Subliminal Number Priming Within and Across the Visual and Auditory Modalities

Sid Kouider[1,2] and Stanislas Dehaene[2,3]

[1]Laboratoire des Sciences Cognitives et Psycholinguistique, EHESS/CNRS/ENS-DEC, Paris, France
[2]Cognitive Neuroimaging Unit, NeuroSpin Center, INSERM/CEA, Gif-sur-Yvette, France
[3]Collège de France, Paris, France

Abstract. Whether masked number priming involves a low-level sensorimotor route or an amodal semantic level of processing remains highly debated. Several alternative interpretations have been put forward, proposing either that masked number priming is solely a byproduct of practice with numbers, or that stimulus awareness was underestimated. In a series of four experiments, we studied whether repetition and congruity priming for numbers reliably extend to novel (i.e., unpracticed) stimuli and whether priming transfers from a visual prime to an auditory target, even when carefully controlling for stimulus awareness. While we consistently observed cross-modal priming, the generalization to novel stimuli was weaker and reached significance only when considering the whole set of experiments. We conclude that number priming does involve an amodal, semantic level of processing, but is also modulated by task settings.

Keywords: subliminal, priming, cross-modal, numerosity

What is the depth of processing of subliminal stimuli? While there is now little disagreement regarding the existence of unconscious perceptual processes, the participation of higher levels remains somewhat controversial (see Kouider & Dehaene, 2007, for an extensive review). More specifically, whether subliminal perception conveys semantic information has not yet been fully resolved. Although several neuroimaging studies have provided strong evidence for brain events associated with semantic-level processing of masked or blinked words (Gaillard et al., 2006; Kiefer, 2002; Luck, Vogel, & Shapiro, 1996), behavioral studies using masked priming have yielded debated results. Claims for semantic-level processing (Naccache & Dehaene, 2001a, 2001b; Reynvoet, Gevers, & Caessens, 2005) have been contested on grounds of lower-level interpretations (e.g., sensorimotor associations; Damian, 2001) or of partial prime awareness (Abrams & Grinspan, 2007; Kouider & Dupoux, 2007). In this study, we will address these aspects in the number domain which, as we shall review below, has been more promising than the domain of words in providing *some evidence in favor* of subliminal processing at higher levels of processing. In particular, we will test, through a cross-modal manipulation, whether subliminal number priming extends beyond perceptual domains. Before presenting our study, we review some of the key issues that have been outlined as confounds in demonstrating subliminal semantic priming.

The very existence of subliminal perception has remained controversial since the very first days of experimental psychology (see Kouider & Dehaene, 2007). After more than a century of research, full of replication failures, experimental artifacts, and awareness underestimation issues, two independent studies provided several methodological improvements allowing for an unequivocal demonstration of subliminal influences (Dehaene et al., 1998; Greenwald, Draine, & Abrams, 1996). Greenwald and colleagues used an affective evaluation task where subjects classified target words as pleasant (e.g., "happy") or unpleasant (e.g., "vomit"), and these words were preceded either by a congruent prime (i.e., a word from the same category, such as "love" preceding the target "happy") or by an incongruent prime ("vomit" preceding "happy"). Subjects were faster for congruent trials compared to incongruent trials, even under conditions where they could not perform the affective evaluation on the prime, evidencing a semantic congruity priming effect in the absence of awareness. Dehaene and colleagues provided a similar demonstration in the number domain. In their study, subjects were asked to classify target numbers, presented as written word forms or in Arabic notation, as either smaller or larger than 5. These visible numbers were preceded by masked number primes that were also smaller or larger than 5 but that participants were unable to consciously detect. Subjects were faster when both the prime and the target belonged to the same category than when they belonged to opposite categories. In addition, using fMRI and ERPs, they found that subliminal stimuli can not only elicit a behavioral influence, but also neural activity in the motor cortex due to response competition. In addition, cross-notation (e.g., from Arabic digit to number word) repetition suppression was also observed in the bilateral intraparietal cortex, a region associated with

DOI: 10.1027/1618-3169.56.6.xxx

semantic-level number processing (Naccache & Dehaene, 2001a). Thus, by the end of the second millennium, the issue of the existence of unconscious perception appeared to be resolved with a positive outcome.

Nevertheless, it did not take long before other studies (Abrams & Greenwald, 2000; Damian, 2001) revealed that congruity effects, although they appear to be genuinely subliminal, could be totally reframed and subsumed a nonsemantic interpretation. Because the two former studies by Dehaene et al. (1998) and Greenwald et al. (1996) used a restricted set of stimuli appearing several times both as primes and as targets, response congruity effect could be as well reflecting conflicting stimulus-response associations (e.g., the prime 4 has been previously associated with the left hand, while the prime 9 has been associated with the right hand, resulting in a motor response conflict) rather than competition between semantic categories. Damian (2001) asked subjects to classify words in terms of the physical size of the object they represented in reference to a 20 × 20 cm frame (e.g., "spider" was smaller while "house" was larger). Damian found that subliminal congruity effects were restricted to practiced primes, that is to prime stimuli that have previously been mapped to a response during the experiment. Unpracticed primes did not give rise to any congruity effect. Damian (2001) argued that the finding of Dehaene et al. (1998) could be best interpreted in terms of the direct motor specification hypothesis (Neumann & Klotz, 1994) according to which subliminal congruity effects do not need to be mediated by the semantic level. Instead, they reflect the unconscious triggering of a motor response that has been associated, through learning, with a given stimulus. Abrams and Greenwald (2000) showed that subliminal priming not only does not generalize to novel words, as in Damian's study, but also that it results from a learned association between fragments of the word primes and a response. For instance, in an affective evaluation task where the target words "smut" and "bile" were repeatedly classified as unpleasant, subliminal presentation of the prime word "smile" (made of smut and bile) initiated an unpleasant response (conversely for "tumor" which initiated a pleasant response following practice with "tulip" and "humor").

Yet, recent studies have shown that the sensorimotor interpretation cannot be the whole story. Indeed, Naccache and Dehaene (2001a) found that subliminal number priming occurred not only for practiced primes (the numbers 1, 4, 6, and 9) but also by generalizing to unpracticed primes (2, 3, 7, and 8), although the latter led to a weaker effect. The fact that priming can extend to prime stimuli that have never been seen as targets suggests that number priming is mediated, at least in part, by semantic representations. Other studies (Greenwald, Abrams, Naccache, & Dehaene, 2003; Reynvoet et al., 2005) have replicated this generalization to unpracticed numbers, although here also not without triggering some controversies. Indeed, Greenwald et al. used two-digit numbers to be compared to 55 and found that, depending on instructions and task context, subjects at times extracted the meaning of a two-digit number prime, and at other times treated the digits independently, sometimes resulting in paradoxical fragment-based effects. For instance, after practice with conscious trials in which the digit 6 was seen when classifying 56 as greater than 55, the masked prime 16 facilitated the greater-than-55 response. Reynvoet et al. have been criticized for not being cautious enough regarding stimulus awareness (assessed in participants that did not participate in the priming experiments), their finding being then interpreted as potentially reflecting supraliminal rather than genuinely subliminal number processing by other researchers (see Elsner, Kunde, & Kiesel, 2008; Kunde, Kiesel, & Hoffmann, 2005). In addition, Elsner et al. (2008) recently found number priming for practiced primes but without generalization to unpracticed primes. Similar inconsistencies can be found in the domain of words. Indeed, while the rule tends to be that word priming is restricted to practiced primes, there also exist a few exception studies showing that it can generalize to unpracticed primes (Klauer, Eder, Greenwald, & Abrams, 2007; Van den Bussche & Reynvoet, 2007). As of today, it remains unclear why some studies report a strong generalization to unpracticed primes while others only found restricted effects.

The Present Study

The goal of the present study was twosome. First, we wished to reassess whether one can obtain genuinely subliminal number priming without experimental confounds that are either due to residual stimulus awareness or due to practice with the number stimuli. Our objective was to reevaluate the seminal study by one of us (Dehaene et al., 1998) while following the rigorous methodological approach to unconscious perception defended by the other author (Kouider & Dupoux, 2001, 2004, 2007). Thus, we decided to replicate the original finding while carefully evaluating the generalization to novel primes, as well as avoiding the possibility of any form of partial awareness. A second objective was to establish whether the subliminal analysis of masked number extends beyond the perceptual domain by examining whether subliminal priming generalizes across modalities. To our knowledge, the possibility of cross-modal transfer in number priming has not been tested so far. As such, we included a cross-modal (visual-to-auditory) priming manipulation similar to the one developed by Kouider and Dupoux (2001) for words. Since the original study by Kouider and Dupoux (2001), very few studies have addressed the modality-specific or amodal nature of unconscious processing. Yet, masked cross-modal priming can be considered as a good index of the involvement of higher-level representations. We return to these aspects in the General Discussion section.

All of the present experiments use a method very similar to that of Dehaene et al. (1998): Classification of target numbers 1, 4, 6, or 9 as larger or smaller than 5, where each target is preceded by a numerical prime. Like Naccache and Dehaene (2001a, 2001b), we used primes that were also either from the target set 1, 4, 6, 9, or from the novel set 2, 3, 6, 7. We also incorporated a visibility manipulation (masked vs. unmasked trials) and, crucially, cross-modal trials with a visual prime and an auditory target. Importantly, we also included here as many repetition trials (e.g., 6 → /six/) as congruent (e.g., 9 → /six/) and incongruent trials (e.g., 4 → /six/), resulting in one third of each type of trial, in order to evaluate independently the presence of repetition and response congruity effects. To fully separate these two effects, we compared the repeated trials with the nonrepeated congruent trials (thus providing a pure measure of the repetition effect, uncontaminated by response congruity), and, separately, the nonrepeated congruent with the nonrepeated incongruent trials (thus providing a pure measure of the response congruity effect uncontaminated by stimulus repetition). The distinction between these two effects is particularly important for cross-modal trials. Finding a cross-modal response congruity effect for practiced primes might still be attributed to direct sensorimotor pathways, separately converging onto the same motor preparation system from visual and from auditory input systems, without requiring any cross-modal semantic transfer. Cross-modal repetition priming, on the other hand, provides strong evidence for a locus of subliminal processing that extends beyond the perceptual domain. Experiment 1 is very close to a replication of Dehaene et al. (1998), with the addition of cross-modal trials. Experiment 2 introduces unpracticed primes, as well a more rigorous method for assessing visibility. Experiment 3 uses only masked primes, in order to overcome potential limitations related to the visibility of supraliminal unpracticed primes. Finally, Experiment 4 relies on a different masking procedure for cross-modal trials, in order to avoid any potential influence of visibility on cross-modal priming.

