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► **To cite this version:**

Jonathan Grainger, Kevin Diependaele, Elsa Spinelli, Ludovic Ferrand, Fernand Farioli. Masked Repetition and Phonological Priming Within and Across Modalities.. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 2003, 29 (6), pp.1256-1269. 10.1037/0278-7393.29.6.1256 . hal-03879055

**HAL Id: hal-03879055**

**<https://hal.science/hal-03879055v1>**

Submitted on 29 Mar 2024

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## Masked Repetition and Phonological Priming Within and Across Modalities

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Short title: Masked cross-modal priming

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## Abstract

Lexical decision latencies to word targets presented either visually or auditorily were faster when directly preceded by a briefly presented (53 ms) pattern-masked visual prime that was the same word as the target (repetition primes), compared to different word primes. Removing participants who correctly identified at least one prime word in a prime visibility test did not modify the pattern of results. Primes that were pseudohomophones of target words did not significantly influence target processing compared to unrelated primes (Experiments 1-2), but did produce robust priming effects with slightly longer prime exposures (67 ms) in Experiment 3. Like repetition priming, these pseudohomophone priming effects did not interact with target modality. Experiments 4 and 5 replicated this general pattern of effects while introducing a different measure of prime visibility and an orthographic priming condition. The results are interpreted within the framework of a bi-modal interactive activation model.

A word is recognized more easily by a participant in a laboratory experiment when it has already been processed by that person on a previous trial. This repetition priming effect has been demonstrated on many occasions in behavioral studies even with quite considerable delays between first and second presentation of targets (e.g., Feustal, Shiffrin, & Salasoo, 1983; Forbach, Stanners, & Hochaus, 1974; Scarborough, Cortese, & Scarborough, 1977), and shows up as reduced N400 amplitudes in electrophysiological measures of word processing (see Rugg, 1995, for a review). Most important for the present study, robust repetition priming is obtained when the first presentation (henceforth the prime stimulus) is masked and unavailable for conscious report, as long as the second presentation (henceforth the target stimulus) follows immediately (Forster & Davis, 1984; Segui & Grainger, 1990). These masked repetition priming effects are assumed to reflect fast automatic activation of representations shared by prime and target. The shared representations could be orthographic, phonological, morphological, or semantic in nature. The orthographic and phonological representations could either be whole-word (lexical) representations or smaller than the whole-word (sublexical).

Up until recently, masked repetition priming had only been reported for primes and targets presented in the same (visual) modality. The present study addresses the question of whether masked repetition priming can cross modalities. Apart from simply establishing the limits of unconscious priming, this is an important question from a theoretical point of view. Given the evidence that has accumulated in favor of fast automatic activation of “phonological” codes during printed word perception (see Frost, 1998, for a review), many current models of word recognition assume direct connectivity across representations involved in processing printed words and those involved in processing spoken words (e.g., Grainger & Ferrand, 1994). Under this view, the phonological codes that are recruited during spoken language comprehension are rapidly activated upon presentation of a printed word. We therefore expect to observe an influence of visually presented prime stimuli on the time it takes to recognize spoken word targets.

Our own initial efforts to obtain unconscious cross-modal priming went unrewarded (Spinelli, 1995). In a large series of experiments using very brief prime exposure durations (30 ms) in order to avoid any conscious processing of prime stimuli, we failed to observe a significant effect of prime-target repetition from visually presented primes on auditory targets. This failure to find unconscious cross-modal priming was confirmed in a recent article by Kouider and Dupoux (2001). These authors showed that significant cross-modal repetition priming only emerged when primes were presented with exposures that were long enough to

allow them to be consciously processed. Within-modality repetition priming was, however, obtained in conditions of unconscious processing of primes. Kouider and Dupoux interpreted their results as evidence for a functional disconnection between the visual and auditory modalities. Unconscious processing of stimuli in one modality is encapsulated relative to the representations and processes associated with the other modality. Only access to a modality-independent central executive (associated with conscious experience) allows integration of information from different modalities (see Dehaene & Naccache, 2001, for a similar proposal).

The recent work of Ford and Marslen-Wilson (2001) points to why previous attempts to obtain unconscious cross-modal priming might have failed. These authors reported being able to present prime stimuli subliminally with prime exposure durations of approximately 50 ms (i.e. 20 ms longer than the durations used in our prior work). Not surprisingly, the type of backward mask that is presented following prime presentation appears to be a critical element in determining prime visibility in cross-modal conditions. Ford and Marslen-Wilson used a random string of consonants, while in our previous research (Spinelli, 1995) we had used a string of hash-marks (Kouider & Dupoux used a string of ampersands). Ford and Marslen-Wilson (2001) reported mixed evidence that morphologically related primes facilitated target recognition in these subliminal cross-modal priming conditions. The present study sought evidence for repetition priming effects in similar experimental conditions.

A brief survey of the literature on visual backward masking provides some indication why random letter strings are more efficient than hash marks or ampersands. Some early empirical work on backward masking effects with complex stimuli (McClelland, 1978; Taylor & Chabot, 1978) showed that backward masking efficiency depends on the mask's structural similarity to the target. These results fit with Walley and Weiden's (1973) lateral inhibitory account of what they called "cognitive masking", which led them to predict that the degree of masking will be related to the similarity between two stimuli. More recent theorizing suggests that backward masking may reflect competition at a capacity-limited stage of processing in pattern recognition (e.g., Di Lollo, Enns, & Rensink, 2000). It remains to be seen, however, exactly how such competitive processes depend on the structural similarity of the competing stimuli. Here, a distinction must be made between competitive processes that depend on whether two stimuli belong to the same functional category or not (e.g., letter strings), as opposed to within-category cooperative interactions as observed in the backward masking experiments of Perfetti and colleagues (e.g., Perfetti & Bell, 1991).

The precise mechanisms underlying differential backward masking effects will not be the focus of the present study. Our major aim is to examine whether unconscious cross-modal priming can be observed in conditions where prime exposure duration can be extended by the use of more powerful backward masking, as determined empirically by prime visibility tests. In pilot work using random consonant masks, we observed significant cross-modal repetition priming at 53 ms prime exposures in participants who were unable to report the identity of a single prime word in a post-experiment visibility test. In the experiments to be reported below, both repetition priming (prime and target are the same word in the related prime condition) and phonological priming (the prime is a pseudohomophone of the target in the related prime condition) will be examined within modalities (visual-visual) and across modalities (visual-auditory). Testing for cross-modal pseudohomophone priming will constrain possible interpretations of any observation of cross-modal repetition priming. Experiments 1-3 test for repetition and pseudohomophone priming effects against unrelated word and nonword controls. Experiment 4 provides a further examination of repetition priming effects while introducing a different measure of prime visibility. Experiment 5 examines pseudohomophone priming effects relative to unrelated nonword controls and orthographically related, non-homophonic nonword primes.

## EXPERIMENT 1

### Method

Participants Forty psychology students at the University of Provence took part in Experiment 1 for course credit. They were tested individually in a quiet room. All participants were native French speakers and reported having no hearing impairment, and normal or corrected-to-normal vision.

Stimuli and Design A set of 40 words and 40 nonwords served as target items in Experiment 1 (see Appendix 1). All stimuli were monosyllabic and were 4 to 6 letters long. The average length for word and nonword targets was 4.5 and 4.7 letters, respectively. Each target was associated with four different prime stimuli, corresponding to the combination of Priming (related versus control) and Type of Priming (repetition versus pseudohomophone). The two types of priming were presented in separate blocks and analyzed separately. In the repetition

priming condition, primes were the same word or nonword as targets (e.g. *nord* – *NORD*) or were unrelated (e.g. *plan* – *NORD*). Unrelated primes were chosen so that they showed no semantic (in the case of word targets) or clear form overlap with the targets. They were also matched with targets for length and printed frequency. In the pseudohomophone block, primes were pseudohomophones of the target (e.g. *nort* – *NORD*), or unrelated controls (e.g. *lane* – *NORD*). The pseudohomophones were nonwords, which according to French grapheme-phoneme conversion rules, could be pronounced like the target word they were paired with. For the repetition priming and the pseudohomophone priming blocks, four experimental lists were constructed by rotating the factors Priming (related versus control) and Target Modality (visual versus auditory) over participants and materials using a Latin-square design. Participants received one of these lists in the repetition priming block, and a different list (with targets assigned to the opposite modality and to the opposite priming condition) in the pseudohomophone priming block, with the order of blocks counterbalanced over participants. Thus each participant saw each target twice, once in each modality.

