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The time course of temporal attention effects on nonconscious prime processing

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Abstract We presented a masked prime at various prime–target intervals (PTIs) before a target that required a speeded motor response and investigated the impact of temporal attention on the nonconscious prime processing. The allocation of temporal attention to the target was manipulated by presenting an accessory tone and comparing that condition with a no-tone condition. The results showed that, independently of the visibility of the prime, temporal attention led to an enhanced effect of prime–target congruency on the reaction times, and that the amount of the enhancement increased with increasing PTIs. This effect pattern is consistent with the assumption of increasing influences of temporal attention and of the increasing PTI on nonconscious prime processing; it argues against the hypothesis that temporal attention narrows the time period in which the prime may affect target processing. An accumulator model is proposed assuming that target-related temporal attention increases the accumulation rate for masked primes and, thus, enhances the impact of the prime on the speed of choice decisions.

Keywords Selective attention · Temporal processing · Nonconscious · Priming · Temporal attention

Studies using the subliminal-priming (SP) task have shown that human behavior may be influenced by stimuli that participants remain unaware of (Ansorge, Klotz, & Neumann, 1998; Eimer, 1999; Greenwald, Draine, & Abrams, 1996; Klotz & Neumann, 1999; Naccache & Dehaene, 2001; Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003). In SP tasks, participants perform a choice reaction on the presentation of a visual target, which is shortly preceded by a prime stimulus that may be congruent, incongruent, or neutral to the target. In congruent trials, the prime and target are related to the same motor responses, whereas in incongruent trials, they are related to different motor responses. The prime affects the motor responses in the SP task even if participants are not able to identify the prime in a subsequent detection task (Abrams, Klinger, & Greenwald, 2002; Dehaene et al., 1998; Klotz & Neumann, 1999; Leuthold & Klopp, 1998). The resulting SP effect (i.e., the difference between the reaction times [RTs] in incongruent and congruent conditions) is usually interpreted as evidence for nonconscious motor activation in humans.

Researchers have begun to investigate the specific attentional characteristics of the mechanisms underlying nonconscious information processing (Ansorge et al., 1998; Schlaghecken & Eimer, 2004). This issue is of considerable theoretical importance, because empirical evidence suggesting that nonconscious information processing depends on attention would imply an important boundary condition for the influence of nonconscious information on human behavior.

A few studies investigated the influence of temporal attention on nonconscious motor activation. For example, Naccache, Blandin, and Dehaene (2002) reported the findings of an experiment in which SP effects did only occur when participants could predict the precise presentation time of the conscious target. In detail, in the predictable condition, the temporal interval between prime and target (PTI) and the response-to-stimulus interval (RSI) were constant. This resulted in a fixed duration of the interval between the targets in two successive trials (ITI) and allowed participants precisely to predict the time of target presentation. Alternatively,

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SP effects did not occur in the nonpredictable condition in which participants could not predict the time of target presentation because the target appeared with a random interval after the prime. Naccache et al. interpreted the exclusive observation of SP effects in the predictable condition with the assumption that the allocation of temporal attention to the time of target presentation is a necessary precondition for nonconscious prime information influencing the cognitive system.

A similar conclusion was proposed by Fischer, Schubert, and Liepelt (2007) who manipulated the allocation of temporal attention by presenting accessory tones in an SP task. Although the ITI was random in the study of Fischer et al., participants could precisely predict the presentation time of the target because an accessory stimulus was presented with a fixed time period before the target (Exp. 1). The presentation of the accessory tone led to a strong increase of the SP effect in the tone condition as compared to a no-tone condition.

As an explanation for such temporal attention effects Naccache et al. (2002) proposed that the anticipation of the target presentation time causes the opening of an attention window that facilitates further processes. Under condition of temporally focused attention the system is optimally prepared to process incoming sensory information and synchronizes the related decision and motor processes on the target (see Coull & Nobre, 1998; Hackley &Valle-Inclán, 2003; Miniussi, Wilding, Coull, & Nobre, 1999). If the nonconscious prime is presented in the attention window—that is, temporally close enough to the conscious target, then it will benefit similarly as the target from the temporally focused attention and this affects the size of the SP effect.

In the present study we continued on this research. In particular, we aimed to reveal the temporal dynamics of the influence of temporal attention on the processing of the nonconscious prime. Because it is assumed that temporal attention generates a time window extending around the presentation time of the target (Naccache et al., 2002), it would be important to know how, in detail, the prime benefits from temporal attention at various points in time across the time window.

This issue is important since previous studies have shown that the influence of the nonconscious prime on the target depends not only on the allocation of temporal attention on the target but also on the time delay between the prime and the target (PTI; Vorberg et al., 2003) (for other factors, see, e.g., Ansorge, Heumann, & Scharlau, 2002). Vorberg et al. (2003) showed that the size of the SP effect increases with increasing size of the PTI (for a size of the PTI between 0 and ~100 ms). According to Vorberg et al. (2003), this pattern results from the fact that the presentation of the nonconscious prime initiates the accumulation of prime-related response activation; this accumulation is a time consuming process and the accumulated prime-related response activation interacts with the response activation that is accumulated on the later presented target stimulus. The longer the PTI, the longer the time for the accumulation of prime-related response activation and, consequently, the stronger the influence of the prime-related activation on the subsequent target processing; that is the larger the SP effect.

Given this dynamic pattern of the accumulation of response activation it is tempting to assume that the temporal attention-related modulation of the SP effect will be additionally modulated by the particular size of the PTI. However, because the studies of Naccache et al. (2002) and Fischer et al. (2007) demonstrated the attention-related effect on the size of the SP effect with only one PTI, we cannot be sure whether the reported effects in their studies are representative for other PTIs as well. Therefore, in the present study we investigated in more detail the temporal dynamics of the attention-related modulation of the SP effect across a wider range of PTIs, which included very small sizes of the PTI (near zero) to larger sizes of about 100 ms (Vorberg et al., 2003).

