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Attentional modulation of perceptual stabilization

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Perceptual priming is generally regarded as a passive and automatic process, as it is obtained even without awareness of the prime. Recent studies have introduced a more active form of perceptual priming in which priming for a subsequent ambiguous stimulus is triggered by the subjective percept, that is, interpretation of a previous ambiguous stimulus. This phenomenon known as stabilization does not require a conscious effort to actively maintain one perceptual interpretation. In this study, we show that distraction of attention, during and even after the prime presentation, interferes with the build-up of perceptual memory for stabilization. This implies that despite the apparent automaticity, stabilization involves an active attentional process for encoding and retention. The disruption during the encoding can be attributed to the reduction in sensory signals for the prime. However, the disruption during the retention suggests that the implicit memory trace of the prime necessitates the attentional resource to fully develop. The active nature of the build-up of perceptual memory for stabilization is consistent with the idea that perceptual memory increases its strength gradually over a few seconds. These findings suggest that seemingly automatic and effortless cognitive processes can compete with online perceptual processing for common attentional resources.

Keywords: priming; attention; bistable perception; implicit memory; motion stabilization

1. INTRODUCTION

Perception of a stimulus is often facilitated by a recent exposure to an associated stimulus. The facilitation is typically characterized as a faster and/or more accurate response to a related stimulus as compared to an unrelated stimulus (Tulving & Schacter 1990). This facilitation is called *perceptual priming* when the facilitation concerns a relatively low-level perceptual feature (e.g. visual motion). Perceptual priming is considered as a form of implicit memory, since it occurs even without an explicit memory of the past percept (Hamann & Squire 1997). Moreover, the encoding process does not require conscious awareness of the prime. This has been shown, for example, in the studies using backward masking, which renders the prime invisible for the observers (Klotz & Wolff 1995; Bar & Biederman 1998; Breitmeyer *et al.* 2004).

Recently, a new form of perceptual priming, which *does* depend on the conscious percept, has been discovered. A hallmark of this percept-dependent priming is the stabilization of a percept for bistable stimuli, which have two possible perceptual interpretations (e.g. a Necker Cube). When a bistable stimulus is presented briefly and repeatedly after blank intervals, the percept for the stimulus is stabilized to one interpretation (Orbach *et al.* 1963; Leopold *et al.* 2002; Maier *et al.* 2003). This stabilization effect is due to the repetition of the percept-dependent perceptual priming, which we have called *perceptual sensitization* (Kanai & Verstraten 2005). Each brief presentation of a stimulus serves as a prime for the next presentation.

This sensitization effect differs from classical perceptual priming in several ways. First, the sensitization depends on the subjective percept for the prime, whereas the conscious percept of a prime itself is often not required for classical priming. Second, the sensitization shows a gradual development over time. That is, the facilitation is weak just after the presentation of a prime, but gradually develops over time (about 3–5 s, see Kanai & Verstraten 2005). This contrasts with the more classical types of perceptual priming, which is most effective immediately after the prime presentation (e.g. Pinkus & Pantle 1997; Jiang *et al.* 2002). These differences suggest that the sensitization involves a more active construction of the memory trace.

If sensitization is indeed a more active construction, it is expected that attentive mechanisms are required for the encoding and retention of perceptual memory. In the present study, we test whether the sensitization requires attention both for encoding and retention. To do so, we examined whether sensitization is degraded when attention is diverted to a second task (a letter identification task) compared to when full attention is given for processing the prime. We show that the distraction of attention during the presentation of the prime or even during the prime-test interval interferes with the development of sensitization. This implies that a conscious percept of a prime as such is not sufficient for sensitization, and that full attention to the prime is essential for successful encoding and development of sensitization.

2. MATERIAL AND METHODS

(a) *Observers*

Eight observers who participated in the two experiments are presented in this study. One of the observers was the author RK, and other seven observers were naive as to the purposes of the experiments. Before the experiments, we conducted a screening test in which the observers had to report the percept for a counterphase grating and an unambiguously drifting

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grating. They were asked to report whether they perceived a grating as moving in one direction (left or right) or as ambiguous (flicker or oscillatory motion). With the screening test, we confirmed that the seven naive observers perceive the counterphase grating as a directional motion rather than a flicker or oscillatory motion in more than 80% of 100 trials. In the screening test, we intermixed 100 trials of counterphase condition with 100 trials of directional motion condition. For a pool of 21 observers, 15 observers satisfied this criterion, and the seven observers who participated in the present study were among the 15 observers who passed the screening test.