Procedure The experimental session consisted of 1 practice block, 2 experimental blocks, and a prime visibility test, in that order. The practice block consisted of 40 targets (i.e. 20 words and 20 nonwords, none of which appeared in the experimental lists), half presented visually and half auditorily, in random order. All primes were unrelated in the practice block. In an experimental block 80 trials were presented (i.e. 40 words and 40 nonwords, each consisting of 20 within and 20 between modality trials, half with related primes and the other half with unrelated primes). Each trial began with the presentation a forward mask (11 hash marks) together with two vertical lines (i.e. one above and one beneath the center of the forward mask). After 500ms the forward mask and the vertical lines were replaced by the prime. The prime was presented in lowercase in Courier New 12 point, and stayed on the screen for 53ms (4 scans of a 75 Hz video monitor), being immediately replaced by a backward mask composed of a pseudo-random string of 11 uppercase consonants (e.g. *WDTHPMXRTZ*). For each target a fixed backward mask was constructed that was used for all the conditions tested with that target. Care was taken that consonants appearing in a given target and its different primes were not present in the corresponding post mask. On within-modality trials, the backward mask remained on the screen for 13 ms and was immediately replaced by the visual target. Visual targets were printed in uppercase letters and were 1.5 times bigger than the primes and masks (Courier New 18 point). On between-modality trials, the auditory target was presented 13ms after the beginning of the backward mask, but here the mask remained on

the screen until the end of the trial. In both cases participants were asked to decide as quickly and as accurately as possible whether the written or spoken stimulus was a French word or not. They did so by pressing the right control key (for a positive response) or the left control key (for a negative response) of a standard PC keyboard. For left handed-participants this response procedure was reversed. Following a response, the visual target or the backward mask disappeared from the screen. The response deadline and the inter-trial interval were set to 4000ms and 532ms, respectively. All visual stimuli were presented in white fixed-width font (Courier New) against a black background. Auditory stimuli were recorded by a female French native speaker. They were presented to participants via a Sennheiser HMD224 headset, connected to a standard PC using a CMI8330/C3D soundboard. Visual stimuli were presented on a monitor with a 75-Hz refresh rate (frame duration of 13.3ms). The experiment was controlled using DMDX (Forster & Forster, 2003).

The main experiment was directly followed by a prime visibility test that used the same procedure except that now the visual targets (in the case of within-modality trials) or the backward masks (on across-modality trials) disappeared from the screen after 500ms. Participants were asked to try to identify the primes, while ignoring the targets. Responses were given using the computer keyboard and without any time pressure. If participants had finished typing in their answer or if they could not identify the prime, they were instructed to press the enter key to go on to the next trial. The visibility test consisted only of word trials and used only 2 prime types: repetition and unrelated word primes (20 identical and 20 unrelated prime-target pairs, each consisting of 10 within and 10 between modality trials). Furthermore, 4 versions of the prime visibility test were constructed, such that in the visibility test participants received prime-target pairings they had not received in the main experiment.

## Results

The data were analysed separately for repetition priming and pseudohomophone priming, and for words and nonwords. For each of these conditions, ANOVAs were run on the RTs and error rates, with Modality and Priming as main independent variables. Prior to these analyses error responses and outliers (RTs > 1500 ms, 0.9% of the data) were removed. *F* values are reported for the analysis by participants (*F*<sub>1</sub>) as well as for the analysis by items (*F*<sub>2</sub>). Table 1 shows the mean RTs for correct responses and the percent errors in each of the experimental conditions. In this and the following experiments, there were no main effects of



Latin-square group or Presentation order, nor did these factors interact significantly with the other independent variables. Unless otherwise stated, in all the experiments manipulating target modality, there was a main effect of this factor (with  $p < .05$  for both  $F_1$  and  $F_2$ ), indicating that lexical decision took longer or was less accurate with auditory compared to visual targets.

Repetition priming For words, the RT analysis showed a significant main effect of Priming ( $F_1(1,38) = 24.64$ ,  $p < .001$ ;  $F_2(1,39) = 22.09$ ,  $p < .001$ ) with a 38 ms advantage in the case of related primes. The Priming X Modality interaction was not significant ( $F_1 < 1$ ;  $F_2 < 1$ ). Apart from the effects of Modality, there were no significant effects in the error analysis for words. The same was true for the analysis of nonword RTs and errors, except that the effect of Modality was not significant in the error analysis ( $F_1(1,38) < 1$ ;  $F_2(1,38) = 1.14$ ,  $p = .29$ ).

Pseudohomophone priming The RT analysis for words revealed a trend to an effect of Priming ( $F_1(1,38) = 2.77$ ,  $p = .10$ ;  $F_2(1,39) = 3.28$ ,  $p = .08$ ), and no interaction between Modality and Priming ( $F_1 < 1$ ;  $F_2 < 1$ ). In the error analysis for words, there was no main effect of Priming ( $F_1(1,38) < 1$ ;  $F_2(1,39) = 2.16$ ,  $p = .15$ ), but the interaction between Modality and Priming was significant in the item analysis ( $F_1(1,38) = 2.19$ ,  $p = .15$ ;  $F_2(1,39) = 8.71$ ,  $p < .01$ ). Error rates to auditory word targets did show a priming effect that was significant in the item analysis ( $F_1(1,38) = 1.11$ ,  $p = .30$ ;  $F_2(1,39) = 7.09$ ,  $p < .01$ ). There were no significant effects in the analysis of RTs or error rates to nonword targets, except for an effect of target modality in the RT analysis.

INSERT TABLE 1 ABOUT HERE

A further analysis was performed after removing the data of 7 participants, who correctly identified one or more primes in the visibility test (correct prime identification in these participants ranged from 1 to 9 out of 40 test trials, i.e. 2.5% to 22.5%, and the mean percent identification for repetition and unrelated primes was 6% and 11%, respectively). Removing these data had very little impact on the observed means, and all effects that were significant in the main analysis remained so in the analysis corrected for prime visibility.

## Discussion

The critical result of Experiment 1 is a cross-modal repetition priming effect for word targets that remained robust after removing 7 participants who had successfully identified one or more prime words in the prime visibility test. Within-modal (visual-visual) and cross-modal (visual-auditory) repetition priming effects were approximately the same size. Nonword targets did not show a repetition priming effect, neither within nor across modalities. We can therefore tentatively conclude that the type of backward mask used in Experiment 1 (random consonant array) allowed us to increase prime exposure duration to a level necessary for obtaining cross-modal repetition priming, without generating a corresponding increase in prime visibility for the great majority of participants.

On the other hand, the effects of pseudohomophone primes were not robust in Experiment 1, neither within nor across modalities. In the cross-modal condition, this is a potentially critical result that should constrain our interpretation of the repetition priming effect that was observed in the same participants and the same experimental conditions. We should, however, note that there was a trend to facilitation in the RT analysis for word targets, and a marginally significant effect in the error scores to auditorily presented word targets that reached significance by items. Thus it appears that pseudohomophone primes are having some influence on target processing, and if anything this influence is clearer in the cross-modal priming condition.

Nevertheless, we need to account for why pseudohomophone priming was so fragile in the present experiment compared to prior reports of this phenomenon in French (Ferrand & Grainger, 1992, 1994, 1996; Grainger & Ferrand, 1996; Ziegler, Ferrand, Jacobs, & Grainger, 2000). There is one obvious feature in which our procedure differs from the one used in previous studies. That is the fact that visual and auditory target presentation was mixed in the present experiments, whereas participants only saw visually presented targets in the other studies. It might be the case that the presence of auditory targets distracts attention from visually presented primes hence weakening their potential impact on target processing. Experiment 2 examines whether presentation of visual targets alone would allow within-model pseudohomophone priming effects to emerge.

## EXPERIMENT 2

In Experiment 2, primes and targets are always presented visually. In order to keep the design as similar as possible to Experiment 1, the target modality factor was replaced by a manipulation of target size. Targets could be 1.5 times bigger than primes (as was the case in the within-modality condition of Experiment 1), or the same size as primes. Target size changed randomly from trial to trial.

### Method

Participants Forty psychology students at the University of Provence participated in Experiment 2 for course credit. All were native French speakers, with normal or corrected-to-normal vision. Participants were tested individually in a quiet room. None of them had taken part in the previous experiment.

Stimuli and Design Apart from the fact that the auditory trials of Experiment 1 now became visual trials with primes and targets that had the same size, Experiment 2 was identical to Experiment 1 in stimuli and design.

Procedure The procedure was the same as for visual targets in Experiment 1, except that targets could be the same size as primes (i.e. font size 12) or 1.5 times bigger (i.e. font size 18).

### Results

As in the previous experiment, the data were analyzed separately for repetition priming and pseudohomophone priming, and for word and nonword targets. For each of these conditions we ran ANOVAs on the RTs and error scores, with Prime-target size (same versus different) and Priming as main independent variables. Prior to these analyses error responses and outliers (0.6% of the data) were removed as in the previous experiment. *F* values are reported for the analysis by participants (*F*<sub>1</sub>) as well as for the analysis by items (*F*<sub>2</sub>). Table 2 shows the mean RTs for correct responses and the percent errors in each of the experimental conditions.

