Consciousness and Cognition 22 (2013) 1422–1430

Contents lists available at ScienceDirect

Consciousness and Cognition

journal homepage: www.elsevier.com/locate/concog

Repeating a strongly masked stimulus increases priming and awareness

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ARTICLE INFO

Article history:
Received 18 April 2013

Keywords:
Repeated masking method
Awareness
Priming

ABSTRACT

Previous studies [Marcel, A. J. (1983). Conscious and unconscious perception: Experiments on visual masking and word recognition. *Cognitive Psychology*, *15*(2), 197–237; Wentura, D., & Frings, C. (2005). Repeated masked category primes interfere with related exemplars: New evidence for negative semantic priming. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31*(1), 108–120] suggested that repeatedly presenting a masked stimulus improves priming without increasing perceptual awareness. However, neural theories of consciousness predict the opposite: Increasing bottom-up strength in such a paradigm should also result in increasing availability to awareness. Here, we tested this prediction by manipulating the number of repetitions of a strongly masked digit. Our results do not replicate the dissociation observed in previous studies and are instead suggestive that repeating an unconscious and attended masked stimulus enables the progressive emergence of perceptual awareness.

1. Introduction

Visual masking is a parsimonious and convenient method through which to contrast conscious and unconscious processing and now constitutes one of the most prominent paradigms to study consciousness (Breitmeyer & Ögmen, 2006). In a nutshell, awareness of a stimulus is prevented when it is surrounded temporally and spatially by another stimulus, called the mask. Effective masking is obtained when the duration of the informative stimulus is sufficiently short ($\leqslant$50 ms; Kouider & Dehaene, 2007) and when the mask shares features with the stimulus or fits its contours closely. The resulting signal is intrinsically weak and fleeting. However, under specific task instructions, the stimulus can be sufficiently processed to influence reaction times to a subsequent visible target (i.e. masked priming, see Kouider & Dehaene, 2007 for a review). A large number of studies have now confirmed that decision making in simple choice tasks can involve unconscious processes (e.g., Schmidt, 2002; Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003), which essentially correspond to the propagation of activation evoked by the stimulus from sensory cortex to motor cortex (Dehaene et al., 1998).

One of the most important methodological issues involved in the study of unconscious processing is to manage to achieve a balance between availability to consciousness and causal influence. Thus, one needs to identify conditions in which a stimulus is strong enough that its influence can be detected at the level of behavioral responses, yet weak enough that the participant fails to consciously perceive it. This is notoriously difficult to obtain using simple masking procedures. Recently however, methods such as continuous flash suppression (CFS, see Tsuchiya & Koch, 2005) or gaze-contingent crowding

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http://dx.doi.org/10.1016/j.concog.2013.09.011

(GCC, see Kouider, Berthet, & Faivre, 2011) have made it possible to present stimuli for long durations (so achieving greater strength) while affording sustained invisibility (e.g. Almeida, Mahon, Nakayama, & Caramazza, 2008; Bahrami et al., 2010; Faivre & Kouider, 2011). Interestingly, Marcel (1983, see also Wentura & Frings, 2005) had already proposed a different manner to achieve both stimulus strength and stimulus invisibility: The repeated masking paradigm. In this paradigm, a strongly masked stimulus is repeated many times, thus resulting in a relatively long stream of identical masked stimuli. In such conditions, both Marcel (1983) and Wentura & Frings, 2005 found that stimulus processing, as reflecting through priming, improved with increasing repetitions while perceptual awareness did not, thus demonstrating reliable subliminal processing.

However, both studies suffer from methodological limitations that hinder their conclusions. Several aspects of the specific method used by Marcel (1983) are suggestive that his findings could have stemmed from partial awareness of the primes rather than from accumulation of unconscious evidence. Indeed, Marcel used a very long duration for the inter-prime interval (IPI, 1000 ms) and inserted a warning signal (a tone) between the final prime and the target, which were also separated by 1000 ms. With this procedure, it is likely that participants withheld their attention until the occurrence of the warning sound, hence dedicating little or no attention to the successive masked primes. Noteworthy, the priming effect found through this method contrasts with other studies on unconscious priming, which have systematically shown that prime influence completely vanishes (1) when the delay between the offset of the prime and the onset of the target exceeds a few hundred milliseconds or (2) when top-down attention is not directed to the masked prime (Dupoux, de Gardelle, & Kouider, 2008; Ferrand, 1996; Greenwald, Draine, & Abrams, 1996; Kiefer & Brendel, 2006; Naccache, Blandin, & Dehaene, 2002). Based on such studies, we might therefore expect, with the Marcel method, that the weak neural trace elicited by the current unattended prime completely disappears before the appearance of the next unattended prime or of the target, unless these masked primes were partially conscious. Importantly, prime awareness was assessed through a subjective measure in the Marcel study, whereas all the studies mentioned above assessed prime awareness through an objective measure, which is currently more prevalent in the literature (see Kouider & Dehaene, 2007 for a review). Thus, the priming effects observed by Marcel might be explained by an underestimation of prime visibility, at least based on an objective threshold of awareness. Therefore, an eclectic approach with objective and subjective awareness concurrently measured, is preferable (Pasquali, Timmermans, & Cleeremans, 2010; Vermeiren & Cleeremans, 2012).