(b) *Apparatus*

Stimuli were generated on a Macintosh computer running MATLAB PSYCHTOOLBOX (Brainard 1997; Pelli 1997) and presented on a 22 in. CRT monitor. The refresh rate of the display was 75 Hz and the resolution 1280×1024 pixels. Stimuli were viewed from a distance of 57 cm. We used a linearized colour lookup table for gamma correction.

(c) *Stimuli and procedure*

The stimulus was a phase-shifting Gabor. The Gabor had a contrast of 1 (Michelson contrast), and the sigma of the Gaussian envelope was 2° and the spatial frequency was 1 cpd. Both the prime and the test stimulus were presented 6° below the fixation point (measured from the centre of the Gabor). We used an apparent motion version of counterphase stimuli. The directional motion was created by shifting the phase of the Gabor 90° every 40 ms, and the ambiguous motion by shifting the phase 180° every 80 ms. For both stimuli, the total presentation time was 320 ms, which means that the directional motion consisted of consecutive presentation of eight frames and the ambiguous motion consisted of four frames.

For the motion prime, both directional motion and ambiguous motion (both 320 ms in duration) were used and they were intermixed across trials. In a control experiment, we also used biased ambiguous stimuli, which were created by shifting the phase by 160°. The test stimulus was always ambiguous motion (i.e. 180° phase shifts).

In the first experiment (encoding), the blank interval between adaptation and the test was varied between 480, 2000 and 3000 ms. In the second experiment (retention and development), the blank interval was varied between 1000, 2000 and 3000 ms. In the second experiment, the shortest duration was replaced with a longer duration (1000 ms) in order to avoid direct interference of the attentional task (see below) with the processing of the prime.

In both experiments, the observers were asked to report both the direction of motion prime and the direction of test stimulus by pressing corresponding keys.

(d) *Attentional task*

Attention was manipulated by a concurrent task in which observers had to identify a letter presented at fixation for 80 ms. The letters were randomly chosen from A to Z in Helvetica and subtended approximately 1.5° (vertical) by 1.2° (horizontal). A mask was presented for 240 ms immediately after the target letter disappeared. The total duration of the letter target and mask (320 ms) coincided with the presentation of the prime-motion. In half the blocks, observers were required to perform the letter identification task and the motion task simultaneously. In the other half, they performed the motion direction task only. The letters and masks were presented also in the single task condition, but the observers were instructed to ignore the letters and masks and focus on the motion task. The block order was counterbalanced across and within observers.

3. RESULTS

(a) *Is attention necessary for the encoding of prime?*

We performed a dual task experiment in which observers had to identify a letter (80 ms) followed by a mask (240 ms, see figure 1*a*), while they had to report the perceived direction(s) of both the prime and the test stimulus. To ensure that observers were able to report the percept of the prime stimulus reliably, we kept the letter identification task easy (97.83%±0.39 (s.e.m.) % correct). The performance for the identification of the unambiguous motion was kept close to 100% correct (99.67%±0.3 (s.e.m.) % correct). This ensures that the observers can report their percept even in the dual task condition.

The results are shown in figure 1*b*,*c*. The percentage of trials in which the observers reported the same direction for the prime and the test is plotted as a function of the interval duration. Despite the relatively low-attentional demand for the task, the attentional manipulation resulted in a significant reduction of the sensitization. For the ambiguous primes, the sensitization in the dual task condition was attenuated compared to the full attention condition (figure 1*b*; A repeated measures of ANOVA shows a significant effect of attentional manipulation, $F_{1,14}=17.6$, $p<0.01$).

One potential concern regarding the results of adaptation to ambiguous motion is that in the dual task, observers might not be able to see the motion stimulus. If so, the observers would indicate the direction randomly and this would result in an apparent reduction of sensitization, because random responses would yield results close to chance level (50% line). However, the condition in which the prime was unambiguous controls for this potential concern. Performance for the motion discrimination task for the unambiguous prime was near 100% correct. This ensures that the observers are reporting the motion directions reliably in the dual task condition. As we have shown in a previous study, a brief adaptation to unambiguous motion produces not only the sensitization effect, but also a rapid form of motion aftereffect (see Anstis *et al*. 1998) for intervals shorter than 1 s (Kanai & Verstraten 2005). However, with a sufficiently long interval (>2 s), a robust sensitization is obtained. Therefore, the results for long intervals can tell us whether the reduction of sensitization can be attributed to the inability to report the perceived direction of the motion prime.