## INSERT TABLE 2 ABOUT HERE

Repetition priming For word targets, in the RT analysis there was a significant main effect of Priming ( $F(1,38) = 24.90, p < .001$ ;  $F(1,39) = 20.41, p < .001$ ) with a 40 ms advantage for the related prime condition. There was no effect of Prime-target size ( $F(1,38) < 1$ ;  $F(1,39) < 1$ ) and no interaction ( $F(1,38) < 1$ ;  $F(1,39) < 1$ ). There were no significant effects in the error analysis for words (all  $F$ s  $< 1$ ). In the RT analysis for nonwords there was also only a significant main effect of Priming ( $F(1,38) = 5.00, p < .05$ ;  $F(1,39) = 5.79, p < .05$ ) with a 17 ms advantage for related primes. There were no significant effects in the error analysis for nonwords.

Pseudohomophone priming For word targets, there were no significant effects in the RT analysis nor in the error analysis. In the RT analysis for nonwords there was a significant main effect of Prime-target size ( $F(1,38) = 7.16, p < .05$ ,  $F(1,39) = 9.01, p < .005$ ) with an 18 ms advantage for bigger targets over smaller targets. There was also a marginally significant effect of Priming ( $F(1,38) = 3.94, p = .05$ ;  $F(1,39) = 2.83, p = .10$ ). The interaction was not significant ( $F(1,38) < 1$ ;  $F(1,39) < 1$ ). The error analysis for nonwords revealed a significant main effect of Prime-target size, but this was restricted to the participant analysis ( $F(1,38) = 6.51, p < .05$ ;  $F(1,39) = 2.36, p = .13$ ). There was no main effect of Priming ( $F(1,38) < 1$ ;  $F(1,39) < 1$ ), and again no interaction ( $F(1,38) < 1$ ;  $F(1,39) < 1$ ).

As for Experiment 1, we performed an additional analysis excluding three participants who correctly identified at least one prime in the visibility test. None of these participants showed correct prime identifications for identical prime-target pairs, and for unrelated primes identification was between 5% and 15%. Excluding these participants did not change the pattern of effects observed in the main analysis.

## Discussion

Experiment 2 replicates the within-modal priming results of Experiment 1. Having only visually presented targets does not appear to have influenced the effects in any major way. The effect sizes are practically identical for word targets across Experiments 1 and 2 (different-size target condition), although average RTs are faster in Experiment 2. Furthermore, the absence of auditory targets did not produce the expected benefits on

processing of visually presented pseudohomophone primes. There is still no significant priming from pseudohomophones in Experiment 2.

Independently of priming effects, target size did not influence the processing of word targets in Experiment 2, but did affect responses to nonwords. It appears that bigger nonword targets were easier to process than smaller targets. This dissociation in the effects of target size as a function of lexical status certainly merits further investigation that is unfortunately beyond the scope of the present work. More directly related to the aims of the present study is the fact that the relative size of primes and targets did not influence priming effects. In a similar vein, Grainger and Jacobs (1993) reported that case-compatibility (prime and target in the same or different case) did not affect masked repetition priming effects in visual lexical decision.

Returning to our failure to find robust pseudohomophone priming effects, it might be that our prime exposure duration, chosen to be at the limits of prime awareness, is just below the critical duration necessary for obtaining significant effects of pseudohomophone primes in the specific testing conditions of the present experiments. Indeed, pilot experimentation using a 67 ms prime duration with the present experimental procedure showed a significant pseudohomophone priming effect in within-modal testing conditions.

### EXPERIMENT 3

The goal of Experiment 3 was to determine whether pseudohomophone priming effects (within and across modalities) would emerge with longer prime exposure durations. The experimental conditions were otherwise identical to Experiment 1. In order to have additional information about participants' level of awareness of prime stimuli, the prime visibility test was modified in Experiment 3 to include a forced-choice procedure to allow the calculation of sensitivity ( $d'$ ) based on signal-detection theory.

#### Method

Participants Thirty-two psychology students at the University of Provence participated in Experiment 3 for course credit. All were native French speakers and reported having normal or corrected-to-normal vision, and no hearing deficit. Participants were tested individually in a quiet room. None of them had participated in the previous experiments.

Stimuli and Design These were the same as in Experiment 1 with both within-modality and across-modality priming conditions.

Procedure The procedure for the main experiment was the same as for Experiment 1 except for the longer (67 ms) prime exposure duration. The visibility test was modified in Experiment 3 in order to include a forced-choice procedure. Thus, participants were first required to indicate whether the prime was a word or not (two-alternative forced-choice), and to guess if they had no idea. Then they had to type in the prime stimulus if they had successfully identified it (as in the previous experiments). Contrary to the previous experiments, both word and nonword primes were therefore included in this test (for the purposes of the forced-choice procedure). However, in order to avoid false alarm rate to pseudohomophone primes causing an underestimation of  $d'$ , the analysis of these data only includes the unrelated prime condition.

## Results

The data were analysed separately for repetition priming and pseudohomophone priming, and for word and nonword targets. For each of these conditions we ran ANOVAs on the RTs and error scores, with Modality and Priming as main independent variables. Prior to these analyses error responses and outliers (1.8% of the data) were removed as in the previous experiments.  $F$  values are reported for the analysis by participants ( $F1$ ) as well as for the analysis by items ( $F2$ ). Table 3 shows the mean RTs for correct responses and the percent errors in each of the experimental conditions.

Repetition priming For words, the RT analysis revealed a significant main effect of Priming ( $F1(1,30) = 22.18, p < .001; F2(1,39) = 12.43, p < .002$ ) with a 40 ms advantage in the related prime condition. The Priming X Modality interaction was not significant ( $F1 < 1; F2 < 1$ ). In the error analysis for words, the effects of Priming and the interaction were not significant ( $F1(1,30) = 1.71, p = .20; F2(1,39) = 2.28, p = .14$ , and  $F1(1,30) < 1; F2(1,39) = 1.13, p = .29$ , respectively). Similarly, there was no effect of Priming and no interaction in the RT analysis ( $F1 < 1; F2 < 1$ , and  $F1(1,30) = 1.41, p = .24; F2(1,39) = 1.61, p = .21$ , respectively) or in the error analysis (all  $F_s < 1$ ) for nonword targets.

Pseudohomophone priming For word targets, the RT analysis showed a significant main effect of Priming ( $F(1,30) = 8.96, p < .006$ ;  $F(1,39) = 8.72, p < .006$ ) with a 24 ms advantage for related primes. The interaction with Modality was not significant ( $F(1,30) < 1$ ;  $F(1,39) = 1.14, p = .29$ ). In the error analysis for words, the main effect of Priming and the interaction between Modality and Priming were not significant ( $F(1,30) < 1$ ;  $F(1,39) = 1.09, p = .30$ , and  $F(1,30) < 1$ ;  $F(1,39) < 1$ , respectively). In the RT analysis for nonwords the main effect of Priming was not significant ( $F(1,30) = 2.42, p = .13$ ;  $F(1,39) = 2.63, p = .11$ ), but the interaction between Modality and Priming was significant, although only marginally in the item analysis ( $F(1,30) = 4.74, p < .04$ ;  $F(1,39) = 3.17, p = .08$ ). Planned comparisons revealed a significant inhibitory priming effect in the case of auditorily presented nonwords ( $F(1,30) = 6.16, p < .02$ ;  $F(1,39) = 4.83, p < .04$ ) with a 30 ms disadvantage for related primes. The error analysis for nonwords showed no significant main effects and no interaction.

INSERT TABLE 3 ABOUT HERE

#### Analysis including prime visibility

Since most of the participants (22 out of 32) correctly identified at least one of the primes in the visibility test, here we decided to do an analysis dividing participants into two groups on the basis of their prime identification scores. In the following analyses we therefore included an additional between participants factor Visibility (high versus low). The mean (and range) of the prime identification scores were 6.3% (0-25%) for the low visibility group and 47.2% (25-85%) for the high visibility group. The visibility factor did not interact with repetition priming in any of the analyses. However, visibility did interact with the effects of pseudohomophone priming in the item analysis of RTs to word targets ( $F(1,28) = 2.93, p = .10$ ;  $F(1,39) = 4.90, p < .04$ ). It is interesting to note that significant effects of pseudohomophone priming only appeared in the low visibility group ( $F(1,28) = 11.55, p < .003$ ;  $F(1,39) = 9.23, p < .005$ ) with a 38 ms advantage in the case of related primes.