Wentura and Frings (2005) compared a standard (i.e., single prime) and a repeated masked prime condition and found the same level of awareness in both cases, but a significant priming effect only in the repeated condition. Importantly however, the two conditions were not strictly comparable, and this is problematic insofar as interpretation is concerned. In the repeated masked prime condition, primes and masks both lasted 14 ms (IPI = mask duration) and each appeared 10 times in quick succession. In the standard masked prime condition, the single prime lasted 28 ms and was followed by a mask of 14 ms and then by of blank of 243 ms. The target was presented 14 ms after the last prime repetition in the repeated condition, while it was presented 257 ms after the single prime in the standard condition. Thus, the activation evoked by the single prime could have already decayed substantially when the target was presented (Greenwald et al., 1996), and the prime itself was probably presented outside the temporal window of attention allocated to the target (Naccache et al., 2002). Both factors can explain the absence of a priming effect in the standard condition (i.e., single prime). Moreover, Avons et al. (2009) failed to obtain a priming effect despite using exactly the same repeated masking procedure.

Whether the repetition of a masked stimulus can increase its potency without increasing its availability to awareness thus remains an open issue. In this respect, it is worth reflecting upon the predictions that contemporary models of consciousness would make in this particular case.

Let us first consider higher-order theories (HOT) of consciousness (see Dienes, 2004, 2008; Lau & Rosenthal, 2011; Rosenthal, 2005), which most naturally align with the use of subjective measures to assess awareness. According to HOT, a representation is a conscious representation when the agent entertains, in a non-inferential manner, a higher-order thought to the effect that the target first-order representation exists. Crucially, the higher-order thought (or representation) does not need itself to be conscious. Its existence, however, makes the agent conscious of the contents of the target first-order representation. An important prediction of HOT is that the strength, or quality of a first-order representation can be wholly dissociated from the extent to which it is available to consciousness. Such a dissociation is precisely what is observed in cases such as blindsight or change blindness, in which high-quality stimuli fail to be available to form the contents of conscious awareness in spite of their strength. HOT accounts for such phenomena by invoking the lack of relevant higher-order thoughts: The stimulus thus elicits appropriate first-order representations, which nevertheless remain unconscious because they fail to be accompanied by relevant higher-order representations. HOT thus predicts that a graded, repetition-dependent increase in priming is possible in the absence of awareness, just as observed in both the Marcel study and in the Wentura and Frings study.

However, and in contrast, the results of both studies appear to be at odds with the predictions of other contemporary models of consciousness (e.g., Cleeremans, 2008, 2011; Dehaene & Naccache, 2001; Lamme & Roelfsema, 2000), most of which would instead predict that repeated presentations of the same masked stimulus should increase availability to awareness. Indeed, according to Lamme and Roelfsema (2000), in the absence of a mask, the neural activation elicited by the stimulus propagates forward in the brain until it reaches higher areas, which then send feedback to the lower areas by means of recurrent interactions. Such re-entrant processing is assumed to maintain stimulus activation and ensure their stability, hence enabling awareness. However, when a mask is presented immediately after a brief stimulus, re-entrant processing—and hence awareness—is interrupted because the stimulus-driven activation in the lower areas is replaced by activation from the mask, so resulting in an absence of coherent feedback. Thus, on this account, if a single masked stimulus is presented, re-entrant processing is impaired and so is conscious access. However, if this masked stimulus is rapidly followed by another masked stimulus, recurrent processing should be possible, and this should in turn result in an increase in awareness: The higher areas activated by the first stimulus could then send feedback to the lower areas activated by the second (prime) stimulus. Thus, the Recurrent Processing Theory (RPT) of Lamme would predict graded increases in both priming and in availability to awareness as the number of repetitions of a masked stimulus increases. The same holds for Cleeremans's Quality of Representation (QoR) account (Cleeremans, 2008, 2011), which would likewise predict, graded increases in both priming and availability to consciousness when the stimulus is of low quality.

The global workspace theory (GWT) of Dehaene and Naccache (2001) predicts the same effect, but through a different neural account. According to GWT, conscious access arises when the parieto-frontal network is activated by the stimulus and sends feedback to the specific modules involved in the task. In GWT, consciousness is characterized as being all or none: A stimulus can elicit a conscious representation only when (1) it receives top-down attentional amplification and (2) it is sufficiently strong to activate the parieto-frontal network. On this basis, we can predict that when the masked stimuli are attended and the inter-stimulus interval is shorter than a few hundreds milliseconds, the weak activation evoked by the first stimulus would not completely disappear when the second is presented, and the successive activations should therefore accumulate. When the total activation becomes sufficiently strong to activate the parieto-frontal network, this would result in a conscious percept. Thus, GWT would predict a repetition-dependent graded increase in priming and a more non-linear, sharp transition between unconscious and conscious processing after a sufficient number of repetitions has taken place.