The results for the unambiguous prime are shown in figure 1*c*. With interval durations suitable for obtaining the sensitization (i.e. 2 and 3 s), a significant reduction of sensitization was observed. A repeated measures ANOVA shows that this pattern of interaction between the attentional condition and the interval duration is significant ($F_{2,14}=4.59$, $p<0.05$). Also, the reduction of rapid motion aftereffect was found for short durations in the dual task condition (figure 1*c*), showing attentional modulation of rapid motion aftereffect.

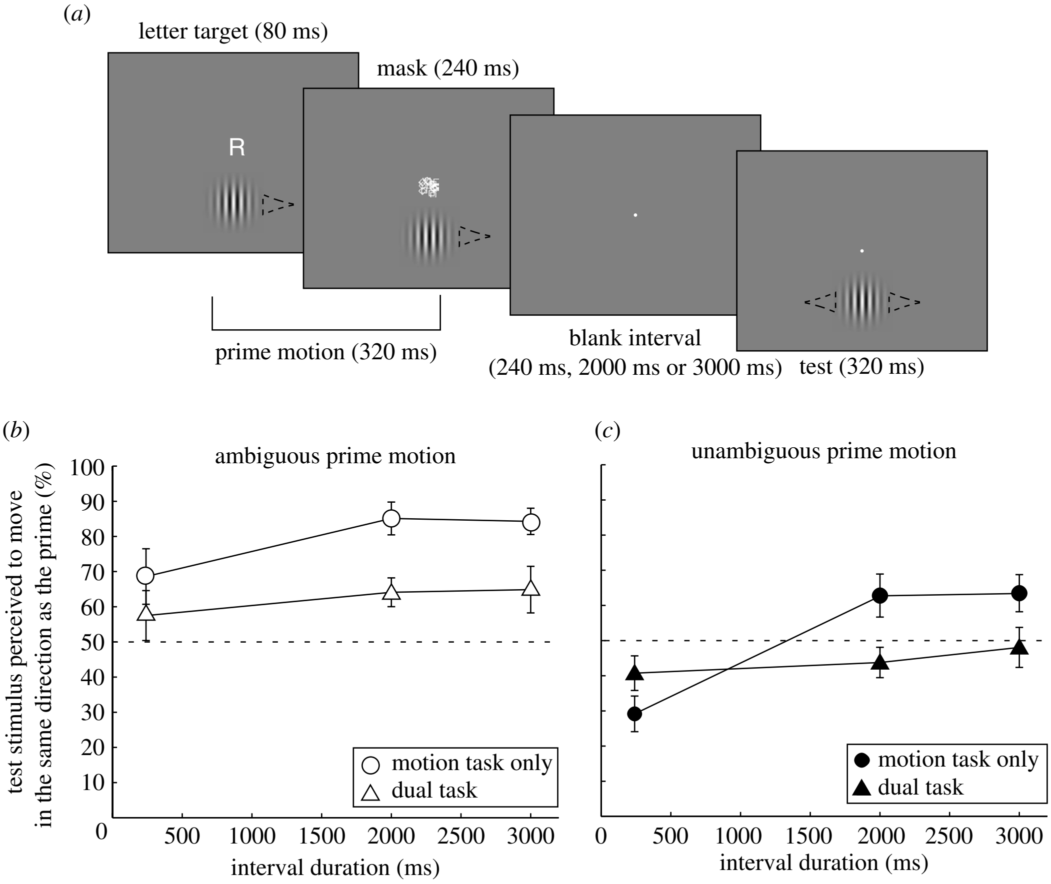

Figure 1. Attentional distraction during adaptation. (*a*) An illustration of a typical stimulus sequence. (*b*) The results of adaptation to *ambiguous* stimuli. Open circles indicate the results of the single task experiment and open triangles the results of the dual task experiment. (*c*) The results of adaptation to *directional* stimuli. Solid circles indicate the results of the single task experiment and solid triangles the results of the dual task experiment. Note that for the shortest interval duration, the effect of attention is reversed, indicating attentional modulation of rapid motion after effect. Error bars indicate one s.e.m. ($n=8$).