In the experimental procedure we manipulated the PTI randomly in several steps and modulated the degree of temporal attention on the target in the SP task in two conditions. In the tone condition, we presented an accessory tone stimulus with a constant foreperiod before the target, which allowed participants for a precise prediction of the time point of target presentation (Coull & Nobre, 1998; Fischer et al., 2007). In the no-tone condition, participants performed the same SP task without an accessory tone. We administered a variable ITI with exponential distribution in both tone conditions, which made it impossible for the participants to predict the target presentation time exclusively by relying on the time structure of the trial (see the Exp. 1 Method section for details). Thus, only in the tone condition participants could precisely anticipate the time of target presentation.

For the formulation of predictions about the time course of the SP effect across the PTIs it is important to consider that there is no consensus about the properties of the attention window. However, as will be seen below, these properties determine the characteristics of the accessory tone effect on the SP effect. Debates concern the width of the window and the way how attention is allocated across the window—that is, with a gradient or not (Shih, 2008). Recent estimations for the possible width of the window stem mostly from studies with a different paradigm, the rapid visual presentation paradigm (RSVP). In that paradigm, participants are asked to report a second target stimulus that is presented with short lag after a first target stimulus and the observation of impaired detection performance of the second stimulus after short lag points to an attention window with restricted time duration. Shih (2008; Shih & Reeves, 2007) calculated about 150 ms as a size for the attentional window in different conditions of a RSVP task, whereas other authors (Olivers & Meeters, 2008) proposed a window width of 200 ms. Although these studies indicated a rather large time of the attention window, it remains an open question whether the estimations about the width of the window in RSVP can be transferred to studies in which the attention window results from the anticipation of the stimulus presentation time in the SP paradigm.

For the case of SP tasks, Kiefer and Brendel (2006) reported findings that may point to a smaller attention window. These authors showed in a semantic SP task that a precue directing temporal attention to the time of target presentation elicited different effects on the electrophysiological markers for semantic processing depending on the size of PTI. While the temporal attention effect was large at a short PTI of 67 ms, it was reduced under conditions of a long PTI (200 ms) suggestive for a smaller attention window in SP tasks than the 150 to 200 ms as might be derived on the basis of findings with the RSVP task. Thus, there is heterogeneous knowledge about the characteristics of the attention window across paradigms and situations. Next, we show that different predictions about the time course of the accessory-stimulus-related modulation of the SP effect across the PTI will result depending on different presumed properties of the emerging attention window.

As one prediction, it might be that the presentation of the accessory tone leads to a very sharp and narrowed form of the attention window that surrounds very closely the point of time of target presentation; for example, with a width of far less than 100 ms (e.g., Kiefer & Brendel, 2006). In that case one would expect that large PTIs (e.g., more than 67 ms) may make the prime fall completely outside the boundary of the attention window; this, in turn, should cause a lacking difference between the SP effect in a situation with as compared to without an accessory tone, specifically, at large PTIs. (Note that the prime will not benefit from attention if it falls outside the attention window.) Conversely, at short PTIs, at which the prime is temporally close to the target the temporal allocation of attention would lead to a strong enhancement of prime processing as compared to the situation without accessory tone because the prime would strongly benefit from the attention allocation. Per analogy, this would be similar to findings about the influence of focal *spatial* attention on the processing of sensory stimuli. For the spatial domain it had been shown that a spatial precue has different effects on the stimulus processing depending on the distance between the target position and the precued position of the attention focus (Downing & Pinker, 1985; Eriksen & St. James, 1986; Ghirardelli & Folk, 1996; LaBerge, 1983; see also Schlaghecken & Eimer, 2000, Exp. 4, for the SP task). Per analogy to those findings, it is expected that primes that are temporally close to the target—that is, at a short PTI—are more affected by the accessory tone manipulation than primes temporally far from the target—that is, at large PTIs—and this should result in corresponding changes of the SP effects.

However, a different pattern is predicted if the attentional window is large enough and primes at long PTIs fall well inside the attentional window as would be the case if the width of the window could indeed cover about 150 to 200 ms as proposed by RSVP studies. Such width would well cover the range of PTIs used by studies of the Vorberg et al. (2003) paradigm. When we, for simplicity, assume a rather uniform allocation of attention across the whole time window (Shih, 2008) then a complex pattern of an interaction between the PTI and the temporal attention is predicted; in particular, the effect of the temporal attention on the size of the SP effect should increase with increasing PTI. In this case, the possible beneficial effect of temporal attention on prime-processing should potentiate the longer the duration of the prime processing—that is, the longer the PTI. Consequently, the SP effects would be enlarged most at the longest PTI, at which temporal attention can enhance the prime influence for longer time duration than at shorter PTI; compared to that, the SP effects would be less affected by temporal attention at short PTI, because here temporal attention will affect the prime processing for shorter time duration than at long PTI.

Besides the empirical investigation of these predictions with RT and the corresponding error data, we subjected the empirical data about the modulation of the SP effect to a simulation analysis. The aim of this simulation analysis was to illustrate possible effects of temporal attention on nonconscious prime processing in a formalized model of the processes during the SP task. According to a number of authors investigating effects of accessory stimuli on choice RT performance, we assumed that the effect of the tone-related temporal attention is primarily located in the decision stages of the SP task. Note that Hackley and Valle-Inclán (1998, 1999) have shown, by measuring event-related potentials, that the presentation of an accessory tone affects rather the cognitive pre-motor stages during choice RT performance than the later motor execution stage as had earlier been proposed by Posner (1978). Therefore, we started the simulation analysis from the accumulator model (AM) proposed by Vorberg et al. (2003), which capitalizes on assumptions about the human-decision making mechanism in RT tasks (Hanes & Schall, 1996; Ratcliff, 2001; Smith & Ratcliff, 2004). The AM assumes independent accumulators collecting sensory evidence from both the prime and the target, which are mapped to the response alternatives of the task. The longer the PTI the longer the accumulation process and the more the prime information may affect the final motor response, thus leading to an increase of the SP effect with increasing PTI (Vorberg et al., 2003).