In this light, the purpose of the present study was to investigate the effects of a repeated masked stimulus with a more controlled methodology than used by either Marcel (1983) or Wentura and Frings (2005). To do so, we manipulated the number of presentations of a masked stimulus in two visibility tests (an objective measure and the subjective PAS scale from Ramsøy & Overgaard, 2004), using a numerical priming paradigm (Dehaene et al., 1998). The objective visibility test and the priming task both involved comparing the presented digit (either the prime or the target digit depending on the task) to a fixed reference of 5. If the digit was smaller than 5, participants were instructed to respond with the left index; if the digit was larger than 5, participants were instructed to respond with the right index. Similar to the design of Marcel (1983), the two kinds of tasks (i.e. visibility and priming tasks) were randomly interleaved in the same blocks. However, information indicating which task had to be performed was presented later in the trial in comparison with the original study. Indeed, the cue ("detection" on the prime or "lexical decision" on the target) was presented at the beginning of the trial in the Marcel study, which in our view was not sufficient to promote continuous attention to the masked primes during the lexical decision task. As mentioned previously, Marcel also used a tone warning signal between the final prime and the target, which makes it possible to withhold attention until the occurrence of the sound. In our study, participants knew which task to perform only when the target was displayed on the screen. If the target was a number, they had to perform the task on this target (priming task). Conversely, if the target was a letter, they had to perform the task on the (repeated) prime (visibility test). Moreover, in the priming task, we compared three different prime-target relationships in order to assess the processing level at which both the priming effect and the accumulation of activation occur. Indeed, Naccache et al. (2002) proposed that the global priming effect may be decomposed in two separate priming effects that correspond to different levels of processing of the masked primes: a visual and a motor effect. The visual effect can be quantified by subtracting reaction times to congruent repeated trials (e.g., both the prime and the target are "4") from the reactions times to congruent non-repeated trials (e.g., the prime is "4" and target is "1"): in both cases, the primes evoke the same response as the target, but they are only visually identical in the congruent repeated trials. The motor effect can likewise be assessed by subtracting the reaction times to congruent non-repeated trials (e.g. the prime is "4" and target is "1") from the reactions times to incongruent trials (e.g. the prime "4" and target is "6"): in both cases, the primes are visually different from the target, but they evoke a different response only in the incongruent trials. Prime digits were always practiced as targets, which reinforced pure visuo-motor processing (Damian, 2001). While Marcel (1983) and Wentura and Frings (2005) used a semantic priming paradigm, we thus opted for a visuo-motor priming task. The underlying idea was to assess a level of processing that was more robustly evidenced in the literature (see Kouider & Dehaene, 2007 for a review) and is the basis of any higher type of processing: perceptual processing of the primes is required to reach any higher level of processing such as semantic processing.

2. Method

2.1. Participants

Twenty-five students (age range: 18–35) from the Université Libre de Bruxelles participated in this study. They reported normal or corrected-to-normal vision and were naive as to the purpose of the experiment. They received credit for a psychology course or were paid (10€) for their participation.

2.2. Apparatus and stimuli

Stimuli were displayed on a CRT monitor (Philips 107T, resolution 800 × 600) at a refresh rate of 75 Hz, and controlled by E-prime 1.1 (PST software, Pittsburgh, USA). Subjects viewed the screen from a distance of 60 cm. Responses were executed with the index fingers of both hands and collected through the two extreme keys of a button box.

All stimuli were black and displayed at the center of the screen on a gray background. Both prime and target stimuli were the Arabic numbers 1, 4, 6 and 9 presented in a Courier New font (size 18). The six different masks consisted of the superposition of (1) a hash mark and (2) a sign randomly chosen amongst £, $, €, §, %, @, also presented in the Courier New font (size 20). The order of the masks varied randomly within and between trials.

2.3. Design and procedure

In the priming task, participants were instructed that they would see a target digit (1, 4, 6 and 9) and that they were to compare it to a fixed reference of 5. They had to press the right button for targets larger than 5 and the left button for targets smaller than 5 as fast and as accurately as possible. In the visibility task, participants were instructed that they would see a digit followed by a letter at the center of the screen. Instructions stressed that (1) the digit would be very difficult to see because of its short duration and the presence of other signals before and after them, and that (2) the digit could be repeated 1, 3, 8 or 20 times. We assessed prime visibility using both a subjective and an objective measure on each trial. For the objective task, participants were instructed to apply the same instructions to the repeated masked digit as in the priming task. If they were unable to categorize the digit primes, they were asked to guess. For the subjective task, we used the PAS scale (Ramsøy & Overgaard, 2004), in which participants report on the quality of their subjective experience through a 4-point scale: ‘‘No experience’’, (2) ‘‘Brief glimpse’’, (3) ‘‘Almost clear experience’’, and (4) ‘‘Absolutely clear experience’’.

The priming and awareness trials were randomly interleaved in the same blocks. Participants were instructed to be ready to perform a task either on the invisible or on the visible digit on each trial. Importantly, information indicating which task was to be performed on any particular trial was conveyed by the identity of the target stimulus (a digit or a letter). If the target was a digit, they had to perform the task on this target (priming task). Conversely, if the target was a letter, they had to perform the task on the prime (visibility tests). Thus, participants only discovered which task they had to perform at the end of the trial, which made top-down attention to the repeated masked stimuli during the priming task necessary.

To prepare participants to our difficult task, a series of three training sessions were performed before the experimental blocks. The first training session consisted of the visibility tests. The second consisted of the priming task. Participants performed 10 trials of each task in two separate and successive training sets. Finally, the third training session consisted of a mixture of the trials of the two preceding training sessions, with 14 trials: 8 priming trials (60%) and 6 awareness trials (40%).

Relative to trial onset, we used a fixed onset delay of the target across all conditions of prime repetitions so that participants could predict exactly when the target was going to appear. Thus, the sequence of each trial for the priming task consisted of 43 visuals displays (see Fig. 1): (1) a fixation cross presented for 500 ms, (2) a forward mask shown for 80 ms, (3) the prime (which could either be an Arabic number or a blank screen) presented for 26.66 ms, and (4) a backward mask displayed for 80 ms. The couple formed by the prime and the backward mask was repeated 20 times (events 3–42). Finally, the target was presented until participants had responded or until 1000 ms had elapsed (43). A feedback (‘‘try to be faster’’) was presented in red for 1500 ms when the response had not been given sufficiently fast (i.e. for RT > 1000 ms). The interstimulus interval was a blank screen presented for 500 ms. Further, in the condition in which the prime was only presented once, only the final prime display contained an Arabic number, with the 19 earlier events consisting of blank screens. Similarly for the conditions in which primes were presented 3 or 8 times, only the final 3 or the final 8 prime displays contained an Arabic number, with the 17 or 12 earlier events consisting of a blank screen. Finally, in the condition with 20 prime repetitions, each prime display contained an Arabic number. Note that all numerical primes were identical within a trial. The sequence of events occurring within a single trial in the visibility task was the same as in the priming task, except that targets were replaced by a random letter chosen from the alphabet. The letter target was presented until the response to the prime's category had been completed. Immediately thereafter, a display containing a description of the 4-point scale of the PAS was presented on the screen. Participants were instructed to indicate their subjective experience of the prime orally. The experimenter manually recoded participants' responses with one of 4 keys of the keyboard.