Based on the forced choice data of the unrelated prime-target pairs in the visibility test, we calculated  $d'$  measures for each participant. The mean  $d'$  value was 0.37 for participants with low identification scores and 0.80 for participants with high prime identification scores. A comparison between the two groups revealed significantly lower  $d'$  values for participants with lower identification scores ( $t(30) = 2.37, p < .03$ ), and prime identification score correlated significantly with  $d'$  across participants ( $r = 0.58, p < .001$ ). Finally, we examined the correlations between the  $d'$  measure for each participant and the size of priming effects for

word targets. The correlation with the within-modality repetition priming effect was  $-.04$  and not significant. The correlation with the cross-modal repetition priming effect was  $.02$  and also not significant. For pseudohomophone priming, the correlation between the  $d'$  values and within-modality effects was  $-.02$  and not significant, while the correlation with cross-modal pseudohomophone priming effects was  $-.42$  and was significant ( $p < .05$ ). The negative correlation indicates that the size of cross-modal pseudohomophone priming increased as  $d'$  values decreased.

## Discussion

Experiment 3 shows robust pseudohomophone priming effects, at prime exposure durations of 67 ms, that do not interact with modality of target presentation. Furthermore, priming effect size tended to interact with participants' level of awareness of prime stimuli. Participants who reported identifying the most primes in the visibility test actually showed lower levels of pseudohomophone priming. This is strong evidence against prime visibility acting as a causal factor in the generation of such priming effects (i.e., primes must be consciously processed to enable cross-modal priming), as argued by Kouider and Dupoux (2001). The influence of prime visibility appeared even more strongly in the cross-modal pseudohomophone priming condition, where effect size correlated negatively with the  $d'$  values for each participant. Repetition priming effects did not appear to be affected by level of prime visibility, given the absence of an interaction with this factor, and the close to zero correlations with  $d'$  values. Finally, pseudohomophone primes were found to have an inhibitory effect on the processing of auditory nonword targets. This can be taken as evidence for the activation of the whole-word phonological representation that corresponds to the pseudohomophone prime. Such whole-word activation would clearly interfere with the generation of a "nonword" response in the lexical decision task. Thus, whole-word phonological representations activated by visually presented pseudohomophone primes could be the locus of both the facilitatory pseudohomophone priming effect for word targets (at least auditorily presented words), and the inhibitory effect for auditory nonword targets. Furthermore, pseudohomophone priming effects were obtained relative to an unrelated nonword prime condition in Experiment 3. This implies that the observed effects could be due to the greater phonological or orthographic overlap across primes and targets in the pseudohomophone prime condition, or a combination of both of these factors. Given that orthographically related non-homophonic primes tend not to facilitate target recognition in



conditions similar to those used in Experiment 3 (e.g., Ferrand & Grainger, 1992), we expect the pseudohomophone priming effect to be primarily driven by phonological representations. We return to this issue in Experiment 5.

## EXPERIMENT 4

A central claim of the present study is that repetition priming can be obtained across modalities in conditions where participants are largely unaware of the nature of prime stimuli. Support for this claim was provided using two different measures of prime visibility: free report, and forced-choice lexical decision. However, on the hypothesis that only consciously perceived information can cross modalities (e.g., Kouider & Dupoux, 2001) it could be argued that these measures of prime visibility are not sensitive enough, and that participants in our experiments did have conscious access to relevant information in the primes. Experiment 4 was therefore designed to provide a replication of the cross-modal repetition priming effects obtained in Experiments 1 and 3, using an extended set of stimuli, and including a different measure of prime visibility. The new measure, adopted from Kouider and Dupoux (2001), is thought to provide a more sensitive evaluation of participants' level of awareness in the masked priming conditions of the present experiments. In the post-experiment visibility test, participants are presented with trials including primes taken from the main experiment and an equivalent number of trials where the prime is composed of non-letters (e.g.,  $\pi\sigma\alpha\rho\mu\theta$ ). Participants are required to make a forced-choice decision as to whether the prime stimulus is composed of real letters or pseudo-letters.

### Method

Participants Forty-eight psychology students at the University of Provence participated in Experiment 4 for course credit. All were native French speakers and reported having normal or corrected-to-normal vision, and no hearing deficit. Participants were tested individually in a quiet room. None of them had participated in the previous experiments.

Stimuli and Design Twenty new word targets and 20 new nonword targets were added to the stimulus set giving a total of 60 words and 60 nonwords (the word stimuli are given in Appendix 2). They matched the same criteria as the stimuli used in the previous Experiments.

Except for these additional stimuli, the design stayed the same as the repetition priming block of Experiments 1 and 3. There was no pseudohomophone priming condition in this experiment.

Procedure The procedure for the main experiment was the same as for Experiment 1 except that one half of the participants were tested with a 53ms prime exposure, and the other half with a 67ms exposure. Furthermore, the visibility test was modified in Experiment 4 in order to include a letter-pseudoletter discrimination task. Participants were first asked to indicate whether the prime consisted of real letters or not (two-alternative forced-choice), and to guess if they had no idea. Then they were asked to type in the prime stimulus if they thought they had recognized a word. In order not to discourage the participants, primes were presented for 80ms in the practice trials for the visibility test. For the same purpose, 3 trials in each condition (12 in total) of the main visibility test were also presented with a 80ms prime exposure. These trials were discarded from all further analyses. When the prime was formed of real letters, it was always identical to the target.

## Results

### Main analysis

An ANOVA was run on the RTs and error scores, with Modality and Priming as main independent variables, and Prime Duration as a between participants variable. Prior to these analyses error responses and outliers (2% of the data) were removed as in the previous analyses. *F* values are reported for the analysis by participants (*F*<sub>1</sub>) as well as for the analysis by items (*F*<sub>2</sub>). Table 4 gives a summary of the data. Prior to the analysis, the word item 'plot' and the nonword item 'loeu'd' were removed from the data set. These items produced more than 50% errors in some conditions.

For words, the RT analysis revealed a significant main effect of Priming ( $F(1,46) = 43.60, p < .001; F(1,58) = 21.90, p < .001$ ) with a 28ms advantage for related primes. The interaction between Prime Duration and Priming was marginally significant ( $F(1,46) = 3.80, p = .06; F(1,58) = 2.83, p = .10$ ). The effect of Priming was significant at both 53ms prime durations ( $F(1,46) = 10.83, p < .002; F(1,58) = 8.29, p < .006$ ) and 67ms prime durations ( $F(1,46) = 36.57, p < .001; F(1,58) = 15.40, p < .001$ ), but it was 18ms smaller at the shorter prime exposure. Priming effects did not interact with target modality ( $F_1 < 1; F_2 < 1$ ). There

were no significant effects in the error analysis for words (apart from effects of target modality), and the same was true for the RT and error analysis for nonword targets.

INSERT TABLE 4 ABOUT HERE

#### Analysis including prime visibility

In the following analyses we considered the data of the two prime duration groups separately. For the 53ms group we ran an ANOVA without the data of 6 participants who correctly identified at least one prime in the visibility test (identification rates ranged from 4% to 21%). This showed a significant main effect of Priming in the RT analysis for word targets ( $F(1,17) = 7.73$ ,  $p < .02$ ;  $F(1,58) = 5.44$ ,  $p < .03$ ), and no interaction with Modality ( $F(1,17) < 1$ ;  $F(1,58) < 1$ ). We also performed a signal detection analysis on the forced-choice data from the visibility test. A  $d'$  measure was calculated for each participant in each group and each modality. It was obtained by treating the presence of real letters as the signal, and the presence of pseudoletters as noise. At 53 ms prime durations, the mean  $d'$  value was  $-.12$  in case of visual targets, and  $-.21$  in case of auditory targets. T-tests against the null mean revealed no significant difference, neither in case of visual targets ( $t(23) = .62$ ,  $p = .54$ ), nor in case of auditory targets ( $t(23) = .92$ ,  $p = .37$ ). There were no significant correlations between the  $d'$  values and the size of the priming effects for word targets, and no significant correlations between the  $d'$  values and the identification scores across participants.

Since most of the participants in the 67ms group correctly identified at least one of the word primes, we decided to an analysis dividing these participants in two subgroups following the factor Visibility (high versus low). The mean (and range) of the prime identification scores were 2% (0-8.3%) for the low visibility group, and 25.6% (12.5-47.9%) for the high visibility group. The ANOVA showed a significant effect of Priming in the RT analysis to word targets ( $F(1,22) = 26.45$ ,  $p < .001$ ;  $F(1,58) = 15.77$ ,  $p < .001$ ), that did not interact with Visibility or Modality (all  $F$ s  $< 1$ ). Apart from effects of target modality, there were no significant effects in the error analysis to word targets, and no significant effects in the RT and error analyses to nonword targets. The signal detection analysis at 67 ms prime durations showed a mean  $d'$  value of  $.73$  for visual targets and  $1.05$  for auditory targets. The value was significantly different from zero in both cases ( $t(23) = 4.22$ ,  $p < .001$  and  $t(23) = 7.23$ ,  $p < .001$ , respectively). A comparison between the two visibility groups showed only a marginally significant difference in  $d'$  values ( $t(23) = 1.83$ ,  $p = .08$ ). There was a significant

positive correlation between the mean  $d'$  value across participants and their mean identification rate, but only for visual targets ( $r = .52, p < .05$ ). However, these  $d'$  values did not correlate significantly with net repetition priming effects per participant, neither within nor across modalities.