Another potential concern about this control experiment is that while subjects were able to report the direction of unambiguous motion correctly, it is not guaranteed that they were also aware of the direction of ambiguous motion under the dual task regime. To further confirm that subjects can correctly report the perceived direction of ambiguous motion, we used an intermediate condition, in which the prime was bistable but was biased either to the right or to the left. As outlined in the methods section, we created such bistable stimuli by shifting the phase of the sinewave by 160° either to the right or to the left.

In our screening test, we showed the biased ambiguous motion to subjects and asked them to report the perceived direction of the stimulus. Each observer completed a total of 40 trials. To ensure that the bias was effective, we selected subjects who reported seeing the direction consistent with the bias on at least 70% of trials. Using this criterion, six out of a total of nine tested observers were selected and participated the main experiment as described below. The three subjects that we did not include a strong internal bias towards rightward motion. Indeed on more than 80% of trials, they reported rightward motion (see Watanabe & Cole 1995).

This control condition with the biased stimuli was basically the same as the experiments reported above. However, we used only one prime-test interval (4 s) that is effective for inducing stabilization. Both a single task experiment and a dual task experiment were conducted, and their order was counterbalanced across the six observers. The attentional task was also identical to previous experiments. Each observer performed 40 trials for each condition.

The results are summarized in figure 2. The effect of bias measured as the percentage of trials in which the prime was perceived in the biased direction did not differ between the single and dual task conditions (figure 2*a*; 75.4% versus 78.7%, $T_5=-1.22$, $p>0.05$). This indicates that the biased prime was processed in a similar manner even when attention is engaged in the letter task. Moreover, this result supports the idea that the conscious percept of an ambiguous prime is not disrupted by a relatively easy concurrent task. Despite the lack of difference in the perception of the prime, the stabilization was drastically reduced by the attentional task (figure 2*b*; 70.8% versus 52.8%, $T_5=2.67$, $p<0.05$).

This set of control experiments indicates that the reduction in sensitization cannot be attributed to the inability to perceive the prime as a result of the attentional load. Instead, the results strongly support the idea that sensitization is dependent on the attentional resources available for processing the prime.

(b) *Is attention necessary for the development of sensitization?*

The retention of perceptual memory in sensitization seems to occur in a rather automatic fashion; it occurs usually without a conscious effort to maintain the previous

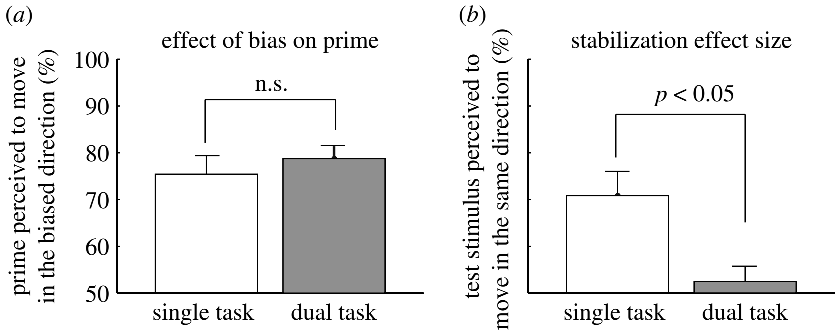

Figure 2. Attentional distraction during adaptation to a weakly biased prime. (*a*) The mean percentage of trials in which the prime was perceived in the biased direction. (*b*) The effect size of stabilization. The mean percentage of trials in which the test stimulus was perceived in the same direction as the perceived direction of prime. Error bars indicate one s.e.m. ($n=6$).

percept. This automaticity is further supported by the fact that the sensitization is not disrupted by a brief presentation of an intervening stimulus (Maier *et al.* 2003). As we have discussed earlier, sensitization is not fully effective immediately after the prime, but it develops gradually over time. This implies that sensitization is achieved via an unconscious process during the interval between the prime and test. In the next experiment, we test whether this apparently automatic process is modulated by a concurrent attentional task. To do so, we imposed the same attentional task as in the previous experiments during the blank intervals (figure 3*a*). The letter target was presented in the middle of the interval duration (e.g. for 2 s intervals, the target appeared 1 s after the offset of the prime), and again the observers were required to identify the letter target in the dual task condition. Although there is no physical stimulus during the blank interval to be attended, the unconscious process could still be operating on the memory trace produced by the prime. If this process requires attentional resources, distraction of attention during this period should interfere with this process.