Experiment 1

Method

Participants

A total of 11 university students recruited in Paris took part in this experiment. For this and all subsequent experiments, all participants had normal or corrected-to-normal vision, were aged between a minimum of 18 years and a maximum of 35 years, were native speakers of French, and were naive regarding the purposes of the experiment.

Stimuli and Apparatus

The stimuli were primarily constituted of numbers and masking stimuli. The numbers were 1, 4, 6, and 9, and were presented either as Arabic digits (e.g., 6), as French written words in uppercase letters (e.g., SIX) or as French spoken words by a male voice (e.g., /sis/). The masks were letter strings that are illegal in French and were constructed by randomly combining 6 upper- and lower-case consonant letters (e.g., mCzTrG). Visual events were presented in a white fixed-width font (i.e., Courier) against a black background and covered up the central area of a CRT monitor (70 Hz refresh rate) at a distance of about 60 cm from the participant. Auditory stimuli were recorded by a male French native speaker, digitized on a PC computer using an OROS-AU22-A/D board, and presented to participants through headphones. The whole protocol was programmed and run with the EXPE software package (Pallier, Dupoux, & Jeannin, 1997).

Procedure and Design

On each trial, participants received a fixation cross, a forward mask, a prime, a backward mask, and a target (see Figure 1). The fixation cross appeared for 200 ms. The prime stimuli were presented only visually as Arabic or written word forms and for a 43 ms duration. The two masks temporally surrounded the prime differently during the masked and unmasked trials. For masked trials, the masks were presented for a duration of 57 ms (four screen refresh cycles). However, for unmasked trials, the prime was not directly surrounded by the masks (see Figure 1). Instead, it was surrounded by blank screens presented for 29 ms (two cycles) which were themselves surrounded by masks also presented for 29 ms. This procedure has the advantage of making the primes highly visible in these unmasked trials, as if they were popping out from the visual stream, while it also allowed us to keep the prime duration and the prime-target interval identical for both types of trials. During each trial, the backward and forward masks differed from each other and were constructed online by the experimental program. Following the backward mask, the target stimuli could appear in one of the three formats (as Arabic digit such as "6", as a French written word such as "six", or as a French auditory word /sis/). The prime was always a visual stimulus appearing either as an Arabic digit or as a written word. For trials with a visual target, the target duration was 200 ms. For auditory numbers, participants were presented with the auditory target along with a third visual mask consisting in a row of 6 hash marks (######) and presented for 200 ms. This third mask was used because the preceding short backward mask on its own (i.e., without a visual target) was not strong enough to prevent prime visibility in the masked cross-modal trials (see Kouider & Dupoux, 2001). Thus, a trial could be masked or unmasked, and it could be within-notation (e.g., 6 → 6, SIX → SIX), cross-notation (e.g., 6 → SIX, SIX → 6), or cross-modal (e.g., 6 → /sis/, SIX → /sis/).

The experiment consisted in four successive blocks of 216 trials separated by a short break. Each block comprised either masked or unmasked trials. The order of the blocks could be either masked → unmasked → unmasked → masked, or it could be unmasked → masked → masked → unmasked. Whether subjects received the former or the latter block order was systematically alternated from one participant to the other. In addition, a separate small block of 12 training trials was performed prior to each block. In previous experiments (e.g., Dehaene et al., 1998), the experimental list was usually based on the full combination of the four primes and four targets, resulting in twice more incongruent trials than repetition or congruent (unrepeated) trials taken separately. Here, because we were as interested in

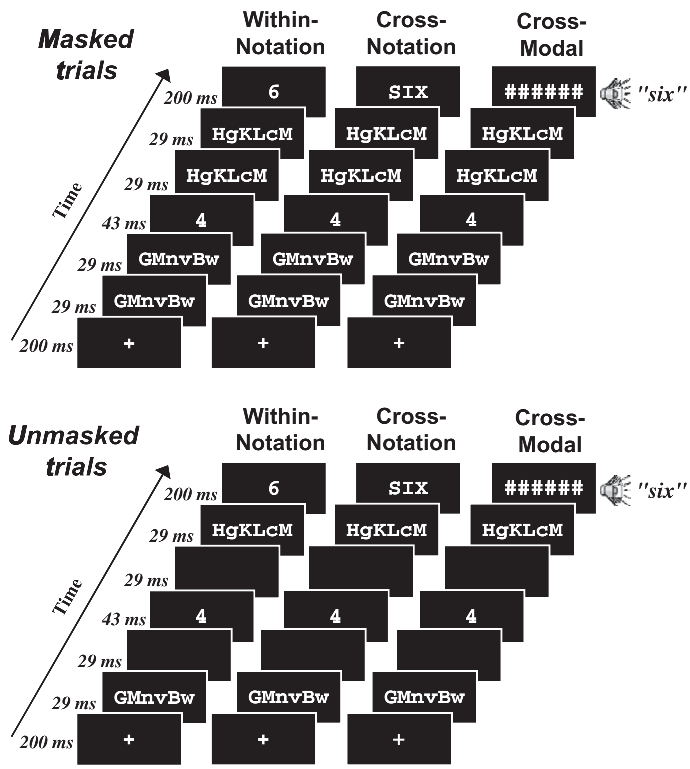


Figure 1. Schematic description of the priming method trials as a function of format change (within-notation, cross-notation, and cross-modal, from left to right) and masking (masked and unmasked trials, from top to bottom).

repetition priming (especially in the cross-modal condition) as in congruity priming, we equated the proportion of repetition, congruent, and incongruent trials (i.e., one third of the trials for each type of relation). We also ensure that participants received the same proportion of within-notation, cross-notation, and cross-modal trials, as well as the same proportion of primes corresponding to an Arabic digit or to a written word.

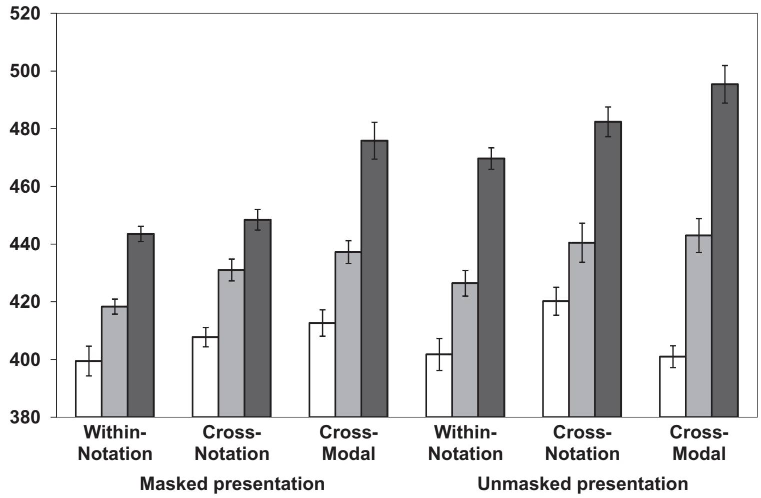
Participants were told that they would see or hear a target number between 1 and 9 (excluding 5), and that they would have to compare it to a fixed standard of 5. They were informed that prior to the target number, they would see some illegal letter strings and, on some trials (i.e., unmasked trials), a number flashed very briefly. They were instructed to ignore these preceding stimuli and concentrate only on the last event to perform the comparison task appropriately. Participants were instructed to make this decision as quickly and as accurately as possible. Performance was measured from a two-button response box in which participants used the left hand for numbers below 5 and the right hand for numbers above 5. Participants were forced to respond within 1,500 ms after the target onset, following which the next trial started with the fixation cross. The whole protocol for the main experiment lasted about 35 min.

Immediately after the main experiment, participants were explained that a number (i.e., the prime) actually preceded the target on each trial since the very beginning of the experiment. They were then instructed to perform the same task as in the main experiment (i.e., comparison to 5) now on the prime and not on the target. Participants were instructed that they should focus primarily on accuracy, not on speed, and that they could now take as long as they wanted to respond. In order to familiarize participants with the new task, they first received a series of training trials ($N = 12$) where the prime was displayed for 200 ms under the same procedure as for masked trials. Then, they received two blocks of 64 trials randomly selected, both with the prime duration set back to normal speed (i.e., 43 ms) but with one block consisting of masked trials while the other was constituted of unmasked trials. The block order (masked trials first or unmasked trials first) was alternated from one participant to the other. In addition, each of these two blocks was preceded by another 12 training trials with the same respective display parameters.

Results and Discussion

Priming

Incorrect responses (12.75%) and reaction times (RTs) shorter than 100 ms (0.67%) or longer than 1,000 ms (0.52%) were excluded from the RT analysis. We first performed a $2 \times 3 \times 3$ analysis of variance (ANOVA) on median RTs by subject and by condition with the factors masking type (masked vs. unmasked), format change (within-notation, cross-notation, and cross-modal), and relation (repetition, nonrepeated congruent, and incongruent).