## Discussion

Experiment 4 replicated the pattern of within-modal and cross-modal repetition priming observed in Experiments 1-3, while incorporating a different measure of participants' level of awareness of the prime stimuli. At the 53 ms prime exposure duration participants were at chance levels of performance in discriminating real letter primes from pseudoletter primes, yet significant priming effects were obtained that did not interact with target modality. In line with the results of Experiment 3, net priming effects did not correlate with the new measure of prime visibility. A comparison of the  $d'$  values obtained in the present experiment, using the same measure as Kouider and Dupoux (2001), suggests that the use of a random consonant backward mask reduces prime stimulus visibility compared to the ampersand mask used by Kouider and Dupoux. This potential difference in masking efficacy merits further investigation in a study focusing on this specific issue.

Having further demonstrated that cross-modal repetition priming can be observed in conditions where participants have very little conscious information available from prime stimuli, we now return to the issue of cross-modal pseudohomophone priming. Experiment 3 found an advantage for pseudohomophone primes compared to unrelated nonwords primes, both within and across modalities, at 67 ms prime exposures. As noted in the discussion of Experiment 3, these priming effects could be due to the greater level of phonological and/or orthographic overlap across primes and targets in the pseudohomophone condition. Experiment 5 examines the relative involvement of phonological and orthographic representations in pseudohomophone priming effects within and across modalities.

## EXPERIMENT 5

Experiment 5 provides a further investigation of pseudohomophone priming effects at the long prime exposure of Experiment 3 (67 ms). An orthographic control condition is added to the present experiment in order to evaluate the extent to which the pseudohomophone

priming effect observed in Experiment 3 is driven by phonological or orthographic factors. The visibility test of Experiment 4 is again used in order to re-evaluate the extent to which pseudohomophone priming varies as a function of participants' level of awareness of prime stimuli. The test is further modified in Experiment 5 by excluding the free report procedure so that participants can concentrate fully on the letter / pseudo-letter discrimination task.

## Method

Participants Twenty-four psychology students at Université de Provence participated in Experiment 5 for course credit. All were native French speakers and reported having normal or corrected-to-normal vision, and no hearing deficit. Participants were tested individually in a quiet room. None of them had participated in the previous experiment.

Stimuli and Design We used the same set of target stimuli as in Experiment 4. Primes were pseudohomophones of the target (e.g. *frant* - FRANC), orthographic controls (e.g. *frinc* - FRANC) having the same degree of orthographic overlap with targets as the pseudohomophone primes, or unrelated nonwords (e.g. *siple* - FRANC). The pseudohomophones were nonwords, which according to French grapheme-phoneme conversion rules, could be pronounced like the target word they were paired with. They shared all but one letter with targets. Orthographic control primes were formed by changing one letter in the target to generate a pronounceable nonword that was not homophonic with the target. The unrelated nonword primes were chosen so that they showed no clear form overlap with the targets. Six experimental lists were constructed by rotating the factors Prime Type (pseudohomophone - orthographic control - unrelated nonword) and Target Modality (visual versus auditory) over participants and materials using a Latin-square design. There was no repetition priming condition in this experiment.

Procedure The procedure of the main experiment was identical to Experiment 3, with a prime exposure duration of 67ms. The visibility test consisted of the letter-pseudoletter discrimination task used in Experiment 4. When primes were formed of real letters in the visibility test, there were an equal number of pseudohomophone, orthographic control, and unrelated primes. As in Experiment 4, we included 8 filler trials with a 80ms prime duration (4 visual and 4 auditory trials, both containing 2 real letter and 2 pseudoletter trials).

## Results

An ANOVA was run on the RTs for correct responses, and error scores to word and nonword targets, with Modality and Priming (pseudohomophone - orthographic control - unrelated nonword) as main independent variables. Outliers (2% of the data) were removed before analysis as in the previous experiments. Table 5 gives a summary of the data. For word targets, there was a significant main effect of Priming ( $F_1(1,23) = 7.76, p < .002$ ;  $F_2(1,118) = 7.51, p < .001$ ). Planned comparisons showed that pseudohomophone primes produced faster RTs compared to the unrelated baseline ( $F_1(1,23) = 16.73, p < .001$ ;  $F_2(1,59) = 14.77, p < .001$ ). Pseudohomophone priming was not significant relative to the orthographic control condition ( $F_1(1,23) = 1.73, p = .20$ ;  $F_2(1,59) = 2.59, p = .11$ ). However, the latter condition differed significantly from the unrelated prime condition ( $F_1(1,23) = 5.97, p < .03$ ;  $F_2(1,59) = 5.01, p < .03$ ). Priming effects did not significantly interact with Modality (all  $F_s < 1$ ). Apart from effects of target modality, there were no significant effects in the error analysis for word targets, and no significant effects in the RT and error analysis for nonwords.

INSERT TABLE 5 ABOUT HERE

In the signal detection analysis of the forced choice data, the mean  $d'$  value was .73 for visual targets, and .39 for auditory targets. The  $t$ -tests against the null mean revealed a significant difference, both for visual targets ( $t(23) = 4.48, p < .001$ ), and for auditory targets ( $t(23) = 3.26, p < .004$ ). Furthermore, the  $d'$  values were significantly smaller in the case of auditory targets ( $t = 2.09, p < .05$ ). However, there were no significant correlations between the  $d'$  values and the size of the priming effects for word targets.

## Discussion

The results of Experiment 5 replicate the pseudohomophone priming effect obtained in Experiment 3 at 67 ms prime exposures. Once again the effect was approximately the same size both within and across modalities. However, the pseudohomophone primes did not generate significant facilitation relative to an orthographic control condition, and the orthographic control primes did facilitate target processing relative to unrelated primes. Thus, with degree of orthographic overlap held constant, the additional phonological overlap across

primes and targets in the pseudohomophone prime condition compared to orthographic control primes, did not produce significant priming. One would therefore be tempted to conclude that the pseudohomophone priming effect we have obtained is an orthographic effect, reflecting variations in the number of letters shared by primes and targets. However, it should be noted that the orthographic control primes also shared phonology with target words, albeit to a lesser extent than the pseudohomophone primes. The pattern of priming effects rather suggests that both orthographic and phonological overlap are necessary for obtaining significant priming in the present conditions. The data are compatible with a gradual increase in priming effects as sublexical phonological and orthographic overlap across prime and target increases, rather than an all-or-none effect of the homophonic status of primes (i.e., a lexical effect). This is in line with the fact that priming effects do not interact with target modality, pointing to a sublexical locus of these effects, to be discussed below.

The inhibitory effect of pseudohomophone primes on RTs to auditorily presented nonword targets, observed in Experiment 3, was not replicated in Experiment 5. The variability in masked priming effects obtained with nonword targets in the lexical decision task is a general phenomenon that probably reflects the use of different strategies for generating negative responses in this task.

## GENERAL DISCUSSION

The present experiments tested for repetition and pseudohomophone priming effects within (visual-visual) and across modalities (visual-auditory) using brief prime exposures and forward and backward masking of the prime. Repetition priming effects (i.e., differences in ease of target word recognition when a given target word is preceded by the same word or a completely unrelated word) were observed with 53ms prime durations, and were unaffected by participants' ability to identify the primes or not. Most important, these repetition priming effects were just as strong in the cross-modal condition as the within-modal condition. However, in the same experiments we failed to observe significant priming from pseudohomophone primes compared to control nonword primes with 53 ms prime exposure durations, but these effects were robust at the 67 ms prime duration of Experiments 3 and 5. Just like the repetition priming effects, these pseudohomophone priming effects were unaffected by target modality.

### Unconscious cross-modal priming.

The results presented here represent the final product of a research project initiated several years ago, and first reported in the unpublished masters dissertation of Spinelli (1995). In these initial experiments, we systematically failed to obtain evidence for cross-modal repetition priming in conditions where participants were unable to successfully report the prime word's identity (using an interleaving procedure where participants saw a string of question marks instead of the target on 10% of trials during the main experiment, and had to report the prime stimulus on those trials). In order to limit prime visibility, exposure durations of approximately 30 ms were used in these experiments. Unpublished work in the same laboratory had established the existence of within-modal repetition priming at such prime exposure durations (see also, Giraudo & Grainger, 2001).