The whole Experiment consisted of 640 trials subdivided in 16 blocks of 40 trials, each block contained 24 priming trials (60%) and 16 visibility trials (40%). In the priming trials, there were 16 possible combinations of prime-target pairs: 4 possible targets (1, 4, 6 and 9) $\times$ 4 possible primes (1, 4, 6 and 9). Out of these 16 combinations, by definition there are 4 congruent-repeated pairs (e.g. 4–4), 4 congruent-non-repeated pairs (e.g. 1–4) and 8 incongruent pairs (e.g. 6–4). To ensure an equal amount of trials in each of these 3 congruency conditions, we presented the congruent-repeated and the congruent-non-repeated combinations 8 times and the incongruent combinations 4 times, leading to 32 trials in each condition. Furthermore, we manipulated the number of prime presentations (1, 3, 8 or 20 prime presentations). In sum, there were 384 priming trials (32 trials $\times$ 3 congruency conditions $\times$ 4 numbers of prime presentations). In the visibility trials, there were also 4 possible primes (1, 4, 6 and 9), but the target was a random letter. The number of prime presentations was also manipulated (1, 3, 8 or 20 prime presentations). We presented each possible combination (4 possible primes $\times$ 4 numbers of prime presentations) 16 times, summing up to 256 awareness trials.

3. Results

Median reaction times for correct responses (96% of the trials) of the priming task were submitted to a repeated measures ANOVA with Number of prime repetitions (1, 3, 8 or 20 times) and Congruency (congruent-repeated, congruent-non-