	Within-Notation (Masked)	Cross-Notation (Masked)	Cross-Modal (Masked)	Within-Notation (Unmasked)	Cross-Notation (Unmasked)	Cross-Modal (Unmasked)
Repetition	400	408	413	402	420	401
Congruent	418	431	437	426	441	443
Incongruent	444	448	476	470	482	495

Figure 2. Average RTs for repetition, congruent, and incongruent trials in Experiment 1 as a function of format change and masking type. Error bars represent ±1 standard error to the mean.

In the analysis below, we refer to global priming (i.e., potentially merging both repetition and congruity effects) as the difference between repetition and incongruent trials, repetition priming as the difference between repetition and nonrepeated congruent trials, and congruity priming as the difference between nonrepeated congruent and incongruent trials. The average median RTs are depicted in Figure 2. Unless otherwise stated, all the results reported in the analysis below are significant by having a p value below .05.

We first looked at main effects and found one of relation, $F(2, 20) = 55.30$, $p < .0001$, and one of format change, $F(2, 20) = 4.96$, $p < .05$. The main effect of masking type approached significance, $F(1, 10) = 4.63$, $p = .06$, with a 12 ms slowing for unmasked compared to masked trials. The relation factor interacted both with format change, $F(4, 40) = 4.74$, $p < .005$, and with masking type, $F(2, 20) = 4.63$, $p < .05$. None of the other interactions reached significance. We then performed planned comparisons by focusing primarily on the relation factor (collapsed across format change and masking type). We observed a significant effect for the three priming contrasts, that is not only for global priming, $F(1, 10) = 80.61$, $p < .0001$, but also when separately considering repetition priming, $F(1, 10) = 24.72$, $p < .001$, and congruity priming, $F(1, 10) = 42.54$, $p < .0001$. Only global priming revealed an interaction with masking type, $F(1, 10) = 9.57$, $p < .05$. Format change interacted with global priming too, $F(2, 20) = 7.66$, $p < .005$, and, in addition, with congruity priming, $F(2, 20) = 3.72$, $p < .05$. These interactions with format change resulted from the fact that global priming for cross-modal trials was higher than for both within-notation, $F(1, 10) = 7.48$, $p < .05$, and cross-notation trials, $F(1, 10) = 11.62$, $p < .01$, and from the fact that similarly congruity priming was also significantly higher for cross-modal trials compared to both within-notation, $F(1, 10) = 5.87$, $p < .05$, and cross-notation trials, $F(1, 10) = 7.00$, $p < .01$.

We then split our analysis to separately study repetition and congruity priming as a function of masking type. The two types of priming were significant both for unmasked trials (repetition priming: $F(1, 10) = 13.55$, $p < .005$ and congruity priming: $F(1, 10) = 21.15$, $p < .001$) and, crucially, for masked trials (repetition priming: $F(1, 10) = 27.29$, $p < .0005$ and congruity priming: $F(1, 10) = 47.24$, $p < .0001$). Considered now separately as a function of masking type, none of the interactions between priming and format change described above reached significance, except for a greater masked congruity effect for cross-modal trials compared to cross-notation trials, $F(1, 10) = 5.62$, $p < .05$. Note also that unmasked repetition priming was also marginally greater for cross-modal compared to cross-notation trials, $F(1, 10) = 4.01$, $p = .07$.

Finally, we further restricted our comparisons to priming effects as a function of both format change and masking type. This resulted in 12 contrasts that were all significant, except for one (unmasked cross-notation repetition priming) which fell short of significance ($p = .07$) (the detailed results are the following: unmasked within-notation repetition priming, $F(1, 10) = 8.06$, $p < .05$; unmasked within-notation congruity priming, $F(1, 10) = 27.47$, $p < .0005$; masked within-notation repetition priming, $F(1, 10) = 6.18$, $p < .05$; masked within-notation congruity priming, $F(1, 10) = 27.78$, $p < .0005$; unmasked cross-notation repetition priming, $F(1, 10) = 4.1365$, $p = .07$; unmasked cross-notation congruity priming, $F(1, 10) = 8.45$, $p < .01$; masked cross-notation repetition priming, $F(1, 10) = 14.12$, $p < .005$; masked cross-notation congruity priming, $F(1, 10) = 11.83$, $p < .01$; unmasked cross-modal repetition priming, $F(1, 10) = 17.00$, $p < .005$; unmasked cross-modal congruity priming, $F(1, 10) = 22.26$, $p < .001$; masked cross-modal repetition priming, $F(1, 10) = 9.84$, $p < .01$; and lastly masked cross-modal congruity priming, $F(1, 10) = 19.61$, $p < .005$).

Prime Visibility

Participants' performances on the visibility measure were 77.1% for unmasked trials and 57.7% for masked trials. We computed d' values for each participant as a function of masking type and format change by treating primes larger than 5 as signal and primes smaller than 5 as noise. For masked trials, the mean d' values across format change were 0.30, 0.43, and 0.86 for within-notation, cross-notation, and cross-modal trials, respectively, while for unmasked trials, these values were 1.61, 1.43, and 2.52, respectively. When considering visibility as a function of format change, planned comparisons on unmasked trials revealed that the cross-modal trials led to significantly higher d' values compared both to cross-notation trials, $F(1, 10) = 18.15$, $p < .001$, and to within-notation trials, $F(1, 10) = 7.80$, $p < .05$, suggesting that unmasked cross-modal trials were more visible than the other format changes. However, none of the format change comparisons reached significance when considering masked trials (all *p*s > .2). Taken as a whole, the mean d' values were significantly different from zero both for unmasked trials ($d' = 1.85$; $t(10) = 6.71$, $p < .0001$) and for masked trials ($d' = 0.53$; $t(10) = 3.00$, $p < .05$), respectively. The effect of masking type was also significant, $F(1, 10) = 18.150$, $p < .001$, evidencing that the primes were more visible in the unmasked condition. Nevertheless, the fact that the d' values for masked trials were significantly higher than zero means that the primes in this situation were still somehow visible, at least for some of the participants. To deal with this recurrent problem, Greenwald, Klinger, and Schuh (1995) introduced a regression method that allows to investigate whether priming is still reliable when extrapolated to null performance on the prime visibility measure. Figure 3 shows the regression of the global masked priming effect for each subject as a function of prime visibility. This analysis revealed that, crucially, the intercept was large and highly significant (49 ms; $t(10) = 5.61$, $p < .0005$), suggesting the presence of a genuinely subliminal locus for priming.

In sum, this first experiment suggests that both repetition and congruity priming occur not only for visible but also for subliminal number stimuli, although masking appears to reduce the magnitude of priming effects. In addition, we observed masked priming not only when the prime and target were in the same or in different notations within the visual domain, which is consistent with previous findings, but we also found both repetition and congruity priming when there was a shift from the visual to the auditory modality. This latter result provides evidence that masked number priming involves amodal representations and extends its locus beyond the perceptual domain. Experiment 2 will address the question as to whether these amodal representations are of a semantic nature rather than involving other (e.g., episodic) types of information by introducing novel (i.e., unpracticed) number stimuli. In addition, we relied on a new, more rigorous measure of prime visibility. Indeed, if participants' responses during the priming experiment are progressively influenced by partial (e.g., fragmentary) elements of the prime, through an overlearnt stimulus-response mapping, then the numerical comparison task on the prime, which requires full identification of the prime stimulus, might actually underestimate prime visibility (see Abrams & Grinspan, 2007; Kouider & Dupoux, 2007). Thus, we decided instead to rely on a two-alternative forced-choice (hereafter 2-AFC) in which participants must decide which one of two numbers displayed on the screen corresponded to the prime in the preceding priming sequence. Here, if the participant relies on the identification of partial elements of the primes, then these elements are redisplayed in one of the two alternatives and they should, consequently, influence performance on the 2-AFC task.[1]

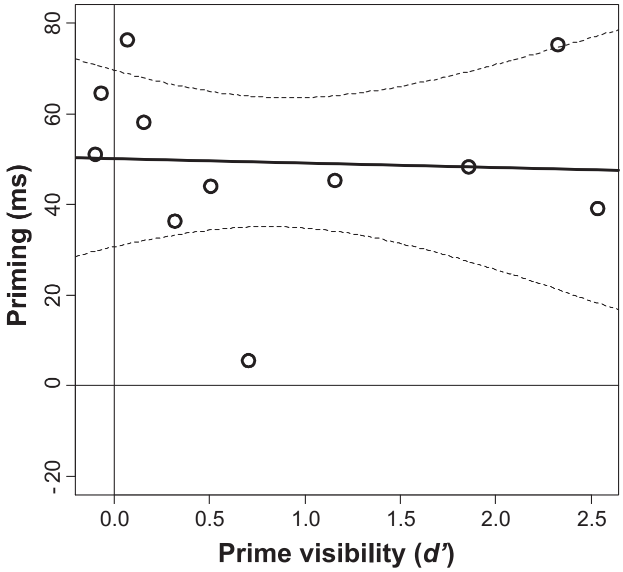


Figure 3. Regression of masked priming on prime visibility in Experiment 1. Each data point represents a participant. The regression functions (dotted lines indicate 95% confidence intervals) show the association between the global priming effect found for masked stimuli and their prime visibility. Priming is interpreted as subliminal when the curve representing the lowest value in the confidence interval passes above the origin.

[1] In addition, this new measure allowed to deal with a potential confound that might, conversely, overestimate prime visibility. Indeed, the inclusion of an equal number of repetition trials leads to a higher proportion of congruent trials collapsed across repeated and nonrepeated prime-target pairs. Thus, there were more trials in which response to the prime and response to the target were the same. As such, a participant who does not see any of the primes, but who responds on the basis of the magnitude of the target, that participant would actually be better than chance on the prime visibility measure used in Experiment 1. The new visibility measure performed in Experiment 2 allows to avoid this confound since the identity of the target becomes irrelevant in the 2-AFC task.

