ERP) waveforms from target letter onset showing effects of repetition priming in the presence of a valid cue (a) and an invalid cue (b) at electrode site CP2

Fig. 2. Scalp maps for voltage differences (net priming effects) between related and unrelated primes with valid cue (a) and invalid cues (b) in the 300-400 ms (P3) time window. The analysis was performed using Cartool software (<http://brainmapping.unige.ch/Cartool.htm>)

Fig. 3. Examples of letters primes (B and K) and their corresponding distortions as pseudo-letters targets

Fig. 4. Timing of events in a typical trial

Fig. 5. Electrode montage and analysis columns. Twenty-nine active tin electrodes were held in place by an elastic cap (Electro-Cap International, Inc., Eaton, OH) and maintained <5 kOhm. Additional electrodes were placed below the left eye (LE) and beside the right eye (HE) to monitor eye movements and blinks. All electrodes were referenced to the left mastoid (A1), and the right mastoid (A2) was recorded actively to detect left/right mastoid asymmetry (none was detected). The four analysis columns (Column 1, Column 2, Column 3, and Midline) are indicated by the grey bars interconnecting the various anterior/ posterior sites