Kouider and Dupoux (2001) replicated our failure to observe unconscious cross-modal repetition priming at 33 ms prime exposures, while confirming the existence of within-modal priming in the same conditions. However, Kouider and Dupoux also found that cross-modal repetition priming was still not robust at 50 ms prime exposures, but did appear with 67 ms prime exposures. Kouider and Dupoux's test of prime visibility involved a forced-choice discrimination of letters from pseudo-letters (as used in Experiments 4 and 5 of the present study). They found that  $d'$  values were not significantly different from zero (i.e., chance performance) at the 33 ms and 50 ms prime durations, but were significantly different from chance at the 67 ms duration. Kouider and Dupoux therefore concluded that cross-modal repetition priming is absent unless primes are consciously perceived. However, the present experiments demonstrated that with random consonant backward masks, letter / pseudo-letter discrimination accuracy was not significantly different from chance at 53 ms prime durations, in conditions where significant cross-modal repetition priming was obtained.

Here we claim that the different backward mask used in the present study (see also, Ford & Marslen-Wilson, 2001) allowed an increase in prime duration to 53 ms without resulting in a concomitant increase in prime awareness. On the basis of the present results we would argue that the size of priming effects for a given priming condition in the masked prime paradigm is a function of prime exposure duration (and stimulus intensity, as well as other temporal factors such as inter-stimulus-interval), but not prime awareness (footnote 1). More precisely, we argue that it is the characteristics of the prime, and not prime awareness, that primarily determines the size of priming effects. Two points are critical for defending this argument. First, we assume that priming effects obtained with the masked prime paradigm, both within and across modalities, are subtended by processes that operate unconsciously. In



an activation framework, this arises by the prime activating representations that are then used during target word recognition, thus giving the lexical processor a head-start compared to when the target is preceded by an unrelated prime. The representations activated by the prime stimulus can be effective in the absence of prime awareness. This can happen simply by assuming that the representations activated by the prime stimulus must reach a critical level of activation in order to generate significant priming effects, and that this “priming threshold” is lower than the activation level required for conscious awareness (i.e., an identification threshold, cf. Grainger & Jacobs, 1996).

Second, we assume that different types of backward mask can affect prime processing to different degrees. More precisely, when primes are strings of letters (words or pseudowords), cross-experiment comparisons suggest that hashmark (#####) or ampersand (@@@@@) masks do not disturb processing to the same degree as the random consonant mask (GMKFH) used in the present study (see also Ford & Marslen-Wilson, 2001). More precisely, the weaker masking procedure might allow prime processing to continue, independently of target processing, thus generating awareness of the prime stimulus. The stronger masking procedure blocks further processing of the prime stimulus, as a perceptual event distinct from the target, thus limiting the level of prime awareness. As noted in the introduction, the hypothesized stronger masking effect of letter masks as opposed to non-letter masks is in line with theories of backward masking as a competitive process. This is a point that certainly merits further investigation in studies specifically examining the mechanisms involved in backward masking with complex stimuli.

Related to the issue of backward masking is one other critical methodological aspect of the present study, concerning how prime awareness was measured. This is a thorny issue that has generated much discussion ever since Holender’s (1986) review. The approach adopted in the present study follows the tradition established by Greenwald and colleagues (Greenwald, Klinger, & Schuh, 1995; Draine & Greenwald, 1998; see also Dell’Acqua & Grainger, 1999) of providing evidence for a dissociation between direct and indirect measures of unconsciously processed stimuli. Thus, we sought to establish null effects in direct measures (the measure of prime awareness) accompanied by non-null indirect effects (the priming effects). Within this general approach, the measure of prime awareness (the direct measure) must be conservative enough to avoid unfounded claims of unconscious processing of prime stimuli, without being too conservative. Using too conservative a measure of direct effects (e.g., simple detection) can generate unfounded claims of conscious processing of the prime stimulus. We would argue that the conditions used to evaluate prime awareness in the

present study are at the limit of how conservative such tests should be. Immediately after the main experiment, the same participants were tested in the visibility test using stimuli repeated from the main experiment in exactly the same conditions, except that no response was required to target stimuli, thus allowing participants to fully focus attention on the prime stimuli. Within-modal and cross-modal repetition priming was obtained in the main experiment when, in the visibility test, participants i) could not correctly identify a prime stimulus, ii) were at chance in deciding if the prime was a word or a nonword, and iii) were at chance in deciding if the prime was formed of real letters or pseudo-letters.

#### Cross-modal interactions in word recognition.

The present results provide further support for a model of word recognition (both visual and auditory) that allows fast, automatic interactivity between orthographic and phonological codes. The framework outlined in Figure 1 provides a straightforward account of the present data. It represents an extension of the basic bi-modal interactive activation model presented by Grainger and Ferrand (1994; see also Jacobs, Rey, Ziegler, & Grainger, 1998). The critical difference relative to earlier versions of the model, is the addition of a more complex interface between orthographic and phonological codes, involving sublexical orthographic codes (Oc units: letters and letter clusters) and sublexical phonological codes (Pc units: phonemes and phoneme clusters). These complex sublexical representations receive activation from simpler orthographic and phonological codes (O-units, P-units) such as letter and phoneme identities coded for their position in a given sequence. In this architecture, repetition priming effects arise earlier (i.e., with shorter prime durations) than pseudohomophone priming effects due to the smaller number of mappings involved in the former. This is obvious for within-modal priming, but is also the case for cross-modal priming, since pseudohomophones require four distinct coding stages (O-unit -> Oc -> Pc -> P-word) compared to three distinct stages for cross-modal repetition priming (O-unit -> O-word -> P-word). The framework also captures the fact that within-modal repetition priming arises earlier than cross-modal repetition priming (Kouider & Dupoux, 2001).

Insert Figure 1 about here

This theoretical framework was first introduced in order to capture the growing evidence in favor of rapid, automatic activation of phonological codes during visual word recognition. Critical evidence in this direction was obtained using the masked priming

paradigm with primes that are pseudohomophones of target words (Ferrand & Grainger, 1992, 1994, 1996; Frost, Ahissar, Gotesman, & Tayeb, 2003; Grainger & Ferrand, 1996; Perfetti & Bell, 1991; Ziegler et al., 2000). The facilitatory effects of pseudohomophone primes found in prior research were replicated in the present study with 67ms prime durations, and were found to be just as strong across as within modalities. However, Experiment 5 of the present study showed that the pseudohomophone prime condition did not differ significantly from an orthographic control condition, which in turn generated significant facilitation compared to the unrelated prime condition. In the discussion of Experiment 5, we argued that this pattern of effects probably reflects a graded influence of the combined effects of orthographic and phonological overlap across primes and targets. The results are in line with the present account of within-modal and across-modal pseudohomophone priming as being subtended by sublexical correspondences between orthographic and phonological representations. Certainly, the fact that priming effects from the orthographic control condition were approximately the same size within-modality as across-modalities, strongly suggests that these particular effects are subtended by sublexical correspondences between orthography and phonology.

The lack of a significant difference between pseudohomophone primes and orthographic controls is in line with the recent work of Frost et al. (2003) showing that quite large differences in phonological overlap between prime and target are required to get robust priming under masking conditions (footnote 2). The lack of a significant difference between pseudohomophone primes and unrelated control primes at the 53 ms prime exposures of the present study is another point that merits further investigation. Since pseudohomophones differed by a single letter from target stimuli, one might have expected some purely orthographic priming in these conditions. The failure to get robust priming here could be due to the use of relatively short, mostly four and five-letter words, the majority of which had several orthographic neighbors (mean 3.5 for Experiments 1-3, and 3.2 for Experiments 4-5). Prior research on masked priming with orthographically related nonword primes has shown that effect sizes can vary as a function of the neighborhood characteristics of prime and target stimuli (Forster & Davis, 1991; van Heuven, Dijkstra, Grainger, & Schrieffer, 2001).

However, the critical conclusion that can be drawn from the results of the present study is that when priming from orthographically and/or phonologically related nonword primes does arise, it is approximately the same magnitude within and across modalities. It is this precise pattern that constrains possible processing architectures. One specific prediction of the framework presented in Figure 1 is that priming effects that have been obtained at short

primes exposures (e.g., 30-50 ms) in previous experiments, and that have been characterized as reflecting fast orthographic coding (i.e., the direct link between O-units and O-words in Figure 1), should require longer prime exposures in order to appear in cross-modal conditions. This is the case for primes that involve removing several of the target word's letters, such as the prime NTUE for the target NATURE, as in the work of Peressotti and Grainger (1999). This is clearly an important issue for future research.