Experiment 2

Method

Participants

Fifteen students were recruited from Paris universities to take part in this experiment. None of them participated in the previous experiment.

Stimuli, Procedure, and Design

The same procedure and the same type of masking, and number stimuli were used in this experiment, except with the following three main aspects: First of all, the set of numbers from the previous experiment (i.e., 1, 4, 6, and 9) was extended to include 2, 3, 7, and 8 presented only as Arabic digit or written words. The former set of numbers could be presented as primes and as target, and then constituted the practiced set, while the latter set constituted the unpracticed set presented only in the prime position and thus never in the target position. Consequently, the priming experiment consisted in four blocks of 288 trials (instead of 216 trials in Experiment 1). Each block included 96 "unpracticed" trials (i.e., trials with an unpracticed prime) and 192 "practiced" trials. The whole protocol for the main experiment now lasted about 50 min. Secondly, the response deadline was extended from 1,500 to 2,000 ms, as it might have been too pressuring and decrease performance considerably in the previous experiment. Thirdly, the procedure for the visibility measure following the priming experiment was modified to become a 2-AFC task. The trial structure was exactly the same as in the priming experiment, except that the target (or the third mask in case of cross-modal trials) was immediately followed by the simultaneous presentation of a pair of choices, one on the left side and the other on the right side of the screen. One alternative corresponded to the prime whereas the other alternative was a different and randomly chosen number between 1 and 9 (excluding 5). Both alternatives appeared in the same format (i.e., both as Arabic digits or as written words). Participants were instructed to choose which of the two alternatives corresponded to the prime within the preceding sequence of events. They responded by pressing the left button if the correct alternative was on the left side and with the right button if it was on the right side. They were told that only response accuracy, not response speed, was important. The two alternatives remained on the screen until a response was made. As in the previous experiment, participants received training sessions with 200 ms primes and then at normal speed, and the same number of experimental trials ($N = 64$ for each masking type).

Results and Discussion

Priming

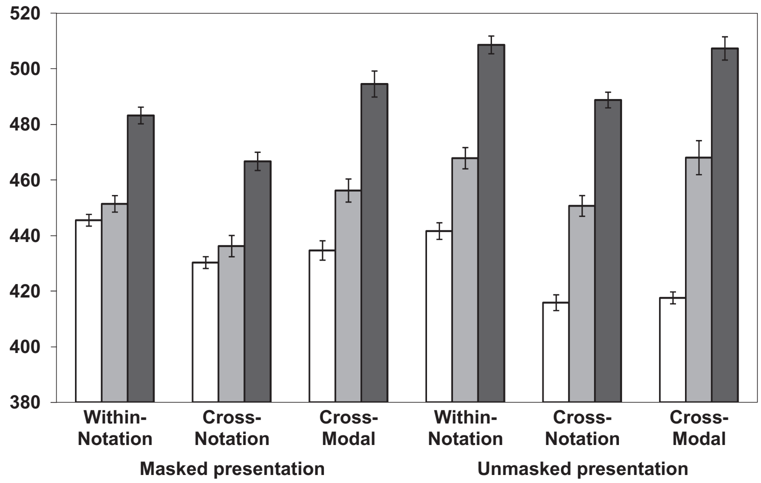
The rate of incorrect responses was now 6.12% (vs. 12.75% in Experiment 1), confirming that extending the response deadline improved performance. We first ran a global ANOVA, similarly to the previous experiment, with the factors masking type, format change, and relation (collapsed across practiced and unpracticed primes). We observed main effects of relation, $F(2, 28) = 151.17$, $p < .0001$, and format change, $F(2, 28) = 6.39$, $p < .01$. The effect of relation interacted both with masking type, $F(2, 28) = 19.36$, $p < .0001$, and with format change, $F(4, 56) = 3.81$, $p < .01$. Further analyses focused on the relation factor and were performed separately for trials with practiced and unpracticed primes.

We started by focusing on priming for practiced primes (see Figure 4) and separated unmasked and masked trials. For unmasked trials (collapsed across format change), we observed a significant effect of priming for both repetition priming, $F(1, 14) = 35.25$, $p < .0001$, and congruity priming, $F(1, 14) = 32.74$, $p < .0001$. Further restrictions to each format change revealed within-notation repetition, $F(1, 14) = 13.38$, $p < .005$, and congruity priming, $F(1, 14) = 19.27$, $p < .001$, cross-notation repetition, $F(1, 14) = 34.49$, $p < .0001$, and congruity priming, $F(1, 14) = 21.60$, $p < .0005$, and cross-modal repetition, $F(1, 14) = 16.85$, $p < .005$, and congruity priming, $F(1, 14) = 15.12$, $p < .005$. We also observed that repetition priming was significantly larger for cross-modal trials compared to within-notation trials, $F(1, 14) = 5.10$, $p < .05$. For masked trials there were significant effects for both repetition priming, $F(1, 14) = 7.028$, $p < .05$, and congruity priming, $F(1, 14) = 26.15$, $p < .0005$. When we further restricted our comparisons to each format change, we found for within-notation trials an effect of congruity priming, $F(1, 14) = 20.47$, $p < .0005$, but surprisingly no significant effect for repetition priming. This was also true for cross-notation trials for which we only observed congruity priming, $F(1, 14) = 10.30$, $p < .01$. By contrast, cross-modal trials led to both congruity priming, $F(1, 14) = 12.49$, $p < .005$, and repetition priming, $F(1, 14) = 8.10$, $p < .05$. Furthermore, we observed that the repetition priming advantage for cross-modal trials compared to both within-notation and cross-notation trials felt short of significance in both cases ($ps = < .10$).

We then turned to congruity priming for unpracticed primes (see Figure 5). For those trials, we observed a global congruity priming effect, $F(1, 14) = 23.95$, $p < .0005$, which interacted with masking type, $F(1, 14) = 7.67$, $p < .05$. This interaction resulted from the fact that priming was significant for unmasked trials, $F(1, 14) = 24.27$, $p < .0005$, but not for masked trials ($p = .14$). Further restrictions revealed priming for unmasked within-notation, $F(1, 14) = 8.76$, $p < .05$, and cross-notation trials, $F(1, 14) = 11.16$, $p < .005$, and a marginally significant effect for cross-modal trials, $F(1, 14) = 4.23$, $p = .06$. For masked trials, no effect of congruity priming reached significance when restricting our comparisons to any of the format change.

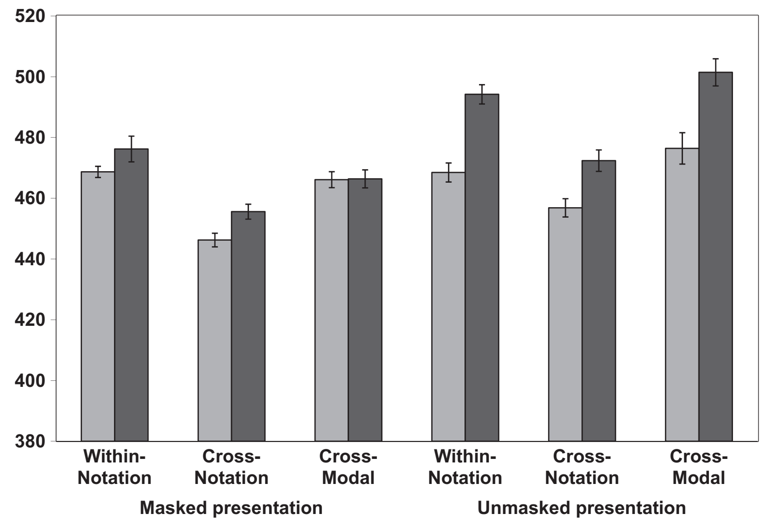
Prime Visibility

Participants' performances on the visibility measure were 74.0% for unmasked trials and 58.7% for masked trials.



Repetition	446	430	435	442	416	418
Congruent	451	436	456	468	451	468
Incongruent	483	467	495	509	489	507

Figure 4. Average RTs for practiced trials (i.e., trials with a practiced prime) in Experiment 2.



Congruent	469	446	466	469	457	476
Incongruent	476	456	466	494	472	501

Figure 5. Average RTs for unpracticed trials (i.e., trials with a novel prime) in Experiment 2.

Values of d' were computed by treating primes on the right side as signal and primes on the left side as noise. For masked trials, the mean d' values across format change were 0.27, 0.51, and 0.69 for within-notation, cross-notation, and cross-modal trials, respectively, and for unmasked trials, 1.30, 1.16, and 2.30, respectively. The mean d' values were significantly different from zero both for unmasked trials, $d' = 1.59$; $t(14) = 7.15$, $p < .0001$, and for masked trials, $d' = 0.49$; $t(14) = 5.56$, $p < .0001$. In addition, there was a main effect of masking type, $F(1, 14) = 29.75$, $p < .0001$, a main effect of format change, $F(1, 14) = 11.11$, $p < .0005$, and an interaction between these two factors, $F(1, 14) = 3.66$, $p < .05$. Planned comparisons across format changes revealed that, for masked trials, d' values were higher for cross-modal compared to within-notation trials, $F(1, 14) = 4.62$, $p < .05$. For unmasked trials, d' values for cross-modal trials were higher compared to both within-notation, $F(1, 14) = 12.49$, $p < .005$, and cross-notation trials, $F(1, 14) = 11.13$, $p < .005$.