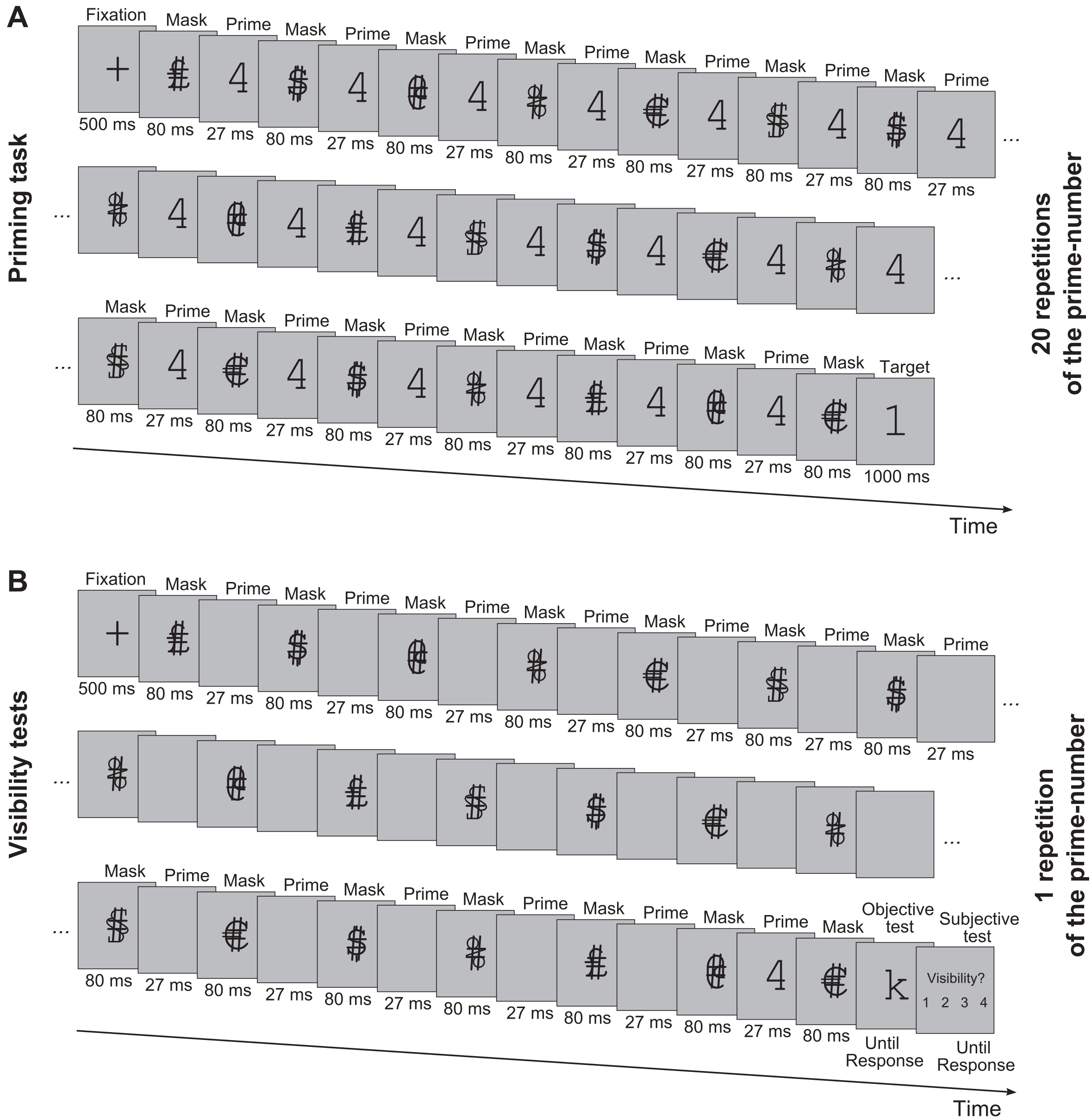

Fig. 1. Experiment design. Each trial always contained 20 presentations of both the prime display and the backward mask, but the prime display could be an Arabic number or a blank screen. In the condition with 20 prime repetitions (A), each prime display contained an Arabic number. In contrast, in the condition with 1 presentation of the prime (B), only the last prime display contained an Arabic number, the 19 others were a blank screen. The conditions with 3 and 8 repetitions of the prime number were constructed with the same logic. In the priming task (A), participants were asked to compare the target with the reference 5. In the visibility tests (B), participants were asked to compare the successive primes with the reference 5, and then, to choose between the 4 levels of subjective visibility of the PAS scale.

repeated or incongruent) as within-subject factors. Results of this analysis are plotted in Fig. 2. A main effect of Congruency was observed ($F(2,48) = 19.72$, $p < .001$). Planned comparisons indicated that the priming effect was only visual ($F(1,24) = 25.17$, $p < .001$, magnitude effect 14.23 ms), and did not reach the motor level of processing ($F < 1$). Crucially, this Congruency effect interacted significantly with the Number of prime repetitions ($F(6,144) = 4.96$, $p < .001$). Planned comparisons indicated that the visual priming was highly significant for 8 and 20 prime repetitions ([8 presentations: $t(24) = 4.21$, $p < .001$; magnitude effect 21.7 ms], [20 presentations: $t(24) = 4.57$, $p < .001$; magnitude effect 31.3 ms]). For 3 prime presentations, the magnitude of the visual priming was 9 ms but failed to reach significance ($t(24) = 1.56$, $p = .132$). All other priming effects (visual priming for one prime presentation and all motor priming effects) were not significant (all $ps > .27$). The same repeated measures analysis performed on error rates revealed no significant effects.

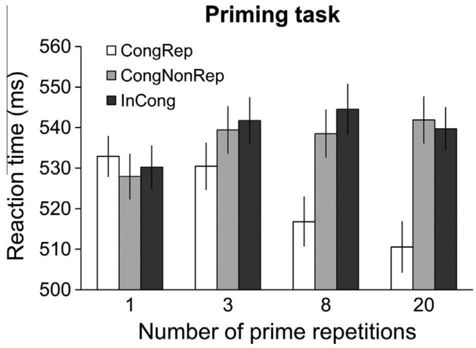

Fig. 2. Priming effect. Median reaction times were plotted separately for each condition of prime–target relationship and for each number of prime repetitions. Error bars represent one standard error of the mean.

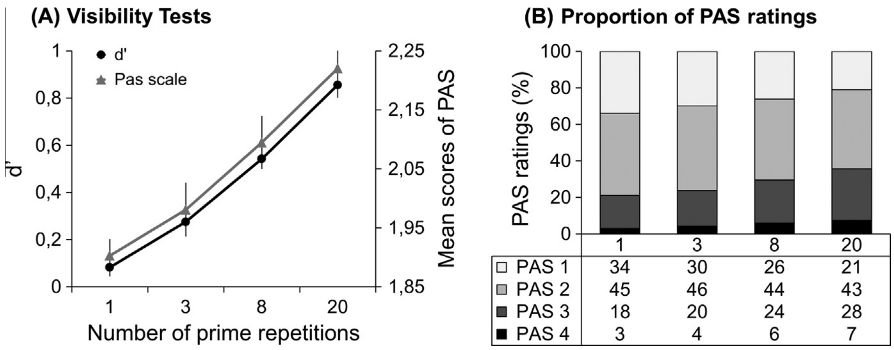

Fig. 3. (A): Objective and subjective visibility performance. d' Values (gray triangle) and mean scores of the PAS scale (black dot) were plotted separately for each number of prime repetitions. Error bars represent one standard error of the mean. (B) Proportion of each PAS rating as function of the number of prime repetitions.

To assess the visibility of the primes, individual d' values were submitted to a repeated measures analysis with Number of prime repetitions (1, 3, 8 or 20 times) as a within-subject factor. Results of this analysis are plotted in Fig. 3A. We observed a highly significant effect of the Number of prime repetitions; $F(3,72) = 18.85$, $p < .001$. A t test against the null mean for each Number of prime repetitions indicated that d' value was not significantly different from zero only for one presentation of the prime ([1 presentation: $t(24) = 1.47$, $p = .153$; $d' = 0.08$, accuracy = 51%], [3 presentations: $t(24) = 3.03$, $p = .006$; $d' = 0.28$, accuracy = 55%], [8 presentations: $t(24) = 6.05$, $p < .001$; $d' = 0.54$, accuracy = 60%], [20 presentations: $t(24) = 8.62$, $p < .001$; $d' = 0.86$, accuracy = 64%]).

Average PAS scores were submitted to a repeated measures analysis with Number of prime repetitions (1, 3, 8 or 20 times) as a within-subject factor. We also observed a highly significant effect of the Number of prime repetitions ($F(3,72) = 43.92$, $p < .001$).