In accordance with earlier studies, we assumed that the effect of attention on decision situations can be approximated by assuming attention-related differences in the accumulation rates for the sensory information; see for example, studies on effects of attention on the efficiency of visual information detection (Carrasco & McElree, 2001), of practice on the speed of motor responses in choice RT tasks (Brown & Heathcote, 2005) and of cuing on simple RT task performance (Smith & Wolfgang, 2004). For the case of the modulation of the SP effect by temporal attention, an increased accumulation rate for the prime processing would increase the specific impact of prime-related information on the decision-making mechanism in the tone condition. This in turn should increase the influence of the prime information in both the congruent and the incongruent conditions of the task and, thus, lead to an increased size of the SP effect in the tone as compared to the no-tone condition.

Experiment 1

In Experiment 1, we applied the SP task of Vorberg et al. (2003) and used a prime duration of 34 ms. The number of PTIs was set to five and ranged from 34 to 102 ms. The presentation of the accessory tone was manipulated blockwise and the onset of the tone was 250 ms before the target stimulus in the SP task. This specific foreperiod has been shown to yield a maximum difference between the SP effect under the tone and the no-tone conditions in the study of Fischer et al. (2007) and, therefore, represents an optimal foreperiod for investigating the combined effects of temporal attention and PTI on the SP effect.

We predicted that the SP effect will be enlarged under the condition of the accessory stimulus. Of main interest was the question how this enlargement will look like at the separate PTI conditions.

Method

Participants A group of 14 undergraduate students (ages 19–32, mean 23.7 years) of Humboldt University participated in the experiment. All had normal or corrected-to-normal vision.

Apparatus Stimuli were presented on a 17-in. color monitor that was connected to a Pentium I PC. The experiments were carried out using the ERTS software (Experimental Run Time System; Beringer, 2000).

Procedure We used the stimulus materials of Vorberg et al. (2003). Participants were asked to respond to a target arrow pointing to the left or to the right. Unbeknownst to the participants, a prime arrow was presented in different PTI before the target and was metacontrast masked by the target. The PTI varied randomly from 34 to 102 ms, in steps of 17 ms. Participants responded with the index and middle finger to the direction of the target; half of the trials has been performed with the right hand and the other half with the left hand. The prime and target stimuli could be congruent (prime arrow and target arrow pointed in the same direction), neutral (the prime stimulus did not indicate any direction), or incongruent (the prime arrow points to the opposite direction as the target arrow) to each other.

Participants performed the task under two conditions, which are illustrated in Fig. 1: In the tone condition, an accessory tone (900 Hz, 70 dB) was presented 250 ms before the target, and no accessory tone was presented in the no-tone condition. Independently of the specific tone condition, a trial started with the presentation of a fixation cross in the middle of the screen for a variable time period. In order to prevent participants from predicting target presentation by the timing of the trials, the trial design involved a random, variable time period distributed exponentially with a mean of 800 ms, thus leading to a variable RSI. The maximum length of this variable period was limited to 12.5 times of the mean of the distribution. The fixation cross remained visible for the whole time of the trial. In the tone condition, the accessory tone, with a duration of 150 ms, was presented 250 ms before target onset.

In the no-tone condition, the fixation cross remained for an additional 250 ms on the screen after the variable time period, until target presentation. The duration of the target was 150 ms (see Fig. 1). The subsequent interval for responding lasted up to 2,000 ms. After a response was executed by the participant, an additional time interval of 800 ms was administered. During that interval, either the fixation cross was presented, on correct trials, or feedback was given for 300 ms. The next trial started after a further presentation of the fixation cross for 700 ms.

The target arrows were black on a white background with a white-colored central cutout. They were positioned 1.38º above or below a fixation cross that was located in the center of the screen. The prime stimuli were black arrows on a white background that were presented at the same position as the following target stimulus. At a viewing distance of 60 cm, the primes subtended a visual angle of 0.8º × 1.86º, the targets an angle of 1.09º × 3.47º. The outer contour of the prime stimuli coincided with the contour of the white cutout of the target stimulus, in order to achieve optimal metacontrast masking of the prime (for reviews, see Enns & DiLollo, 1997; Vorberg et al., 2003).

Design Each participant started the experimental session with a practice block of 12 trials. After completing the practice block, half of the participants performed six blocks of 60 trials of the tone condition, and after that the same