Because here, as in the previous experiment, d' values for masked trials were still significantly different from zero, we relied on the regression method to investigate the amount of priming when performance on the prime visibility measure is extrapolated to zero. Crucially, as can be seen in Figure 6, the intercept of the regression was significant (32 ms; $t(14) = 3.992$, $p < .005$) when collapsing across

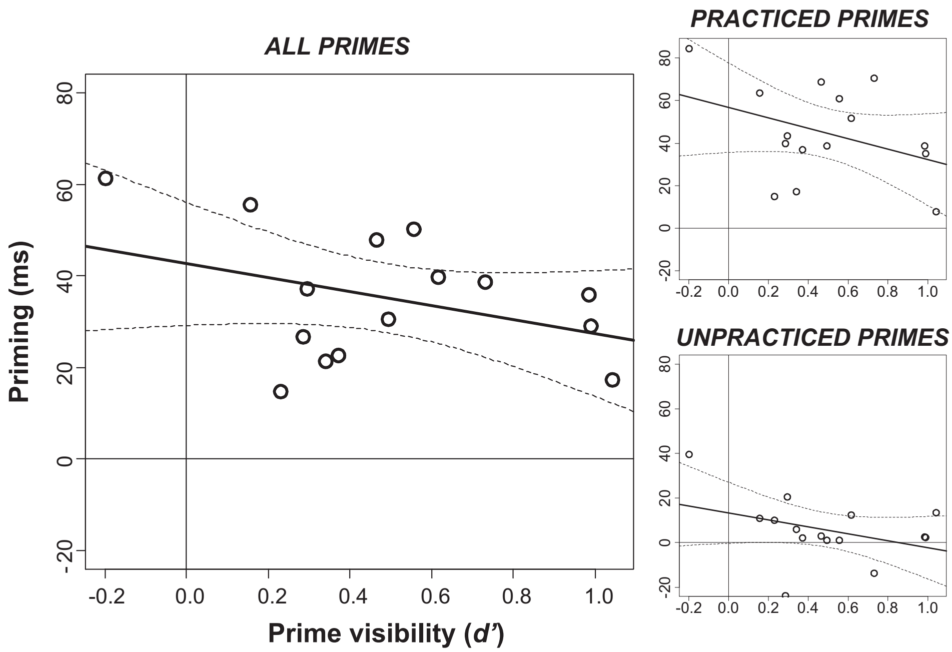


Figure 6. Regressions of masked priming on prime visibility in Experiment 2, for all trials (large left panel) or as a function of practice with the prime stimuli (two small right panels).

trials with practiced and unpracticed primes. However, when separating the two types of trials, this was clearly true for practiced trials (57 ms; $t(14) = 5.813$, $p < .0001$) while it only approached significance for unpracticed trials (13 ms; $t(14) = 2.12$, $p = .054$).

In sum, this second experiment replicated the masked congruity priming effect for practiced items found in Experiment 1. Yet, masked repetition priming vanished almost entirely in this second experiment. Interestingly the global masked priming effect for practiced items (i.e., comparing incongruent vs. repetition trials) had a similar magnitude in Experiments 1 and 2 (49 and 45 ms, respectively). Therefore, one possibility is that congruity and repetition effect in masked priming are modulated depending on individual task strategies (for instance, by now relying less on perceptual identification than categorical classification of motor or semantic attributes). This is consistent with indications from the masked priming literature that repetition priming vanishes in the presence of strong congruity effects (Dell'Acqua & Grainger, 1999; Fabre, Lemaire, & Grainger, 2007), although this issue clearly needs to be further addressed and specified.

By contrast to practiced items, masked congruity priming for unpracticed items was weak and nonsignificant. This result is at odds with the study by Naccache and Dehaene (2001a) showing in two experiments that although congruity priming for novel primes is smaller than for practiced primes, it was still highly reliable. Yet, one main difference in the present study was that participants received both subliminal and supraliminal trials. Thus, although the novel primes were not practiced in the sense that they received a response, here they were nevertheless seen during the course of the experiment. One possibility is that participants inhibited these novel primes when perceiving them consciously, mainly because they are distracting and task-irrelevant. For this reason, we decided to exclude unmasked trials in the next experiment.

Experiment 3

Method

Participants

Fifteen students were recruited from Paris universities to take part in this experiment. None of them participated in any of the previous experiments.

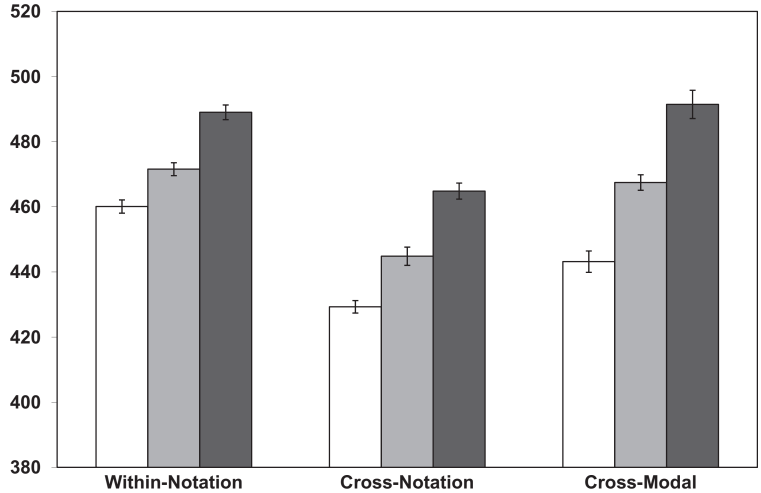
Stimuli, Procedure, and Design

The stimuli, procedure, and design were exactly the same as for Experiment 2 when excluding the two blocks with unmasked trials. Thus, this experiment was about half the duration of the previous one because it contained only two blocks of stimuli with masked trials.

Results and Discussion

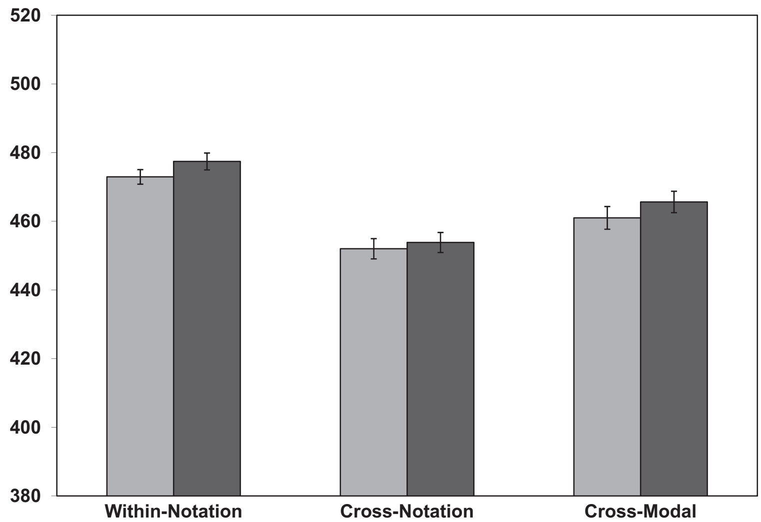
Priming

A first global ANOVA (collapsing across practiced and unpracticed primes) revealed a main effect of relation, $F(2, 28) = 37.15$, $p < .0001$, and format change,



	Within-Notation	Cross-Notation	Cross-Modal
□ Repetition	460	429	443
■ Congruent	472	445	467
■ Incongruent	489	465	491

Figure 7. Average RTs for practiced trials (i.e., trials with a practiced prime) in Experiment 3.



	Within-Notation	Cross-Notation	Cross-Modal
■ Congruent	473	452	461
■ Incongruent	477	454	466

Figure 8. Average RTs for unpracticed trials (i.e., trials with a novel prime) in Experiment 3.

$F(2, 28) = 10.95$, $p < .0005$. For practiced trials (see Figure 7), we found a significant repetition priming, $F(1, 14) = 23.15$, $p < .0005$, that marginally interacted with format change, $F(2, 28) = 3.163$, $p = .06$, as well as a congruity priming effect, $F(1, 14) = 28.015$, $p < .0005$. Repetition priming was significant for within-notation, $F(1, 14) = 4.65$, $p < .05$, cross-notation, $F(1, 14) = 14.50$, $p < .005$, and cross-modal trials, $F(1, 14) = 29.24$, $p < .0001$. It was marginally greater for cross-modal compared to within-notation trials, $F(1, 14) = 4.42$, $p = .05$. Congruity priming was also significant for within-notation, $F(1, 14) = 10.96$, $p < .01$, cross-notation, $F(1, 14) = 11.54$, $p < .005$, and cross-modal trials, $F(1, 14) = 6.83$, $p < .05$. For unpracticed trials (Figure 8), there was no congruity priming either when collapsing all the trials across format changes or when considering the different format changes separately (all *p*s > .25).