Research using long-lag repetition priming has also investigated the effects of changing modalities across first and second presentation of items. Typically, maintaining the same modality across study and test generates significantly larger priming effects than when there is a change in modality, at least when implicit memory tasks such as word-stem completion are used at test (see Kirsner, Dunn, and Standen, 1989, for a review). However, these conclusions were drawn on the basis of experiments in which presentation at test is in the visual modality (i.e., visual-visual priming is greater than auditory-visual, e.g., Berry, Banbury, & Henry, 1997). More recent work (Loveman, van Hoof, & Gale, 2002) has shown that when words are presented visually at study, then there is no influence of the modality at test (see Greene, Easton, & LaShell, 2001, for a similar result with non-verbal stimuli). These recent results are in line with those of the present study. Furthermore, they show a clear asymmetry in cross-modal long-lag priming (stronger priming from visual to auditory than vice versa) that merits investigation in an immediate priming situation.

The connections in the model described in Figure 1 are bi-directional, thus allowing information from an auditory stimulus to activate orthographic representations. In support of this, there are now several studies showing an influence of orthographic codes during spoken word recognition (e.g., Hallé, Chereau, & Segui, 2000; Ziegler & Ferrand, 1998; Ziegler, Muneaux, & Grainger, 2003). The asymmetry in long-lag cross-modal repetition priming suggests that the connection strengths might be stronger in the direction of orthography to phonology than from phonology to orthography. This asymmetry makes perfect sense in a perceptual system where one must learn to map orthographic codes onto previously established phonological representations.

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## Appendix 1

Word stimuli used in Experiments 1-3

| Targets | Unrelated prime | Pseudo-homophone prime | Unrelated nonword prime |
|---------|-----------------|------------------------|-------------------------|
| NERF    | tige            | nerd                   | clon                    |
| BANC    | luxe            | bant                   | pime                    |
| LONG    | vrai            | lont                   | tabe                    |
| GROS    | type            | grop                   | tase                    |
| BASE    | gris            | baze                   | gron                    |
| CHEZ    | donc            | chei                   | lure                    |
| JOIE    | bleu            | jois                   | tran                    |
| NORD    | plan            | nore                   | lane                    |
| ROND    | chat            | ront                   | pive                    |
| PAIX    | cher            | pais                   | sube                    |
| BRAS    | soir            | brat                   | cove                    |
| DRAP    | four            | dras                   | plor                    |
| CAGE    | poil            | caje                   | roil                    |
| LENT    | jupe            | lant                   | fiec                    |
| NOIX    | rite            | noie                   | cune                    |
| CLAN    | loge            | klan                   | dorc                    |
| DOSE    | cerf            | doze                   | fien                    |
| OCRE    | bouc            | okre                   | muif                    |
| TRUC    | onze            | truk                   | aule                    |
| RUSE    | chic            | ruze                   | blas                    |
| FROID   | mille           | froie                  | vagne                   |
| GENRE   | bruit           | jenre                  | dronc                   |
| LARGE   | choix           | larje                  | croin                   |
| CORDE   | fruit           | korde                  | flane                   |
| FREIN   | nappe           | frain                  | guile                   |
| BOIRE   | chaud           | boyre                  | teuil                   |
| FORCE   | suite           | forse                  | prond                   |
| PENTE   | lueur           | pante                  | flomb                   |
| TROIS   | monde           | troie                  | bieur                   |
| CRISE   | doigt           | cryse                  | blime                   |
| FLOT    | brun            | flos                   | cabe                    |
| MOIS    | ciel            | moie                   | pite                    |
| ANGE    | choc            | anje                   | gric                    |
| TRAIN   | cause           | trein                  | suque                   |
| AIGLE   | bourg           | eigle                  | grois                   |
| STAGE   | blond           | staje                  | fueur                   |
| CIRQUE  | bronze          | sirque                 | glaibe                  |
| GROTTE  | claque          | grothe                 | sphonx                  |
| SINGE   | noeud           | sinje                  | flour                   |
| SPORT   | brume           | spore                  | vrime                   |

## Appendix 2

## Word stimuli used in Experiments 4-5

| Targets | Unrelated prime | Pseudo-homophone prime | Othographic control prime | Unrelated nonword prime |
|---------|-----------------|------------------------|---------------------------|-------------------------|
| AIGLE   | bourg           | eigle                  | oigle                     | grois                   |
| ANGE    | choc            | anje                   | onge                      | gric                    |
| BANC    | luxe            | bant                   | balc                      | pime                    |
| BASE    | gris            | baze                   | bame                      | gron                    |
| BLOND   | deuil           | blont                  | blone                     | frate                   |
| BOIRE   | chaud           | boyre                  | boile                     | teuil                   |
| BRAS    | soir            | brat                   | bres                      | cove                    |
| CAGE    | poil            | caje                   | coge                      | roil                    |
| CAISSE  | preuve          | kaisse                 | coisse                    | streup                  |
| CHEZ    | donc            | chei                   | crez                      | lure                    |
| CIME    | gant            | sime                   | cive                      | fluc                    |
| CIRQUE  | bronze          | sirque                 | corque                    | glaiibe                 |
| CLAIR   | somme           | klair                  | cloir                     | frone                   |
| CLAN    | loge            | klan                   | clon                      | dorc                    |
| CORDE   | fruit           | korde                  | carde                     | flane                   |
| CRISE   | doigt           | cryse                  | crose                     | blime                   |
| DOSE    | cerf            | doze                   | dase                      | fien                    |
| DRAP    | four            | dras                   | drup                      | plor                    |
| FLOT    | brun            | flos                   | flat                      | cabe                    |
| FORCE   | suite           | forse                  | norce                     | prond                   |
| FRAIS   | ligne           | fraie                  | flais                     | plour                   |
| FRANC   | coude           | frant                  | frinc                     | siple                   |
| FREIN   | nappe           | frain                  | flein                     | guile                   |
| FROID   | mille           | froie                  | froin                     | vagne                   |
| FRONT   | masse           | frond                  | frone                     | mivre                   |
| GENRE   | bruit           | jenre                  | gonre                     | dronc                   |
| GRAINE  | menthe          | greine                 | graune                    | clodre                  |
| GRANGE  | mŕurs           | granje                 | gringe                    | diosse                  |
| GROS    | type            | grop                   | dros                      | tase                    |
| GROTTE  | claque          | grothe                 | gritte                    | sphonx                  |
| JOIE    | bleu            | jois                   | jole                      | tran                    |
| LAINÉ   | stock           | leine                  | laipe                     | drouit                  |
| LARGE   | choix           | larje                  | lorge                     | croin                   |
| LENT    | jupe            | lant                   | lert                      | fiec                    |
| LINGÉ   | poing           | linje                  | lirge                     | breuc                   |
| LONG    | vrai            | lont                   | lone                      | tabe                    |
| MOIS    | ciel            | moie                   | moil                      | pite                    |
| NERF    | tige            | nerd                   | norf                      | clon                    |
| NOIX    | rite            | noie                   | naix                      | cune                    |
| NORD    | plan            | nore                   | nard                      | lane                    |

|        |        |        |        |        |
|--------|--------|--------|--------|--------|
| OCRE   | bouc   | okre   | icre   | muif   |
| PAIX   | cher   | pais   | maix   | sube   |
| PEIGNE | louche | paigne | pligne | straid |
| PENTE  | lueur  | pante  | pelte  | flomb  |
| PLAGE  | creux  | plaje  | plige  | trinc  |
| PLOT   | dune   | plos   | plit   | beul   |
| PROIE  | bľuf   | prois  | praie  | gleur  |
| ROND   | chat   | ront   | rone   | pive   |
| ROUGE  | plein  | rouje  | roige  | plonf  |
| RUSE   | chic   | ruze   | rese   | blas   |
| SAGE   | fuir   | saje   | soge   | flile  |
| SCORE  | di□se  | scord  | scure  | flein  |
| SINGE  | noeud  | sinje  | sange  | flour  |
| SOURD  | brave  | soure  | seurd  | blain  |
| SPORT  | brume  | spore  | spart  | vrime  |
| STAGE  | blond  | staje  | stame  | fueur  |
| TRAIN  | cause  | trein  | prain  | suque  |
| TREIZE | chľur  | traize | treuze | buinte |
| TROIS  | monde  | troie  | troin  | bieur  |
| TRUC   | onze   | truk   | trus   | aule   |

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## AUTHOR NOTE

The authors would like to thank Ken Forster and two anonymous reviewers for their very helpful comments on an earlier version of this work. Kevin Diependaele was supported by a Socrates exchange grant between the University of Ghent and the University of Provence, and we thank Andre Vandierendonck for his help in arranging this. Kevin Diependaele is now at Antwerp University, Belgium, and Elsa Spinelli is at the University of Grenoble, France. Correspondence concerning this research can be addressed to Jonathan Grainger, Laboratoire de Psychologie Cognitive, Université de Provence, France ([grainger@up.univ-mrs.fr](mailto:grainger@up.univ-mrs.fr)).