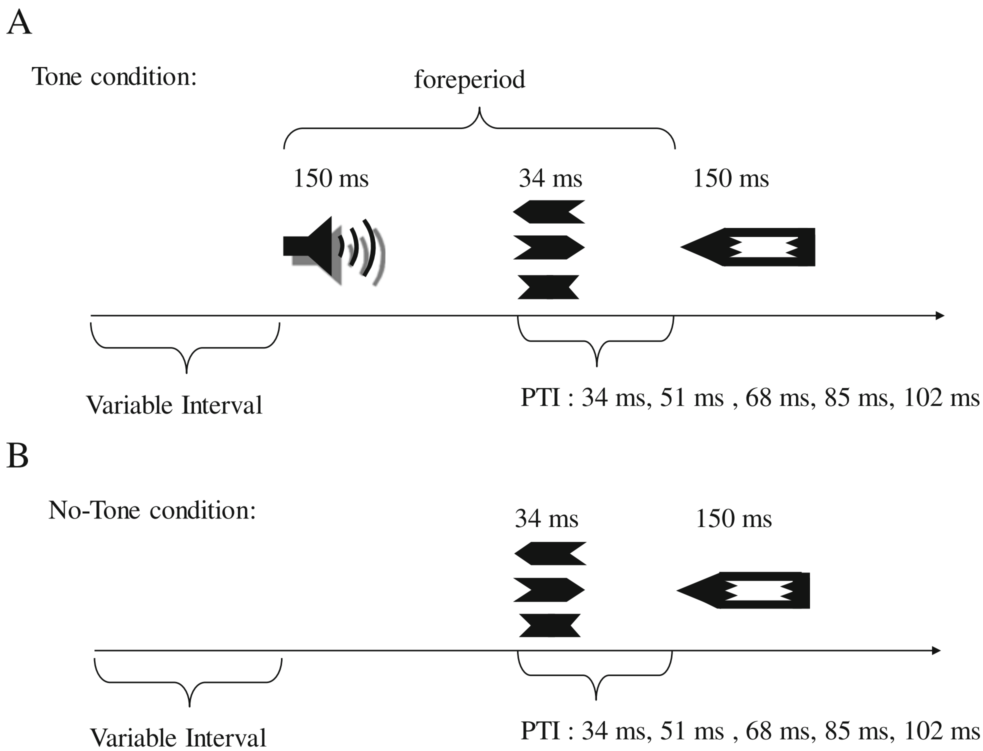

Fig. 1 Illustration of the experimental design of Experiment 1. Allocation of temporal attention to the time of target presentation is possible in the tone condition (upper panel) and is prevented in the no-tone condition (lower panel). The prime and target stimuli both appeared either above or below a centrally located fixation cross (for details, see the Exp. 1 Method section). In each trial, only one of the primes was presented; the primes consisted of either a left- or a right-pointing black arrow, and the neutral prime had cutouts at both the left and right sides. The accessory tone was presented at a constant foreperiod of 250 ms before target onset. PTI, prime target interval

amount of blocks with the no-tone condition. The other half performed the conditions in the reversed order. The different PTI conditions were randomly distributed within the separate tone conditions. In total, the experimental structure followed a 2 (target) × 3 (prime) × 2 (location) × 5 (PTI) design. Excluding practice trials, participants performed 720 trials (360 with and 360 without accessory tone) in total.

Prime visibility assessment After participants had finished the RT task, prime visibility was assessed individually through subjective and objective measures. In a prime signal detection analysis, the participants were informed about the presence of the prime stimulus, and the presentation of the prime stimulus before the target stimulus was demonstrated in slow motion. In the prime signal detection task, participants performed 360 trials, half of them in the tone condition and the other half in the no-tone condition. As before, the two conditions were presented block-wise. Participants were asked to indicate whether or not the prime and target pointed in the same directions. Examples for different response categories were shown to the participants; in detail, the participants were shown a congruent condition and told that this would be an example for a "yes" response; examples of a neutral and an incongruent trial were presented and explained as examples of "no" responses, because in these conditions the primes and targets did not point in the same directions. Participants were told that these situations could occur with equal probability. "Yes" and "no" responses were balanced across participants' index and middle fingers. In the case of uncertainty, participants were instructed to respond intuitively. No error feedback was given. The order of the conditions and the assigned reaction hand were the same for each participant as in the RT task.

Results

In an outlier test, we rejected RTs longer or shorter than two standard deviations of the mean RT, separately for the different tone, PTI, and congruency conditions. This test resulted in the elimination of 4.2 % of the trials. Error trials were excluded from the statistical analysis.

RT analysis As can be seen in Fig. 2, the difference between incongruent and congruent RTs increased in the tone condition as compared to the no-tone condition, and this difference increased with larger PTIs. This pattern was substantiated by the results of a repeated measures analysis of variance (ANOVA) on RTs, with the factors PTI, Congruency, and Tone. In particular, the analysis revealed main effects of

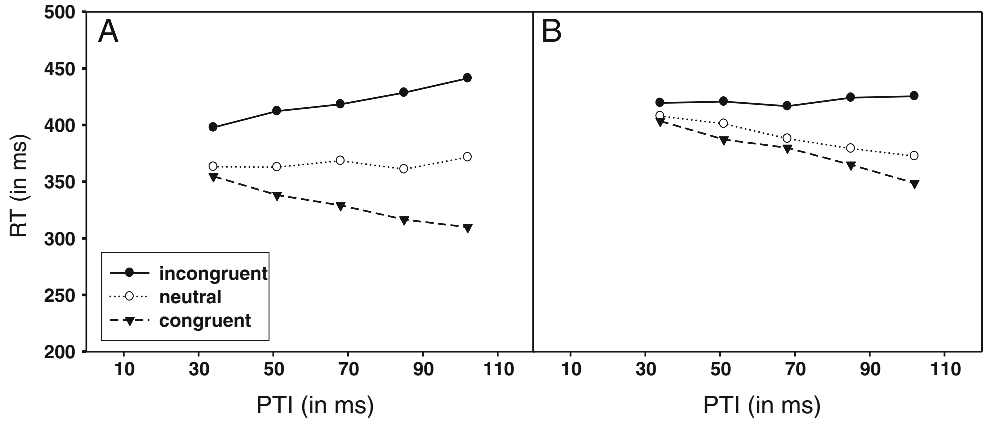

Fig. 2 Experiment 1: Reaction times (RTs) as a function of congruency and prime–target interval (PTI), presented for the tone condition (panel **a**) and the no-tone condition (panel **b**)