Prime Visibility

Performance on the visibility test was 58.85% and resulted in a mean d' value of 0.56. This value was significantly different from zero, $t(14) = 4.61$, $p < .0005$. When dissociating it as a function of format change, we obtained d' values of 0.43 for within-notation trials, 0.47 for cross-notation trials, and 0.77 for cross-modal trials. Yet, the main effect of format change

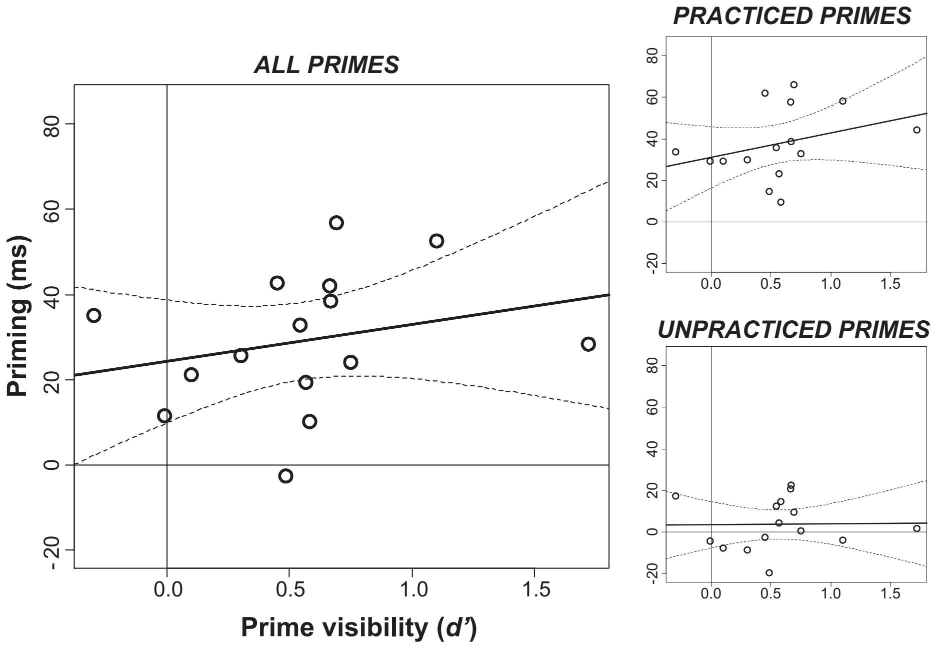


Figure 9. Regressions of masked priming on prime visibility in Experiment 3.

was not significant, nor were pairwise comparisons across these values (all *p*s > .30). As in the previous experiment, the Greenwald's regression method (Figure 9) revealed that priming extrapolated to null performance was significant as a whole (24 ms; $t(14) = 3.632$, $p < .005$) and when restricted to practiced trials (31 ms; $t(14) = 4.542$, $p < .001$) but not when restricted to unpracticed trials (3 ms; $t < 1$).

In sum, the exclusion of unmasked trials in this third experiment did not improve the observation of congruity effects for novel primes. These were still absent, contrary to congruity effect for practiced primes. Note also that, as in Experiment 1 and contrary to Experiment 2, the contribution of repetition trials to masked priming was now highly significant. Interestingly, and in accordance with the explanation proposed in the discussion of Experiment 2, the occurrence of repetition priming was accompanied with a weaker congruity priming effect (for practiced primes) in Experiment 3 compared to Experiment 2. The repeated absence of congruity effects for novel primes, even if we could sometimes observe small nonsignificant trends, is problematic for semantic interpretations of subliminal number priming. Yet, the recurrent observation of a masked cross-modal effect suggests that subliminal processing extends beyond the perceptual level. Before discussing further the implication of these findings, we wanted to ensure that the cross-modal effect did not result from residual prime awareness. Indeed, masked cross-modal priming was consistently higher than within-notation and cross-notation priming in the previous experiment. However, *d*′ values were also consistently higher for cross-modal trials, although this difference was significant only in Experiment 2. Therefore, we decided to run a fourth experiment with a different backward masking procedure for cross-modal trials. Piloting work revealed that replacing the series of hash marks (e.g., ######) serving as a final backward mask (see Figure 1) with another random letter string (e.g., FTfVkG) considerably reduced prime visibility.

Experiment 4

Method

Participants

Twenty-three students were recruited from Paris universities to take part in this experiment. None of them participated in any of the previous experiments. One participant was excluded because of extreme error rate and RTs.

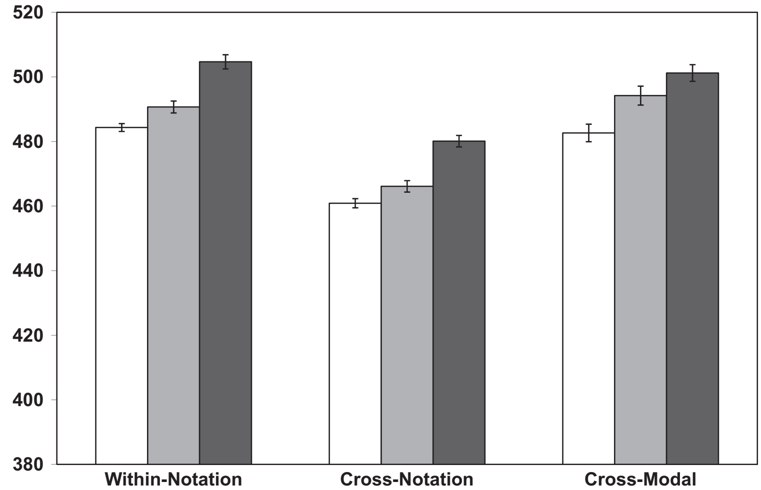
Stimuli, Procedure, and Design

The stimuli, procedure, and design were exactly the same as for Experiment 3 with one exception: the third mask during cross-modal trials, rather than being a series of hash marks (e.g., ######), was now another combination of 6 upper- and lower-case consonant letters (e.g., FTfVkG) constructed along the same principle as for the other masks.

Results and Discussion

Priming

The global ANOVA revealed a main effect of relation, $F(2, 42) = 37.51$, $p < .0001$. For practiced primes



	Within-Notation	Cross-Notation	Cross-Modal
□ Repetition	484	461	483
■ Congruent	491	466	494
■ Incongruent	505	480	501

Figure 10. Average RTs for practiced trials (i.e., trials with a practiced prime) in Experiment 4.

(Figure 10), we observed both a significant effect of repetition priming, $F(1, 21) = 7.22$, $p < .05$, and a significant effect of congruity priming, $F(1, 21) = 8.69$, $p < .01$. Although none of the two forms of priming interacted with format change, we performed restricted comparisons and found that the six priming contrasts were significant or marginally significant (all *p*s < .10), except for the cross-modal congruity effect ($F = 1.02$). For unpracticed primes (Figure 11), priming felt short of significance only when considered as a whole regardless of format change, $F(1, 21) = 3.05$, $p < .10$.

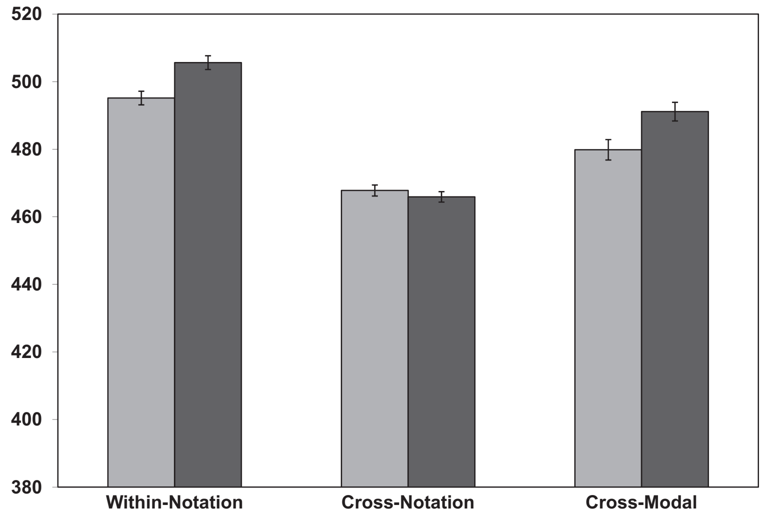
Prime Visibility

Performance on the visibility test was 55.5% resulting in a mean d' value of 0.25 that was significantly different from zero ($t(21) = 2.88$, $p < .01$). Considered as a function of format change, these values were 0.38 for within-notation trials, 0.42 for cross-notation trials, and 0.09 for cross-modal trials. Greenwald's regression method (Figure 12) showed that priming extrapolated to null performance reached significance as a whole (13 ms; $t(21) = 4.56$, $p < .0005$) and also for practiced (17 ms; $t(21) = 3.68$, $p < .005$) but not for unpracticed trials although there was a trend of 7 ms ($p = .11$).

General Discussion

The present study was aimed at examining two markers of the depth of subliminal number priming. One was the possibility of a subliminal transfer from the visual to the auditory modality, suggesting that subliminal number priming extends beyond the perceptual level. The other was the robustness of generalization to novel numbers, suggesting further that subliminal number priming necessarily involves semantic attributes. We performed four experiments in order to test these two hypotheses. In regard to transfer across modalities, we consistently found masked cross-modal priming across the four experiments. In addition, the improved masking method used in Experiment 4 showed that it genuinely reflected a subliminal effect that cannot be explained as resulting from a residual form of stimulus awareness. By contrast, the results we found for novel primes were much weaker and lead to an ambiguous interpretation. Indeed, on the one side, none of the three experiments containing novel primes (Experiments 2–4) showed a robust and significant effect of generalization. On the other side, we consistently observed small trends in the expected direction. As such, it remains difficult to interpret these effects, and more fundamentally their participation in subliminal priming.

In order to deal with this ambiguous outcome, we further performed two global analyses, one collapsing all the masked trials with practiced primes from the four experiments reported in this study, and the other one collapsing all the masked trials with unpracticed primes (thus excluding Experiment 1). For practiced trials, we observed a main effect of repetition priming of 13 ms, $F(1, 62) = 49.31$, $p < .0001$, and a main effect of congruity priming of 22 ms, $F(1, 62) = 71.10$, $p < .0001$. When considering these two effects as a function of the three conditions of format change, we observed highly significant effects in the six resulting contrasts (all *p*s < .001). For unpracticed primes, we observed a much smaller main effect of congruity of 6 ms which, nevertheless, was statistically significant, $F(1, 51) = 6.91$, $p < .02$. When considering this main effect as a function of notation change, it reached significance for within-notation trials, $F(1, 51) = 4.41$ $p < .05$, but not for cross-notation trials, $F(1, 51) = 0.53$ $p = .46$, or



	Within-Notation	Cross-Notation	Cross-Modal
Congruent	495	468	480
Incongruent	506	466	491

Figure 11. Average RTs for unpracticed trials (i.e., trials with a novel prime) in Experiment 4.