The results are shown in figure 3*b*,*c*. For the ambiguous prime (figure 3*b*), the attentional manipulation resulted in a reduction of the sensitization for all the ISIs tested (a repeated measures ANOVA showed a significant effect of attentional manipulation, $F_{1,14}=6.89$, $p<0.05$). Neither the interval duration, nor the interaction between the attentional manipulation and the interval was significant (both $F<1$).

As we have argued earlier, the unambiguous condition serves as a control for the visibility of the prime. The performance for the motion discrimination task was close to 100% (98.34%). The sensitization observed at the interval durations of 2 and 3 s was reduced when the letter task was performed. A repeated measures ANOVA shows a significant interaction between the attentional manipulation and the interval duration ($F_{2,14}=5.18$, $p<0.05$). The attentional manipulation itself did not reach significance ($F_{1,14}=3.45$, $p=0.106$). However, the data shows the non-significant trend that the concurrent task decreases the frequency that observers report the same-direction percept. The interval duration itself was not significant ($F_{2,14}<1$), due to the use of long interval durations in which the rapid aftereffect is not prominently present, if at all.

Taken together, these results show that interference during the retention period also disrupts sensitization. This implies that the apparently automatic development of sensitization is in fact an active process, which *does* require attentional resources.

4. DISCUSSION

We have demonstrated that attentional distraction with a relatively easy concurrent task is sufficient for disrupting the perceptual sensitization. While the sensitization is driven by conscious perception of the prime rather than the mere exposure to the stimulus, our results show that the strength of sensitization depends on the attentional resources allocated to the processing of prime. The attentional modulation was found both for the encoding and the retention periods.

The disruption during the encoding can be attributed to a reduced strength of perceptual signals. In the studies on perceptual adaptation, attention modulates the strength of aftereffects (e.g. Lankheet & Verstraten 1995) by selectively enhancing the signals for an attended stimulus. In a similar vein, the attentional effect on the encoding of sensitization can be understood as a consequence of the reduction of the sensory signals for the prime.

The dependence on subjective percept is a key feature of sensitization, since classical priming effects usually do not require conscious registration of the prime. For example, semantic priming does not require awareness of the prime (Marcel 1983; Forster & Davis 1984; Dehaene *et al.* 1998; Valdes *et al.* 2005). Some of the past studies on perceptual priming have shown that attentional manipulation during the encoding does not affect the magnitude of priming effect, whereas the same manipulation does deteriorate performance for explicit memory tasks (Kellogg *et al.* 1996; Szymanski & MacLeod 1996). However, more recent studies show evidence that at least under restricted conditions, attention is critical for successful priming (Bentin *et al.* 1998; Kentridge *et al.* 1999; Mulligan 2002; Naccache *et al.* 2002; Lachter *et al.* 2004). In semantic priming, imposing a dual task during encoding completely abolishes the effect, even when the prime is consciously perceived (Duscherer & Holender 2003). Moreover, repetition priming requires attention (Stone *et al.* 2000). Taken together, attention to the prime seems to be vital for the encoding process in priming, whereas awareness of the prime as such is not. The attentional modulation of the encoding for sensitization agrees with these findings on the general class of priming effects.

We found that attentional distraction during the retention interval also reduces the sensitization effect.