congruency, $F(2, 26) = 181.55$, $MSE = 893.59$, $p < .001$, of PTI, $F(4, 52) = 8.50$, $MSE = 290.13$, $p < .001$, and of tone, $F(1, 13) = 16.83$, $MSE = 3{,}697.84$, $p = .001$. The significant interaction between PTI and congruency, $F(8, 104) = 24.34$, $MSE = 240.22$, $p < .001$, reflects the observation that the RTs in congruent trials decreased with increasing PTIs, whereas the RTs in incongruent trials increased with increasing PTIs. This led to an increasing RT difference between the two conditions and replicated the findings of Vorberg et al. (2003). The significant Tone × PTI × Congruency interaction, $F(8, 104) = 2.40$, $MSE = 180.80$, $p < .05$, indicates that the PTI-related modulation of the RTs was additionally affected by the tone condition: It was more pronounced under the tone than under the no-tone condition, and the pattern differed between the congruency conditions. In the case of incongruent RTs, the presentation of the accessory tone led to a stronger increase of the RTs with increasing PTIs than in the no-tone condition, $F(4, 52) = 6.11$, $MSE = 228.39$, $p < .001$; the difference between the RTs at the longest and shortest PTIs was 44 ms under the tone condition, whereas it was reduced to 5 ms under the no-tone condition. In the case of congruent trials, the presence of an accessory tone produced only a main effect on the RTs, $F(1, 13) = 46.59$, $MSE = 1{,}668.16$, $p < .001$, reflecting a general decrease of the RTs in congruent trials in the tone as compared to the no-tone condition.

Figure 3 illustrates the resulting SP effects—that is, the difference between incongruent and congruent RTs—for the tone conditions and across the PTIs. As can be seen, the difference between the SP effects in the tone and the no-tone conditions was smallest at the shortest PTI and largest at the longest interval between prime and target presentation.[1] An ANOVA with the factors PTI and Tone on the SP effect yielded significant effects of PTI, $F(4, 52) = 55.30$, $MSE = 419.0$, $p < .001$, and of tone, $F(1, 13) = 97.63$, $MSE = 743.45$, $p < .001$. The significant interaction between tone and PTI, $F(4, 52) = 3.00$, $MSE = 318.83$, $p < .05$, reflects the observation of a different sizes of the SP effect in the tone and no-tone condition across the PTIs. Additional planned contrasts confirmed that the difference between the SP effects in the two tone conditions was smaller at a PTI of 34 ms than at PTIs of 85 ms, $F(1, 13) = 5.312$, $MSE = 1{,}737.753$, $p < .05$, or 102 ms, $F(1, 13) = 6.227$, $MSE = 1{,}707.656$, $p < .05$. In sum, this pattern reflects a rising difference between the SP effects in the tone conditions with increasing PTI.s

Error analysis Error rates are presented in Table 1. Participants committed an average number of 2.5 % errors. The same ANOVA as for RTs was performed on error rates. It revealed a main effect of congruency, $F(2, 26) = 8.46$, $MSE = 81.06$, $p < .05$, reflecting that participants produced more errors in

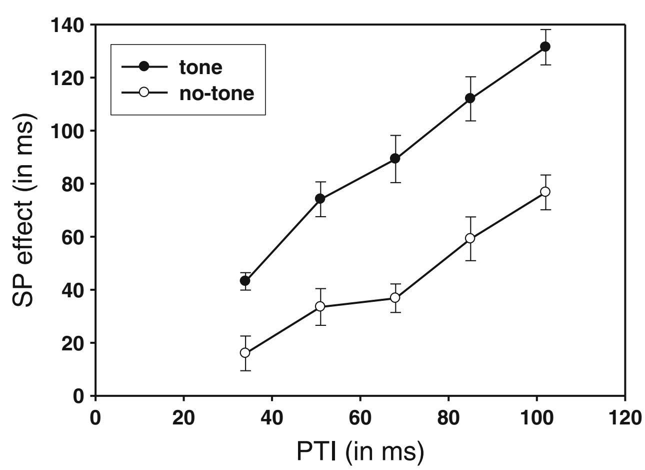

Fig. 3 Experiment 1: Subliminal-priming (SP) effects as a function of prime–target interval (PTI) and tone condition

[1] We conducted a separate analysis for the SP effect because of the computational analysis at later stages of this research; the model of Vorberg et al. (2003) makes explicit predictions concerning the SP effect across the PTI manipulation.

Table 1 Percentages of errors as a function of tone, prime–target interval (PTI), and congruency in Experiment 1

PTI (in ms)	34	51	68	85	102
No Tone					
Incongruent	1.42	4.64	2.50	5.35	6.07
Neutral	1.42	0.71	1.42	2.50	1.42
Congruent	1.07	0.35	0.71	1.42	1.42
Tone					
Incongruent	1.07	1.78	6.42	8.21	12.14
Neutral	1.42	0.00	1.42	3.21	2.50
Congruent	0.71	0.71	0.35	0.00	1.07

incongruent trials ($M = 5.11$) than in neutral ($M = 1.69$) and congruent ($M = 0.84$) trials. The error rate increased with increasing PTIs, $F(4, 52) = 7.02$, $MSE = 19.72$, $p < .001$. The significant interactions of tone and congruency, $F(2, 26) = 7.01$, $MSE = 7.41$, $p < .05$, and of PTI and tone, $F(4, 52) = 4.69$, $MSE = 7.39$, $p < .05$, were specified by the triple interaction of PTI, tone, and congruency, $F(8, 104) = 3.08$, $MSE = 9.16$, $p < .05$. The latter interaction reflects that the error rate is especially increased in incongruent conditions at long PTIs, and that this effect is prominent under the tone condition (Table 1). In particular, this allowed us to exclude a speed–accuracy trade-off (SAT) as an explanation for the observed RT modulation in the tone versus the no-tone condition. An SAT means that RTs get faster, with the cost of poor accuracy. In our study, this was definitely not the case, because RTs in incongruent trials increased more with increasing PTIs under the tone than under the no-tone condition. A separate influence of the tone on error rates in the congruent condition was not found, $F(1, 13) = 1.56$, $p > .20$