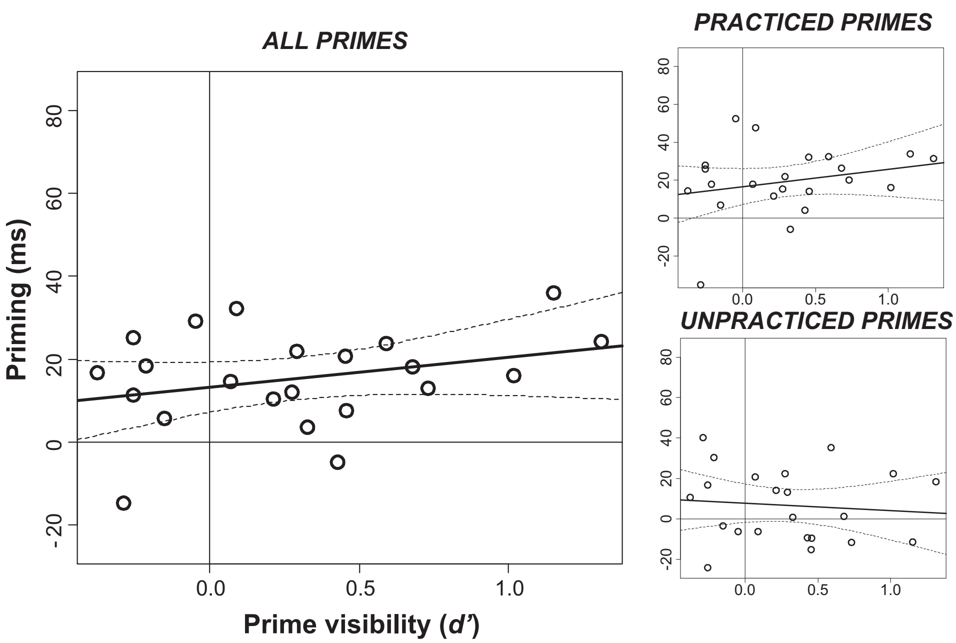


Figure 12. Regressions of masked priming on prime visibility in Experiment 4.

cross-modal trials, $F(1, 51) = 2.10$ $p = .15$. Importantly, as depicted in Figure 13, regressions of the priming effect with d' measures of prime awareness revealed that the regression intercept was significantly different from zero not only for practiced primes (31 ms; $t(62) = 8.10$, $p < .0001$), but also for unpracticed primes (8 ms; $t(51) = 2.60$, $p < .02$), indicating that the effect could not be attributed to prime visibility. We therefore conclude, together with Naccache and Dehaene (2001a), that subliminal number priming can extend to unpracticed stimuli, although this effect turns out to be relatively small. These results provide evidence that semantic information contributes to subliminal number priming (Dehaene et al., 1998; Naccache & Dehaene, 2001a), although they also show that priming can, in a large part, be affected by the deployment of stimulus-response associations (Abrams & Greenwald, 2000; Damian, 2001).

Why are semantic effects so weak and unstable in masked number priming? From a theoretical perspective,

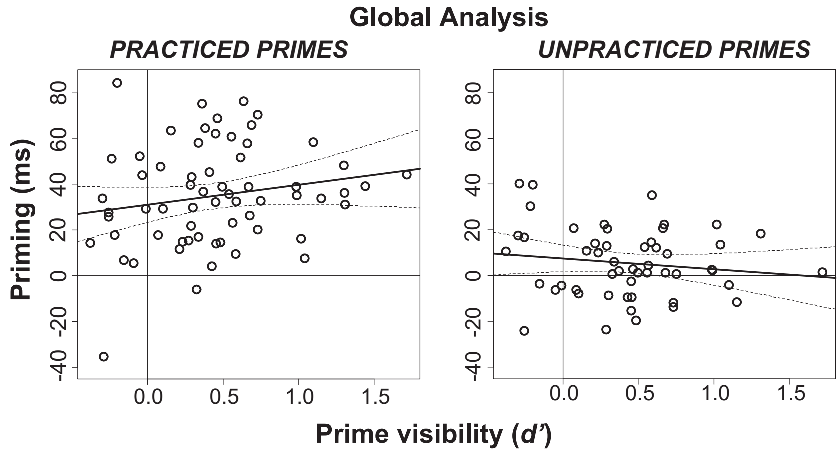


Figure 13. Regressions of masked priming on prime visibility across all experiments, as a function of practice with the prime stimuli.

in fact, masked priming is predicted to be weaker than for supraliminal primes, since masked primes are assumed to convey neural information only in a bottom-up fashion, preventing any contribution from reinforcing feedback loops (Lamme, 2003). In addition, brain imaging and neurophysiological data have shown that masking also prevents the efficient propagation of bottom-up stimulus activation in successive perceptual areas, leaving only a short pulse of activity whose amplitude decreases at each synaptic step (Dehaene et al., 2001; Del Cul, Baillet, & Dehaene, 2007; Kovacs, Vogels, & Orban, 1995; Lamme, 2003; Thompson & Schall, 1999). As such, we have recently proposed that although behavioral priming effects can be detected when they involve neural processing at a certain distance from sensory systems, they are expected to decrease with synaptic distance and become very small and sometimes undetectable in distant semantic areas (Kouider & Dehaene, 2007). Additionally, as predicted by the neuronal workspace theory (Dehaene & Naccache, 2001), the occurrence of subliminal semantic priming should also be modulated by the reinforcement of semantically mediated pathways during task execution. That is, the more the task involves the extraction of semantic information in a routine manner, the more this semantic stream of processing will be automatized and operate in an unconscious fashion (see Nakamura, Dehaene, Jobert, Le Bihan, & Kouider, 2007, for brain imaging evidence of how task context influences the neural circuitry at the origin of subliminal priming). As such, it is possible that the involvement of subliminal semantic processing in the numerical comparison task depends on intrinsic experimental features and participants' response strategies, stressing either numerical magnitude estimation or rather sensorimotor mappings. Along the same lines, the fragility of semantic effects when using behavioral priming methods might also result from a problem of sensitivity. Indeed, the single data point obtained in RTs only reflects a partial read-out of the processing stream triggered by the stimulus. As such it is possible that semantic processing occurs without being detected, because the decisional components leading to priming are mainly driven by other (i.e., sensorimotor) stages of processing. Consistent with this idea, it appears that neuroimaging methods, that can in principle cover the locus of any processing stage, have been more consistent than behavioral methods in observing subliminal semantic influences (see Kouider & Dehaene, 2007).

Finally, another possible interpretation for the weakness of subliminal number priming for novel stimuli can be found in the theory of "action-triggers" (Elsner et al., 2008; Kiesel, Kunde, & Hoffmann, 2007; Kunde, Kiesel, & Hoffmann, 2003). Kunde, Kiesel, and colleagues suggested that apparently inconsistent data patterns in subliminal priming might be explained by considering that subjects prepare action triggers in order to quickly associate each possible experimental stimulus with its appropriate response in minimal time. The setting of action triggers happens during the instructions or practice phase and depends on the stimulus set size, as it is efficient only for narrow categories (e.g., Arabic numbers from 1 to 9). According to this account, even novel primes (e.g., 2 and 3) may prime the appropriate response not because the meaning of these primes has been extracted, but rather because the adequate response to these stimuli was consciously prepared in advance. Consequently, according to this interpretation, the absence or presence of priming for novel stimuli will depend on participants' exact interpretation of the instructions and on their expectations that these novel stimuli will be presented during the experiment. In our study, it is possible that participants did not prepare action triggers efficiently because they were faced with three formats (Arabic, written words, and auditory word), leading to a rather large set of possible triggers. We suspect that these factors do contribute to the weaker and somewhat variable priming effects observed with novel primes, compared to the strong effects consistently observed with practiced primes, although recent research clearly indicates that it cannot be the whole story as priming *can* be observed with unpracticed primes even when very large stimulus categories are used (e.g., Klauer et al., 2007; Van den Bussche & Reynvoet, 2007). An alternative explanation is that subliminal category congruity effects are obtained with novel primes as a function semantic overlap, that is as long as the prime and target share many semantic features (e.g., Quinn & Kinoshita, 2008). Clearly, more research is needed to characterize more precisely how priming does generalize to novel primes.

The most convincing finding for unconscious processing beyond the perceptual level is the subliminal cross-modal priming effect we observed. Indeed, our study revealed that subliminal priming involves amodal representations during number processing, as we found both repetition and congruity priming for masked visual-to-auditory trials. This finding is consistent with the triple-code theory (Dehaene, 1992) which postulates that numerical cognition involves a lower step of modality-specific analysis of number stimuli, and then a higher processing stage where these representations reach an abstract "number sense", that is an amodal numerical estimation module computing magnitude estimation and contributing to mathematic performances. Neuropsychological investigations have found that these numerical representations imply cerebral activity in the intraparietal sulcus (Dehaene & Cohen, 1995). This region is identically activated when processing target numbers in the visual and in the auditory modality (e.g., Eger, Sterzer, Russ, Giraud, & Kleinschmidt, 2003). Importantly, using fMRI, Naccache and Dehaene (2001b) have observed masked numerical repetition suppression in this area across the Arabic and written notations, although this study remained in the visual domain. The extension of repetition priming to cross-modal conditions in the present study is highly suggestive of the involvement of this intraparietal magnitude representation, and thus of some form of semantic processing, in subliminal number priming.

It is important to note, finally, that the weakness of cross-modal congruity effects for novel stimuli does not allow for an unequivocal semantic interpretation of subliminal cross-modal priming. It could therefore still be argued that subliminal cross-modal priming for repeated primes resulted from the construction of amodal representations "on the fly", as a function of the specific experimental context in use. Under this interpretation, participants would, through practice during the experiment, build episodic representations that are shared between visual and auditory numbers, and use these representations both for categorizing the incoming stimuli (primes as well as targets) and for activating the relevant motor codes. This episodic interpretation of priming might explain why cross-modal subliminal priming itself is not consistently observed in the literature.[2]

In sum, our experiments revealed that number priming transfers across modalities, suggesting that it involves higher-level representations beyond the perceptual stage and possibly semantic attributes related to magnitude estimation. Nevertheless, the weakness of priming effects in generalizing to novel stimuli suggests that semantic-level activation is heavily reduced by masking and that priming effects are often, though not always, dominated by lower-level perceptual effects.