4. Discussion

The assumed advantage of the repeated masked paradigm is to circumvent one of the most important methodological problems in the study of unconscious processing, which is that unconscious influences might be short-lived because the stimulus itself is very brief (Dupoux et al., 2008; Ferrand, 1996; Greenwald et al., 1996). In other words, the observed limits of subliminal processing might result not from the fact that such processing is unconscious, but rather from the fact that the stimuli themselves are very weak because of the specific methods used to degrade the signal (Barbot & Kouider, 2012; Wentura & Frings, 2005). The repeated making method was thus based on the idea that repeating the same masked stimulus would increase the total duration of an unconscious stimulus without increasing its availability to conscious access. Two other methods have been developed to increase the duration of a stimulus that remains unconscious: Tsuchiya & Koch, 2005's Continuous Flash Suppression (CFS) paradigm on the one hand, and Kouider et al., 2011's Gaze-Contingent Crowding (GCC) on the other hand. While it has now been well demonstrated that both methods make it possible to prolong the duration of the stimulus while maintaining it outside of awareness (Almeida et al., 2008; Bahrami et al., 2010; Faivre & Kouider, 2011), the effects of a repeated masked stimulus remain unclear and somewhat controversial. Indeed, Marcel (1983) and Wentura and Frings (2005) found that repeatedly presenting a masked stimulus improves priming without increasing perceptual awareness, suggesting that unconscious processing is preserved over time by using this method. However, contemporary theories of consciousness diverge regarding the effect of repeating the same masked stimulus. Both the Recurrent Processing Theory (RPT) of Lamme & Collaborators (e.g., Lamme, 2010; Lamme & Roelfsema, 2000) and Cleeremans's (2008, 2011) Quality of Representation (QoR) framework predict that both priming and awareness should gradually increase with stimulus strength in a repeated masking paradigm, at least when the stimulus is overall of low quality. The Global Workspace Theory (GWT) of Dehaene and Naccache (2001), Dehaene, Changeux, Naccache, Sackur, and Sergent (2006), Dehaene and Changeux (2011) would likewise predict a repetition-dependent graded increase in priming, but also a more non-linear, sharp transition between unconscious and conscious processing after a sufficient number of repetitions has taken place. Higher-order theories (HOT) of consciousness (Dienes, 2004; Dienes, 2008; Lau & Rosenthal, 2011; Rosenthal, 2005) would instead predict that a graded, repetition-dependent increase in priming is possible in the absence of awareness.

The goal of the present study was thus to examine the effect of repeating a strongly masked stimulus on both priming and subjective/objective awareness with a better methodology than previous studies. Consistent with the RPT and the GWT theories of consciousness, our results demonstrate a systematic increase in perceptual awareness, using both objective and subjective measures: both tests showed an increase in awareness with the number of prime repetitions, beginning at chance level performance for a single presentation and gradually increasing with up to 20 repetitions, a condition for which participants exhibited a high ability to discriminate. Therefore, multiple presentations of a masked stimulus enable conscious access where a single presentation does not. Noteworthy, the proportion of visible trials according to the subjective measure (PAS responses 3 and 4) was 35% for 20 repetitions and it was 21% for one repetition (see Fig. 3). We might therefore question whether the strong priming observed for 20 repetitions and the absence of a priming effect in the case of only one repetition stems from the increased proportion of visible trials in the former case (+14%). Thus, it remains possible that the repetition-dependent increased priming might on some trials be associated with unconscious processing at a subjective threshold of awareness even though both subjective and objective awareness increased with prime repetitions based on all trials. Further studies using a subjective visibility measure on each priming trial would be helpful to explore whether priming also increases through repetition for invisible trials only (e.g. PAS response 1 or 2).

The increase of both objective and subjective awareness was gradual rather than non-linear (see Fig. 3), which is more consistent with the Recurrent Processing Hypothesis of Lamme and Roelfsema (2000), Lamme (2010) and with Cleeremans' QoR framework. According to the model of Lamme, when a single masked stimulus is presented, re-entrant processing is impaired and so is conscious access. However, when this masked stimulus is rapidly followed (i.e. before the activation from the stimulus has completely vanished) by another masked stimulus, recurrent processing should no longer be precluded because the higher areas activated by the first stimulus could then send feedback to the lower areas activated by the second stimulus. Recurrent processing should be reinforced by each repetition of the same masked prime and this might result in turn in an increase in awareness. Although the increase of awareness with prime repetition might be due to this form of physiological summation (Lamme, 2010; Lamme & Roelfsema, 2000), another, intriguing, possibility is that the increase in prime awareness might simply stem from probability summation. According to this hypothesis, which is congruent with the Partial Awareness Hypothesis (Kouider, de Gardelle, Sackur, & Dupoux, 2010), the probability that the prime reaches awareness based on a unique prime presentation increases with the total number of prime presentations. In our study, we found that with a single presentation of the prime, the average proportion of correct detections is 0.51. This value is very close to the guessing probability of 0.50. If we assume that in the singe-presentation condition, the prime reaches awareness and is therefore correctly detected with a proportion of only .01, then, based on simple probability summation, the probability of the prime being detected and reaching awareness at least once in N repetitions is $.01 * N$. For $N = 3$, that probability is 0.03; for $N = 8$, it is 0.08; and for $N = 20$, it is 0.20. When these values are added to the guessing probability of 0.5, the resulting values of 0.53, 0.58 and 0.70 are in fact close to the actual values of 0.55, 0.60 and 0.64. Further studies manipulating the Inter-Prime-Interval (IPI) might help to disentangle the two hypotheses, or the respective contributions of their purported underlying mechanisms. According to the continuous physiological accumulation hypothesis, the increase of awareness with prime repetition would be affected by the duration of IPI. If the IPI is very long (e.g. 2 s), the weak representation evoked by the first prime would completely vanish from the brain before the next prime would appear (see Gaillard et al., 2009). In this case, increase of awareness with repetition would not occur anymore. Conversely, the probability summation hypothesis predicts that the IPI would not affect the increase of awareness with prime repetition. Indeed, this hypothesis concerns the conscious perception of the prime at each individual repetition, and thus irrespectively of the delay inserted between each prime repetition.