Prime visibility assessment After completing the RT task, participants performed a prime signal detection task to allow us to analyze prime visibility. Although a few participants noticed a slight flicker during the presentation of the target, no participant reported having noticed the existence of specific primes in the RT part of the experiment. Objective measures of prime visibility were analyzed in several steps. First, we calculated the mean d' values separately for the tone ($d' = 0.25$) and no-tone ($d' = 0.24$) conditions, which did not differ significantly from each other, $t(13) = -0.199$, $p = .845$. As had Fischer et al. (2007), we treated “yes” responses in congruent trials as hits and “yes” responses in neutral trials as false alarms. Note that neutral primes had a cutout at each side, and therefore, the question of whether the prime and the arrow pointed in the same direction had to be answered with “no,” whereas a “yes” response represents a false alarm. Probabilities of the “yes” response categories were calculated by dividing their absolute numbers by 120, which was the number of the trials in both the congruent and neutral conditions.[2] When using “yes” responses in incongruent trials, the d' values followed patterns similar to those when using neutral primes (see notes 3 and 5 below). Statistical testing revealed that the d' values were significantly different from zero, both χ^2s$(df = 1) > 12$, $p < .001$, suggesting rudimentary visibility of the prime stimuli in both tone conditions. However, a further analysis of the d' values at the individual PTIs revealed for both tone conditions that the elevation of the d' values was caused by enhanced prime visibility in the longer PTI conditions only. For the no-tone condition, the d' values amounted to 0.03, 0.14, 0.24, 0.30, and 0.48, and for the tone condition, to 0.29, 0.08, 0.13, 0.27, and 0.49, for the conditions with 34-, 51-, 68-, 85-, and 102-ms PTIs, respectively. Significant d' values were found for the no-tone condition at the 85-ms and 102-ms PTIs, and for the tone-condition at the 102-ms PTI, χ^2s(1) = 5.534, 10.958, and 12.144, all ps < .05, respectively. Except for these elevated d' values, the d' values at the other PTIs—that is, at shorter and medium PTIs—were not significant, all χ^2s(1) < 3, smallest $p > .07$.[3] This finding was substantiated by the results of a subsequent ANOVA with the factors Tone Condition and PTI, which revealed a significant effect of the PTI, $F(4, 52) = 2.68$, $p < .05$, on the d' values of the participants. The factor Tone Condition, $F(1, 52) = 0.4$, $p > .8$, and the Tone × PTI interaction, $F(4, 52) = 0.596$, $p > .6$, were not significant.

Subsequently, we performed a regression analysis, as proposed by Draine and Greenwald (1998; see also Greenwald et al., 1996) and regressed the averaged SP effects as the dependent variable on the d' values (independent variable). The intercept in a regression analysis represents the value of the dependent variable if the independent variable is at zero. Therefore, in the present analysis, the intercept predicted the size of the SP effect when d' was equal to zero (e.g., under conditions of zero visibility). An intercept that is significantly different from zero indicates significant priming even under conditions of zero prime visibility (see also Greenwald, Klinger, & Schu, 1995).[4] In Experiment 1, the intercept of

[2] This avoided underestimation of the false alarm rates for neutral trials, as compared to a different procedure, in which the number of false alarms would have been calculated by dividing the number of “yes” responses on neutral trials by 240, which was the number of all possible “no” responses in the detection part (neutral plus incongruent trials). Vorberg, Mattler, Heinecke, Schmidt, and Schwarzbach (2004) favored separate calculations of d' in situations with trials types that might provide different information (i.e., neutral or incongruent prime–target combinations) about prime existence in detection tasks.

[3] The d' values calculated with incongruent “yes” responses as false alarms, and according to the same procedure as for the neutral trials, amounted to 0.23, 0.11, –0.1, 0.47, and 0.59 (no tone) and to 0.23, 0.25, 0.35, 0.56, and 0.54 (tone), for the PTIs of 34, 51, 68, 85, and 102 ms, respectively. The d's were significant at the 68-, 85-, and 102-ms PTIs—χ^2s(1) = 5.43, 7.2, and 10.95, respectively, all ps < .05—and nonsignificant at the two shorter PTIs, χ^2s(1) < 3.

[4] See also Klauer and Greenwald (2000) and Miller (2000) for a debate about the validity of inferences about zero prime visibility.

the regression (41.14) was significantly greater than zero, $t(13) = 5.74$, $p < .001$, indicating that the SP effect was significant even under conditions of zero visibility of the prime stimulus. The additional analysis of the slope coefficients (β) of the resulting regression function allowed us to test whether individual differences in the visibility of the prime affected the size of the priming effect. If β—that is, the slope coefficient—does not differ from zero, the priming effect does not depend on the prime visibility. In Experiment 1, the slope coefficient β did not differ from zero, $\beta = 13.8$, $t(13) = 0.68$, $p > .5$, suggesting that the size of the SP effect was not affected by individual differences in the prime visibility.

Discussion

In Experiment 1, the size of the SP effect increased in the tone as compared to the no-tone condition. Most importantly, the presentation of the accessory tone did not only modulate the SP effect in general but the amount of that modulation depended on the time period available for prime processing—that is, on the PTI. In particular, the difference between the SP effect in the tone and the no-tone conditions increased with increasing PTIs. While the SP effect in the tone condition exceeded that in the no-tone condition by 27 ms at short PTIs, the difference in size amounted to 55 ms at the longest PTI.

Obviously, the findings of Experiment 1 rule out the assumption that the presentation of the accessory tone leads to a narrowed focus of temporal attention that is very close to the time point of target presentation and that does not span the whole range of the current PTIs. In that case, we would have expected to see a large impact of the accessory tone at short PTIs and an abruptly strong decrease of that influence at larger PTIs, in which the prime might have been presented outside the temporal attention focus. The present findings are also not consistent with a more relaxed version of the narrowed-focus assumption, according to which there is a gradient (instead of sharp boundaries) across the attentional window, with a larger impact of the accessory tone under conditions of shorter PTIs than at longer PTIs. Note that this assumption may result if an analogy is drawn between the attention effects in the spatial (Downing & Pinker, 1985; Erickson & St. James, 1986; LaBerge, 1983) and temporal domains. In that case, the effect of the accessory tone on the SP effect should have been larger at short than at long PTIs, which is not consistent with the present data set.