## FOOTNOTES

1. Humphreys, Besner, and Quinlan (1988) and Grainger and Jacobs (1998) have argued that prime awareness can influence inhibitory priming effects that arise from mechanisms involved in identifying the prime as a distinct perceptual event from the target.
2. Frost et al. (2003) do obtain robust phonological priming with greater phonological contrasts. This is taken as evidence against an alternative approach to phonological coding of printed words, as expressed in the dual-route cascaded (DRC) model of Coltheart, Rastle, Perry, Langdon, and Ziegler (2001). Such fast phonological priming is predicted by the present bi-modal model.

Table 1. Mean reaction times (in milliseconds) and percent errors in Experiment 1 (53 ms prime exposures).

|                 |                   | Within modality |               | Between modality |               |
|-----------------|-------------------|-----------------|---------------|------------------|---------------|
|                 |                   | Mean RT         | <i>Errors</i> | Mean RT          | <i>Errors</i> |
| <u>Words</u>    | Primes            |                 |               |                  |               |
|                 | Repetition        | 629             | 2%            | 806              | 7%            |
|                 | Unrelated         | 664             | 2%            | 846              | 7%            |
|                 | effect:           | <b>35</b>       | <b>0%</b>     | <b>40</b>        | <b>0%</b>     |
|                 | Pseudohomophone   | 648             | 3%            | 819              | 5%            |
|                 | Unrelated nonword | 661             | 2%            | 831              | 8%            |
| effect:         | <b>13</b>         | <b>-1%</b>      | <b>12</b>     | <b>3%</b>        |               |
| <hr/>           |                   |                 |               |                  |               |
| <u>Nonwords</u> | Primes            |                 |               |                  |               |
|                 | Repetition        | 799             | 6%            | 911              | 5%            |
|                 | Unrelated         | 797             | 6%            | 920              | 6%            |
|                 | effect:           | <b>-2</b>       | <b>0%</b>     | <b>9</b>         | <b>1%</b>     |
|                 | Pseudohomophone   | 785             | 6%            | 908              | 6%            |
|                 | Unrelated nonword | 802             | 7%            | 908              | 6%            |
| effect:         | <b>17</b>         | <b>1%</b>       | <b>0</b>      | <b>0%</b>        |               |

Table 2. Mean reaction times (in milliseconds) and percent errors in Experiment 2 (53 ms prime exposures).

|                 | Primes            | Prime-target same size |           | Prime-target different size |           |            |
|-----------------|-------------------|------------------------|-----------|-----------------------------|-----------|------------|
|                 |                   | Mean RT                | Errors    | Mean RT                     | Errors    |            |
| <u>Words</u>    | Repetition        | 576                    | 5%        | 577                         | 5%        |            |
|                 | Unrelated         | 619                    | 5%        | 613                         | 5%        |            |
|                 |                   | effect:                | <b>43</b> | <b>0%</b>                   | <b>36</b> | <b>0%</b>  |
|                 | Pseudohomophone   | 602                    | 4%        | 594                         | 5%        |            |
|                 | Unrelated nonword | 604                    | 4%        | 607                         | 6%        |            |
|                 |                   | effect:                | <b>2</b>  | <b>0%</b>                   | <b>13</b> | <b>1%</b>  |
| <u>Nonwords</u> | Repetition        | 697                    | 8%        | 688                         | 7%        |            |
|                 | Unrelated         | 710                    | 7%        | 708                         | 5%        |            |
|                 |                   | effect:                | <b>13</b> | <b>-1%</b>                  | <b>20</b> | <b>-2%</b> |
|                 | Pseudohomophone   | 713                    | 9%        | 694                         | 5%        |            |
|                 | Unrelated nonword | 726                    | 8%        | 709                         | 5%        |            |
|                 |                   | effect:                | <b>13</b> | <b>-1%</b>                  | <b>15</b> | <b>0%</b>  |

Table 3. Mean reaction times (in milliseconds) and percent errors in Experiment 3 (67 ms prime exposures).

|                 | Primes            | Within modality |            | Between modality |           |
|-----------------|-------------------|-----------------|------------|------------------|-----------|
|                 |                   | Mean RT         | Errors     | Mean RT          | Errors    |
| <u>Words</u>    | Repetition        | 592             | 2%         | 792              | 7%        |
|                 | Unrelated         | 632             | 3%         | 831              | 11%       |
|                 | effect:           | <b>40</b>       | <b>1%</b>  | <b>39</b>        | <b>4%</b> |
|                 | Pseudohomophone   | 614             | 3%         | 790              | 7%        |
|                 | Unrelated nonword | 633             | 3%         | 819              | 8%        |
|                 | effect:           | <b>19</b>       | <b>0%</b>  | <b>29</b>        | <b>1%</b> |
| <u>Nonwords</u> | Repetition        | 771             | 6%         | 918              | 9%        |
|                 | Unrelated         | 783             | 4%         | 904              | 9%        |
|                 | effect:           | <b>12</b>       | <b>-2%</b> | <b>-14</b>       | <b>0%</b> |
|                 | Pseudohomophone   | 790             | 6%         | 924              | 8%        |
|                 | Unrelated nonword | 795             | 8%         | 894              | 9%        |
|                 | effect:           | <b>5</b>        | <b>2%</b>  | <b>-30</b>       | <b>1%</b> |



Table 4. Mean reaction times (in milliseconds) and percent errors in Experiment 4 (53 ms and 67 ms prime exposures).

|                 | Prime Duration | Primes     | Within modality |            | Between modality |            |
|-----------------|----------------|------------|-----------------|------------|------------------|------------|
|                 |                |            | Mean RT         | Errors     | Mean RT          | Errors     |
| <u>Words</u>    | 53ms           | Repetition | 649             | 2%         | 809              | 5%         |
|                 |                | Unrelated  | 670             | 2%         | 827              | 4%         |
|                 |                | effect:    | <b>21</b>       | <b>0%</b>  | <b>18</b>        | <b>-1%</b> |
|                 | 67ms           | Repetition | 640             | 3%         | 816              | 4%         |
|                 |                | Unrelated  | 674             | 2%         | 854              | 8%         |
|                 |                | effect:    | <b>34</b>       | <b>-1%</b> | <b>38</b>        | <b>4%</b>  |
| <u>Nonwords</u> | 53ms           | Repetition | 785             | 8%         | 914              | 4%         |
|                 |                | Unrelated  | 780             | 7%         | 913              | 4%         |
|                 |                | effect:    | <b>-5</b>       | <b>-1%</b> | <b>-1</b>        | <b>0%</b>  |
|                 | 67ms           | Repetition | 820             | 9%         | 925              | 4%         |
|                 |                | Unrelated  | 820             | 6%         | 936              | 4%         |
|                 |                | effect:    | <b>0</b>        | <b>-3%</b> | <b>11</b>        | <b>0%</b>  |

Table 5. Mean reaction times (in milliseconds) and percent errors in Experiment 5 (67ms prime exposures).

| Primes          | Within modality                 |           | Between modality |           |            |
|-----------------|---------------------------------|-----------|------------------|-----------|------------|
|                 | Mean RT                         | Errors    | Mean RT          | Errors    |            |
| <u>Words</u>    | Pseudohomophone                 | 677       | 3%               | 849       | 8%         |
|                 | Orthographic Control            | 687       | 2%               | 864       | 11%        |
|                 | Unrelated nonword               | 713       | 3%               | 887       | 6%         |
|                 | effect (orthographic baseline): | <b>10</b> | <b>-1%</b>       | <b>15</b> | <b>3%</b>  |
|                 | effect (unrelated baseline):    | <b>36</b> | <b>0%</b>        | <b>38</b> | <b>-2%</b> |
| <u>Nonwords</u> | Pseudohomophone                 | 807       | 3%               | 946       | 3%         |
|                 | Orthographic Control            | 818       | 5%               | 949       | 2%         |
|                 | Unrelated nonword               | 822       | 6%               | 952       | 5%         |
|                 | effect (orthographic baseline): | <b>11</b> | <b>2%</b>        | <b>3</b>  | <b>-1%</b> |
|                 | effect (unrelated baseline):    | <b>15</b> | <b>3%</b>        | <b>6</b>  | <b>2%</b>  |

## FIGURE LEGEND

Figure 1. Architecture of a bi-modal interactive activation model of word recognition (the details of the inhibitory within-level and excitatory between-level connections are not provided). The architecture extends that proposed by Grainger and Ferrand (1994) by including an interface between complex sublexical orthographic (Oc) and phonological (Pc) codes that receive activation from orthographic input units (O-units) and phonological input units (P-units), and send on activation to whole-word orthographic (O-word) and phonological (P-word) representations.

Figure 1