It is important to note that the present study was an exact replication neither of Marcel (1983) nor of Wentura and Frings (2005). For this reason, critical methodological differences between our study and those prior reports might explain why we found an increase of awareness with prime repetition and they did not. The most important difference is that they used a larger set of more complex stimuli (i.e. words) to examine semantic priming, whereas we used only 4 prime digits practiced as target to examine visuo-motor priming. Stimulus set size and stimulus complexity might influence conscious access (Kouider et al., 2010; Windey, Gevers & Cleeremans, 2013), and might thus also affect the number of stimulus repetitions necessary to have a conscious percept. However, we consider it unlikely that repeating simple masked stimuli would increase availability to awareness while repeating complex masked stimuli would not. An increase of awareness with the number of masked prime presentations is predicted by extant leading theories independently of the complexity of the stimuli.

While our study suggests that repeating exactly the same masked stimulus over time seems not very efficient to prevent conscious access, presenting slightly different stimuli successively might be more efficient. Indeed, Jaskowski, Skalska, and Verleger (2003) found increased priming without increasing awareness when they successively presented several stimuli arranged so that the next stimulus in the sequence was slightly larger than the previous ones. This way, each stimulus also acted as a metacontrast mask for the preceding one. Nevertheless, Jaskowski et al. (2003) only used four repetitions of the stimulus. Thus, it remains an open issue whether an improvement of conscious access might occur with a larger amount of repetitions of slightly different primes. Systematically comparing these two repeated masking methods would be necessary to determine the extent to which they might differ in precluding conscious access.

Finally, only visual priming increased with repetitions, while motor priming failed to influence behavior, suggesting that priming could only reach a low level of processing in our paradigm and that perceptual and motor priming might be dissociated from each other with masked prime repetition. Unlike previous studies using the same numerical comparison task (e.g., Del Cul, Dehaene, & Leboyer, 2006; Kouider & Dehaene, 2009; Naccache et al., 2002), we also failed to find unconscious priming for a single presentation of the masked prime. Importantly however, and in contrast to these prior studies, we mixed two different kinds of trials within the same blocks: the priming trials for which instructions required fast and accurate response to a visible target, and the visibility trials for which instructions required accurate responding to the strongly masked primes. Although the task was the same in both situations (i.e. categorize an Arabic number), our design might be considered as involving a dual-task situation because participants were required to execute the categorization task on either the masked prime or the target depending on information conveyed by the target: if the target was a number then they were required to categorize it, and if not they were required to use the information they had perceived about the prime to carry out the same task. Ansorge (2004) directly tested the impact of dual-task interference on unconscious priming and observed that unconscious processing was significantly reduced in a dual-task condition compared to a single-task condition. In the same way, it might be possible that our dual-task design had a detrimental effect on unconscious prime processing. The absence of unconscious priming might also be due to the specific masks we used to degrade the stimulus signal. Indeed, whereas previous studies used either strings of random letters or geometric forms, we opted for stronger masks consisting in the superposition of a hash-mark and a sign randomly chosen among different symbols (i.e. £, $, €, §, %, @).

To conclude, our results show, in contrast to previous studies using a similar design, that successive repetitions of a strongly masked stimulus in a priming task as well as in two visibility tests increases both priming and perceptual awareness. Our study thus suggests that the repeated masking method seems inefficient to improve stimulus signal without increasing visibility. This finding is also consistent with the Recurrent Processing Theory of Lamme and Roelfsema (2000), Lamme (2010) and with the probability summation hypothesis, according to both of which perceptual awareness should increase with the repetition of an unconscious masked stimulus.

Funding

Anne Atas, Astrid Vermeiren and Axel Cleeremans are supported by grants from the National Fund for Scientific Research (FNRS, Belgium). This research was partly supported by IAP program P7/33 from the Belgian Federal Science Policy Office (BELSPO). The authors declare no conflicts of interest that might be interpreted as influencing the research, and APA ethical standards were followed in the conduct of the study. Correspondence should be addressed to Anne Atas (aatas@ulb.ac.be or aatas86@gmail.com).

Acknowledgments

We thank Wim Gevers and Zoltan Dienes for their helpful comments on the manuscript.

References

Almeida, J., Mahon, B. Z., Nakayama, K., & Caramazza, A. (2008). Unconscious processing dissociates along categorical lines. *Proceedings of the National Academy of Sciences of the United States of America, 105*(39), 15214–15218.
Ansorge, U. (2004). Top-down contingencies of nonconscious priming revealed by dual-task interference. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 57A*, 1123–1148.
Avons, S. E., Russo, R., Cinel, C., Verolini, V., Glynn, K., McDonald, R., et al (2009). Associative and repetition priming with the repeated masked prime technique: No priming found. *Memory & Cognition, 37*(1), 100–114.
Bahrami, B., Vetter, P., Spolaore, E., Pagano, S., Butterworth, B., & Rees, G. (2010). Unconscious numerical priming despite interocular suppression. *Psychological Science, 21*(2), 224–233.
Barbot, A., & Kouider, S. (2012). Longer is not better: Nonconscious overstimulation reverses priming influences under interocular suppression. *Attention, Perception, & Psychophysics, 74*(1), 174–184.
Breitmeyer, B. G., & Ögmen, H. (2006). *Visual masking: Time slices through conscious and nonconscious vision*. New York: Oxford University Press.
Cleeremans, A. (2008). Consciousness: The radical plasticity thesis. *Progress in Brain Research, 168*, 19–33.
Cleeremans, A. (2011). The radical plasticity thesis: How the brain learns to be conscious. *Frontiers in Psychology, 2*, 86.
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., & Changeux, J. P. (2011). Experimental and theoretical approaches to conscious processing. *Neuron, 70*(2), 200–227.
Dehaene, S., Changeux, J. P., Naccache, L., Sackur, J., & Sergent, C. (2006). Conscious, preconscious, and subliminal processing: A testable taxonomy. *Trends in Cognitive Sciences, 10*(5), 204–211.