The present findings show that temporal attention affects prime processing across the whole range of the present PTI manipulation (34–102 ms). Across that PTI range, the SP effect increased steadily across the PTIs, resulting in larger effects of the accessory tone at the longer than at the shorter PTIs. The particular effect pattern of Experiment 1 shows that temporal attention and PTI affected the size of the SP effect in an interactive and enhancing manner.

Experiment 2

In Experiment 2, we tested the influences of temporal attention and of the PTI on the size of the SP effect under conditions of a degree of prime visibility lower than in Experiment 1. The reason for this was the increased prime visibility in Experiment 1, which was elevated at the long PTI conditions. Although prime visibility in Experiment 1 did not differ between the two tone conditions, the presentation of the accessory tone may not only have improved the anticipation of the visible target but may, additionally, have led to improved anticipation of the time of the *prime* presentation. However, if this anticipation had occurred, the observed tone-related modulation of the SP effect might have been a side effect of improved conscious prime anticipation with longer PTIs only. Therefore, in Experiment 2 we presented primes with a duration of 17 ms. As had been shown by Vorberg et al. (2003), primes with a duration less than 30 ms lead to lower d' values than do primes lasting more than 30 ms under conditions of the materials used in Experiment 1.

It is important to note that we held constant the number of PTIs to the number in Experiment 1. Because in Experiment 1 the shortest PTI was equal to the duration of the prime, in Experiment 2 the shortest PTI amounted to 17 ms, and the longest PTI duration amounted to 85 ms.

Method

A group of 13 undergraduate students of Humboldt University, Berlin (ages 21–32, mean 24.8 years), participated in this experiment. All had normal or corrected-to-normal vision and were not provided with any information about the aim of the experiment.

The apparatus, stimuli, procedure, design, and initial data processing were identical to those in Experiment 1, except for the following changes. The prime duration lasted 17 ms, and the PTI had possible values of 17, 34, 51, 68, or 85 ms. After the RT experiment, the participants performed a prime visibility assessment task like that in Experiment 1, but the total number of trials in this task was 600.

Results

The outlier test on the data of Experiment 2 resulted in the elimination of 4.9 % of the trials from the RT analysis.

RT analysis In Experiment 2, the analysis of the RT functions (Fig. 4) yielded a data pattern almost identical to that in Experiment 1. A repeated measures ANOVA showed that

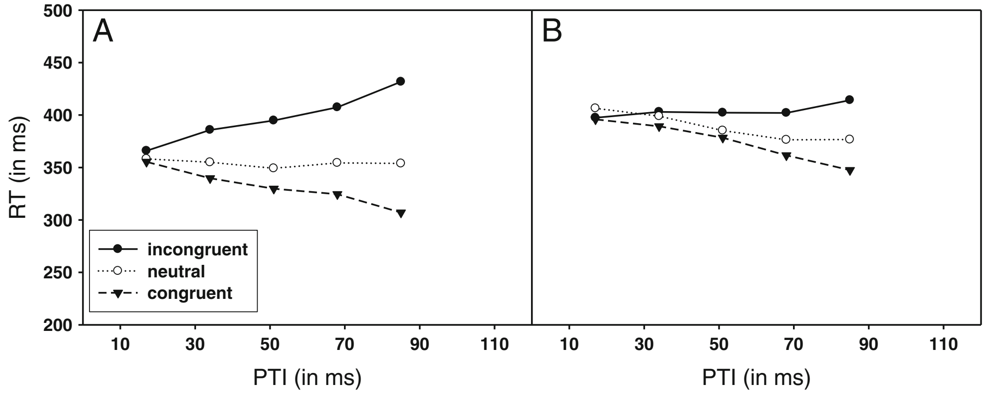

Fig. 4 Experiment 2: Reaction times (RTs) as a function of congruency and prime–target interval (PTI), presented for the tone condition (panel **a**) and the no-tone condition (panel **b**)

congruency significantly affected the RTs, $F(2, 24) = 116.53$, $MSE = 641.44$, $p < .001$, as did the factor PTI, $F(4, 48) = 4.30$, $MSE = 296.34$, $p < .005$. The significant interaction of PTI and congruency, $F(8, 96) = 29.54$, $MSE = 260.06$, $p < .001$, reflected a general decrease of the RTs in congruent trials and an increase of RTs in incongruent trials with increasing size of the PTI. This result again replicated the findings of Vorberg et al. (2003). As in the previous experiment, the presentation of the accessory tone led to a significant decrease of RTs, relative to the no-tone condition, $F(1, 12) = 26.91$, $MSE = 2{,}872.60$, $p < .001$. Most importantly, the presentation of the tone affected the modulation of the congruency effect by the PTI manipulation, which was reflected by the significant interaction of PTI, tone, and congruency on RTs, $F(8, 96) = 2.13$, $MSE = 253.53$, $p < .05$. As in Experiment 1, separate ANOVAs on the RTs in the tone and no-tone conditions showed that the modulation of the RTs across PTIs was more pronounced in the tone than in the no-tone condition. This was specified by the significant interaction between PTI and tone on the RTs in incongruent trials, $F(4, 48) = 10.41$, $MSE = 228.87$, $p < .001$. Additionally, the presence of a tone led to general decrease of the RTs in congruent trials, relative to the no-tone condition, $F(1, 12) = 69.18$, $MSE = 877.42$, $p < .001$.