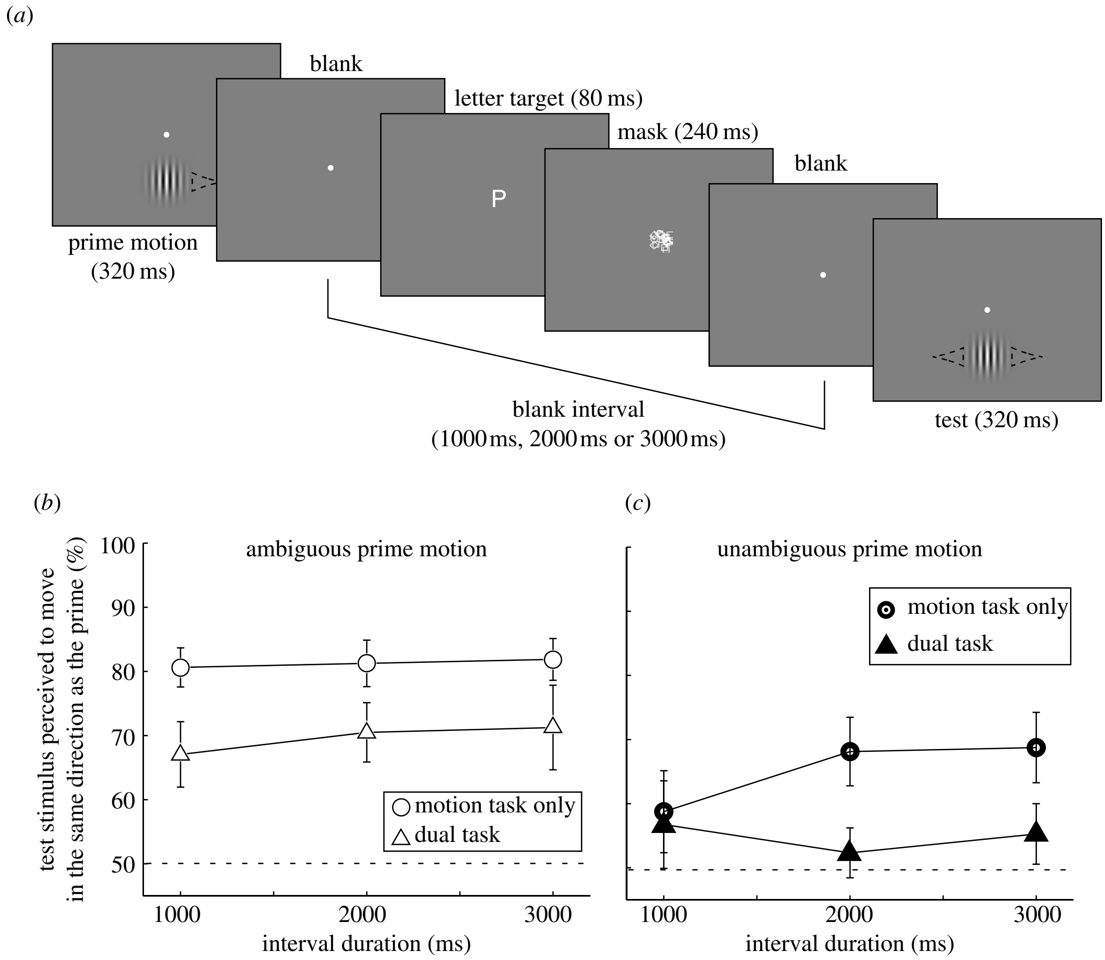

Figure 3. Attentional distraction during the blank interval. (*a*) An illustration of typical stimulus sequence. (*b*) The results of adaptation to *ambiguous* stimuli. Open circles indicate the results of the single task experiment and open triangles the results of the dual task experiment. (*c*) The results of adaptation to *directional* stimuli. Solid circles indicate the results of the single task experiment and solid triangles the results of the dual task experiment. Error bars indicate one s.e.m. ($n=8$).

Previously we have shown that the perceptual sensitization gradually develops over a few seconds, and the effect is weak or almost absent for short, blank intervals (Kanai & Verstraten 2005). Our present findings imply that attentional distraction interferes either with this build-up stage, or the maintenance of the memory trace. While it remains undecided which process was hindered by the concurrent task, our results indicate that there is an active process involved in stabilization, which operates even after the offset of a prime.

An interesting issue that we have touched upon experimentally is how the attentional manipulation can interfere with sensitization even when the prime has disappeared from the display. Since the motion prime and the letter target are well separated in time (1500 ms in the largest case), it is unlikely that the neural responses evoked by those stimuli directly interfere with each other. In other words, at the time when the letter stimulus was presented, sensory processing for the motion prime should have been completed without being disturbed. Instead of the sensory processing, the mental representation, which has been constructed after the sensory processing, seems to be disturbed by the attentional demand of a second task.

In this sense, attentional effects during the development of sensitization are somewhat surprising. During this period, the prime is no longer present on the display, and direct interference with the sensory processing of the prime is no longer possible. Our previous studies show that the perceptual sensitization develops gradually over a few seconds, and the effect is weak or almost absent for short, blank intervals (Kanai & Verstraten 2005). This implies that a memory trace is present immediately after the prime. However, it is still in its incipient stage. Attentional demand on other tasks during this period apparently disrupts the memory trace from developing to its full strength. Moreover, the requirement of the attentional resource contradicts our subjective impression that sensitization is passive. Our naive intuition is that sensitization develops without any conscious effort to actively maintain the memory trace. In contrast to this subjective impression, our results indicate that the development of sensitization is an active process that requires attentional resources.

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