Dehaene, S., & Naccache, L. (2001). Towards a cognitive neuroscience of consciousness: Basic evidence and a workspace framework. *Cognition, 79*(1–2), 1–37.
Dehaene, S., Naccache, L., Le Clec, H. G., Koechlin, E., Mueller, M., Dehaene-Lambertz, G., et al (1998). Imaging unconscious semantic priming. *Nature, 395*(6702), 597–600.
Del Cul, A., Dehaene, S., & Leboyer, M. (2006). Preserved subliminal processing and impaired conscious access in schizophrenia. *Archives of General Psychiatry, 63*(12), 1313–1323.
Dienes, Z. (2004). Assumptions of subjective measures of unconscious mental states: Higher order thoughts and bias. *Journal of Consciousness Studies, 11*, 25–45.
Dienes, Z. (2008). Subjective measures of unconscious knowledge. *Progress in Brain Research, 168*, 49–64.
Dupoux, E., de Gardelle, V., & Kouider, S. (2008). Subliminal speech perception and auditory streaming. *Cognition, 109*(2), 267–273.
Faivre, N., & Kouider, S. (2011). Multi-feature objects elicit nonconscious priming despite crowding. *Journal of Vision, 11*(3).
Ferrand, L. (1996). The masked repetition priming effect dissipates when increasing the inter-stimulus interval: Evidence from word naming. *Acta Psychologica, 91*(1), 15–25.
Gaillard, R., Dehaene, S., Adam, C., Clemenceau, S., Hasboun, D., Baulac, M., et al (2009). Converging intracranial markers of conscious access. *PLoS Biology, 7*(3), e61.
Greenwald, A. G., Draine, S. C., & Abrams, R. L. (1996). Three cognitive markers of unconscious semantic activation. *Science, 273*(5282), 1699–1702.
Jaskowski, P., Skalska, B., & Verleger, R. (2003). How the self controls its "automatic pilot" when processing subliminal information. *Journal of Cognitive Neuroscience, 15*, 911–920.
Kiefer, M., & Brendel, D. (2006). Attentional modulation of unconscious "automatic" processes: Evidence from event-related potentials in a masked priming paradigm. *Journal of Cognitive Neuroscience, 18*, 184–198.
Kouider, S., Berthet, V., & Faivre, N. (2011). Preference is biased by crowded facial expressions. *Psychological Science, 22*(2), 184–189.
Kouider, S., de Gardelle, V., Sackur, J., & Dupoux, E. (2010). How rich is consciousness? The partial awareness hypothesis. *Trends in Cognitive Sciences, 14*, 301–307.
Kouider, S., & Dehaene, S. (2007). Levels of processing during non-conscious perception: A critical review of visual masking. *Philosophical Transactions of the Royal Society of London Series B, Biological sciences, 362*(1481), 857–875.
Kouider, S., & Dehaene, S. (2009). Subliminal number priming within and across the visual and auditory modalities. *Experimental Psychology, 56*(6), 418–433.
Lamme, V. A. F. (2010). How neuroscience will change our view on consciousness. *Cognitive Neuroscience, 1*(3), 204–220.
Lamme, V. A., & Roelfsema, P. R. (2000). The distinct modes of vision offered by feedforward and recurrent processing. *Trends in Neurosciences, 23*(11), 571–579.
Lau, H., & Rosenthal, D. (2011). Empirical support for higher-order theories of conscious awareness. *Trends in Cognitive Sciences, 15*, 365–373.
Marcel, A. J. (1983). Conscious and unconscious perception: Experiments on visual masking and word recognition. *Cognitive Psychology, 15*(2), 197–237.
Naccache, L., Blandin, E., & Dehaene, S. (2002). Unconscious masked priming depends on temporal attention. *Psychological Science, 13*(5), 416–424.
Pasquali, A., Timmermans, B., & Cleeremans, A. (2010). Know thyself: Metacognitive networks and measures of consciousness. *Cognition, 117*, 182–190.
Ramsøy, T., & Overgaard, M. (2004). Introspection and subliminal perception. *Phenomenology and the Cognitive Sciences, 3*(1), 1–23.
Rosenthal, D. M. (2005). *Consciousness and mind*. Clarendon Press.
Schmidt, T. (2002). The finger in flight: Real-time motor control by visually masked color stimuli. *Psychological Science, 13*, 112–118.
Tsuchiya, N., & Koch, C. (2005). Continuous flash suppression reduces negative afterimages. *Nature Neuroscience, 8*(8), 1096–1101.
Vermeiren, A., & Cleeremans, A. (2012). The validity of d′ measures. *PloS One, 7*.
Vorberg, D., Mattler, U., Heinecke, A., Schmidt, T., & Schwarzbach, J. (2003). Different time courses for visual perception and action priming. *Proceedings of the National Academy of Sciences of the United States of America, 100*(10), 6275–6280.
Wentura, D., & Frings, C. (2005). Repeated masked category primes interfere with related exemplars: New evidence for negative semantic priming. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31*(1), 108–120.
Windey, B., Gevers, W., & Cleeremans, A. (2013). Subjective visibility depends on level of processing. *Cognition, 129*, 404–409.