References

Abrams, R. L., & Greenwald, A. G. (2000). Parts outweigh the whole (word) in unconscious analysis of meaning. *Psychological Science, 11*, 118–124.

Abrams, R. L., & Grinspan, J. (2007). Unconscious semantic priming in the absence of partial awareness. *Consciousness and Cognition, 16*, 942–953.

Abrams, R. L., Klinger, M. R., & Greenwald, A. G. (2002). Subliminal words activate semantic categories (not automated motor responses). *Psychonomic Bulletin and Review, 9*, 100–106.

Damian, M. (2001). Congruity effects evoked by subliminally presented primes: Automaticity rather than semantic processing. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 154–165.

Dehaene, S. (1992). Varieties of numerical abilities. *Cognition, 44*, 1–42.

Dehaene, S., Changeux, J.-P., Naccache, L., Sackur, J., & Sergent, C. (2006). Conscious, preconscious, and subliminal processing: A testable taxonomy. *Trends in Cognitive Science, 10*, 204–211.

Dehaene, S., & Cohen, L. (1995). Towards an anatomical and functional model of number processing. *Mathematical Cognition, 1*, 83–120.

Dehaene, S., & Naccache, L. (2001). Towards a cognitive neuroscience of consciousness: Basic evidence and a workspace framework. *Cognition, 79*, 1–37.

Dehaene, S., Naccache, L., Cohen, L., Le Bihan, D., Mangin, J.-F., Poline, J.-B., et al. (2001). Cerebral mechanisms of word masking and unconscious repetition priming. *Nature Neuroscience, 4*, 752–758.

Dehaene, S., Naccache, L., Le Clec'H, G., Koechlin, E., Mueller, M., Dehaene-Lambertz, G., et al. (1998). Imaging unconscious semantic priming. *Nature, 395*, 597–600.

Del Cul, A., Baillet, S., & Dehaene, S. (2007). Brain dynamics underlying the non-linear threshold for access to consciousness. *PLOS Biology, 5*, e260.

Dell'Acqua, R., & Grainger, J. (1999). Unconscious semantic priming to pictures. *Cognition, 73*, B1–B15.

Eger, E., Sterzer, P., Russ, M. O., Giraud, A. L., & Kleinschmidt, A. (2003). A supramodal number representation in human intraparietal cortex. *Neuron, 37*, 719–725.

Elsner, K., Kunde, W., & Kiesel, A. (2008). Limited transfer of subliminal response priming to novel stimulus orientations and identities. *Consciousness and Cognition, 17*, 657–671.

Fabre, L., Lemaire, P., & Grainger, J. (2007). Attentional modulation of masked repetition and categorical priming in young and older adults. *Cognition, 105*, 513–532.

Gaillard, R., Del Cul, A., Naccache, L., Vinckier, F., Cohen, L., & Dehaene, S. (2006). Nonconscious semantic processing

[2] Indeed, in the first study using this method, Kouider and Dupoux (2001) used masked words and found that only within-modal repetition priming was reliable under subliminal conditions, cross-modal priming showing a perfect correlation with prime awareness. However, more recent studies by Grainger, Diependaele, Spinelli, Ferrand, and Farioli (2003), and by Nakamura et al. (2006) revealed the presence of cross-modal priming under subliminal conditions. One main difference that can explain this discrepancy is that the latter studies used stimuli that were repeated and appeared both as primes and as targets during the experiment, while Kouider and Dupoux used a large set of words which appeared only once during the experiment.

of emotional words modulates conscious access. *Proceedings of National Academy of Sciences USA, 103*, 7524–7529.

Grainger, J., Diependaele, K., Spinelli, E., Ferrand, L., & Farioli, F. (2003). Masked repetition and phonological priming within and across modalities. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29*, 1256–1269.

Greenwald, A. G., Abrams, R. L., Naccache, L., & Dehaene, S. (2003). Long-term semantic memory versus contextual memory in unconscious number processing. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29*, 235–247.

Greenwald, A. G., Draine, S. C., & Abrams, R. L. (1996). Three cognitive markers of unconscious semantic activation. *Science, 273*, 1699–1702.

Greenwald, A. G., Klinger, M. R., & Schuh, E. S. (1995). Activation by marginally perceptible (''subliminal'') stimuli: Dissociation of unconscious from conscious cognition. *Journal of Experimental Psychology: General, 124*, 22–42.

Holender, D. (1986). Semantic activation without conscious identification in dichotic listening, parafoveal vision, and visual masking: A survey and appraisal. *Behavioral and Brain Sciences, 9*, 1–23.

Kiefer, M. (2002). The N400 is modulated by unconsciously perceived masked words: Further evidence for a spreading activation account of N400 priming effects. *Cognitive Brain Research, 13*, 27–39.

Kiesel, A., Kunde, W., & Hoffmann, J. (2007). Mechanisms of subliminal response priming. *Advances in Cognitive Psychology, 3*, 307–315.

Klauer, K. C., Eder, A. B., Greenwald, A. G., & Abrams, R. L. (2007). Priming of semantic classifications by novel subliminal prime words. *Consciousness and Cognition, 16*, 63–83.

Kouider, S., & Dehaene, S. (2007). Levels of processing during non-conscious perception: A critical review. *Philosophical Transactions of the Royal Society of London B, 362*, 857–875.

Kouider, S., Dehaene, S., Jobert, A., & Le Bihan, D. (2007). Cerebral bases of subliminal and supraliminal priming during reading. *Cerebral Cortex, 17*, 2019–2029.

Kouider, S., & Dupoux, E. (2001). A functional disconnection between spoken and visual word recognition: Evidence from unconscious priming. *Cognition, 82*, B35–B49.

Kouider, S., & Dupoux, E. (2004). Partial awareness creates the ''illusion'' of subliminal semantic priming. *Psychological Science, 15*, 75–81.

Kouider, S., & Dupoux, S. (2007). How ''semantic'' is response priming restricted to practiced items? A reply to Abrams & Grinspan (2007). *Consciousness and Cognition, 16*, 954–956.

Kovacs, G., Vogels, R., & Orban, G. A. (1995). Cortical correlate of pattern backward masking. *Proceedings of National Academy of Sciences USA, 92*, 5587–5591.

Kunde, W., Kiesel, A., & Hoffmann, J. (2003). Conscious control over the content of unconscious cognition. *Cognition, 88*, 223–242.

Kunde, W., Kiesel, A., & Hoffmann, J. (2005). On the masking and disclosure of unconscious elaborate processing. A reply to van Opstal, Reynvoet, & Verguts. *Cognition, 97*, 99–105.

Lamme, V. A. (2003). Why visual attention and awareness are different. *Trends in Cognitive Science, 7*, 12–18.

Luck, S. J., Vogel, E. K., & Shapiro, K. L. (1996). Word meanings can be accessed but not reported during the attentional blink. *Nature, 383*, 616–618.

Mack, A., & Rock, I. (1998). *Inattentional blindness*. Cambridge, MA: MIT press.

Marcel, A. J. (1974). Perception with and without awareness. Paper presented at the meeting of the Experimental Psychology Society, Stirling, Scotland.

Naccache, L., & Dehaene, S. (2001a). Unconscious semantic priming extends to novel unseen stimuli. *Cognition, 80*, 215–229.

Naccache, L., & Dehaene, S. (2001b). The priming method: Imaging unconscious repetition priming reveals an abstract representation of number in the parietal lobes. *Cerebral Cortex, 11*, 966–974.

Nakamura, K., Dehaene, S., Jobert, M., Le Bihan, D., & Kouider, S. (2007). Task-specific change of unconscious neural priming in the cerebral language network. *Proceedings of National Academy of Sciences USA, 104*, 19643–19648.

Nakamura, K., Hara, N., Kouider, S., Takayama, Y., Hanajima, R., Sakai, K., et al. (2006). Task-guided selection of the dual neural pathways for reading. *Neuron, 52*, 1–8.

Neumann, O., & Klotz, W. (1994). Motor responses to nonreportable, masked stimuli: Where is the limit of direct parameter specification? In C. Umilta & M. Moskovitch (Eds.), *Attention and performance* XV (pp. 123–150) Cambridge, MA: MIT Press.

Pallier, C., Dupoux, E., & Jeannin, X. (1997). EXPE: An expandable programming language for on-line psychological experiments. *Behavior Research Methods, Instruments, & Computers, 29*, 322–327.

Raymond, J. E, Shapiro, K. L., & Arnell, K. M. (1992). Temporary suppression of visual processing in an RSVP task: An attentional blink? *Journal of Experimental Psychology. Human Perception and Performance, 18*, 849–860.

Reynvoet, B., Gevers, W., & Caessens, B. (2005). Unconscious primes activate motor codes through semantics. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31*, 991–1000.

Sergent, C., Baillet, S., & Dehaene, S. (2005). Timing of the brain events underlying access to consciousness during the attentional blink. *Nature Neuroscience, 8*, 1391–1400.

Thompson, K. G., & Schall, J. D. (1999). The detection of visual signals by macaque frontal eye field during masking. *Nature Neuroscience, 2*, 283–288.

Van den Bussche, E., & Reynvoet, B. (2007). Masked priming effects in semantic categorization are independent of category size. *Experimental Psychology, 54*, 225–235.

Received August 20, 2008
Revision received October 31, 2008
Accepted November 3, 2008

Sid Kouider

Ecole Normale Supérieure
29 rue d'Ulm
75005 Paris
France
Tel. +33 1 44 32 26 22
Fax +33 1 44 32 26 30
E-mail sid.kouider@ens.fr