Again, as a consequence of this particular RT pattern, the SP effect increased more with increasing PTIs in the tone condition than in the no-tone condition. Figure 5 shows that the difference between the SP effects in the tone and no-tone conditions grew with increasing PTIs. A subsequent ANOVA, with the factors PTI and Tone, on the SP effects yielded significant effects of PTI, $F(4, 48) = 60.84$, $MSE = 486.16$, $p < .001$; of tone, $F(1, 12) = 50.49$, $MSE = 859.73$, $p < .001$; and of the interaction, PTI × Tone, $F(4, 52) = 3.00$, $MSE = 318.83$, $p < .05$. Planned contrasts revealed that the difference between the SP effects in the no-tone and tone conditions was smaller at the PTI of 17 ms than at all of the other PTIs, that the SP difference at the PTI of 34 ms was smaller than that at 85 ms, and, finally, that the SP difference at the PTI of 68 ms was smaller than that at 85 ms, all $Fs(1, 12) > 6.06$, all $ps < .05$.

In sum, the findings obtained with a prime duration of 17 ms led to similar effects of the tone condition and of the PTI manipulation on the size of the SP effect and on the RT functions, as compared to the situation with a prime duration of 34 ms in Experiment 1.

Error analysis Participants committed an average number of 2.9 % errors, which are presented separately for the different experimental conditions in Table 2. The ANOVA revealed a significant effect of congruency, $F(2, 24) = 11.48$, $MSE = 28.84$, $p < .001$, reflecting increased error rates in incongruent ($M = 4.53$) as compared to neutral ($M = 2.88$) and congruent ($M = 1.34$) trials. Error rates increased with increasing PTIs, $F(4, 48) = 6.09$, $MSE = 17.35$, $p < .001$. However as can be seen in Table 2, the increase of the error rates with increasing PTIs was more pronounced for incongruent trials, as compared to both neutral and congruent trials, $F(8, 96) = 2.55$, $MSE = 16.77$, $p < .05$. In addition, although the interaction of PTI, tone, and congruency did not reach significance, visual inspection of Table 2 suggests a tendency toward increased error rates especially for incongruent trials under the tone condition.

Prime visibility assessment Prime visibility was analyzed with the procedure described for Experiment 1. Unlike in that experiment, no participants reported noticing the prime stimuli. Moreover, the prime signal detection analysis revealed an overall d' value in Experiment 2 (i.e., averaged across the two tone conditions) of $d' = 0.06$. This was significantly lower than the corresponding d' value of Experiment 1 ($d' = 0.25$), $F(1, 25) = 6.35$, $p < .02$. This suggests that a decrease of the prime duration led to a successful reduction of prime visibility in Experiment 2. The detailed analysis of the prime signal detection data separately for the two tone conditions in Experiment 2 revealed values of $d' = 0.05$ and 0.07 for the tone and the no-tone conditions, which did not differ significantly from zero, $\chi^2s(1) = 0.78$, and 1.22, both $ps > .16$. Hence, the prime stimuli were not visible in Experiment 2. Separate tests of the d' values at the different PTIs showed that

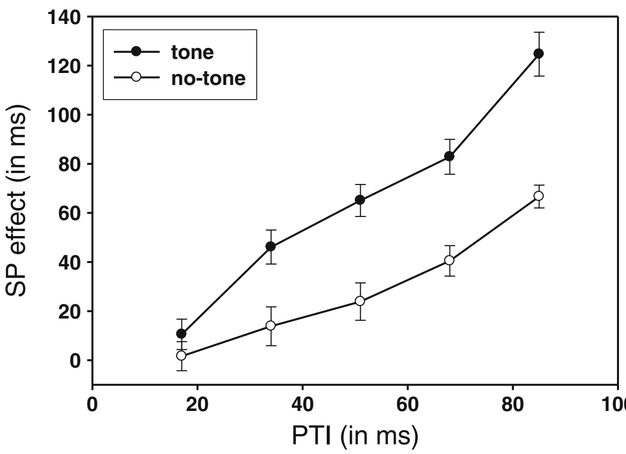

Fig. 5 Experiment 2: Subliminal-priming (SP) effects as a function of prime–target interval (PTI) and tone condition

Table 2 Percentages of errors as a function of tone, prime–target interval (PTI), and congruency in Experiment 2

PTI (in ms)	17	34	51	68	85
No Tone					
Incongruent	1.92	2.69	4.23	4.61	3.46
Neutral	1.92	2.69	2.30	5.00	2.69
Congruent	1.53	1.53	2.30	0.76	0.76
Tone					
Incongruent	2.69	2.30	5.00	6.53	11.92
Neutral	0.38	1.15	3.84	5.00	3.84
Congruent	1.53	0.00	1.53	1.92	1.53

at neither PTI did the d' values differ significantly from zero; the largest $\chi^2(1)$ was smaller than 1.97, $p > .15$, in the tone condition, and smaller than 2.03, $p > .15$, in the no-tone condition. For the no-tone condition, the d' values amounted to –0.23, 0.04, –0.02, –0.14, and –0.007, and for the tone condition, to 0.18, –0.22, –0.13, –0.01, and –0.09, for the PTI conditions of 17, 34, 51, 68, and 85 ms, respectively.[5]

As in Experiment 1, the intercept of the subsequent regression analysis (30.2) was significantly larger than zero, $t(12) = 8.12$, $p < .001$, indicating that the SP effect was significant even with zero prime visibility. Furthermore, the slope coefficient β (–9.25) was not significantly different from zero, $t(12) = –0.58$, $p > .5$, suggesting that the size of the SP effect was not affected by interindividual differences in the prime visibility.

Discussion

Despite the decreased visibility of the prime stimuli, the findings for the RT data in Experiment 2 replicated very well the findings of Experiment 1. As in Experiment 1, the size of the SP effect was larger in the tone than in the no-tone condition, and most importantly, the larger was the PTI, the more the SP effect in the tone condition exceeded the SP effect in the no-tone condition. To summarize, the findings of Experiments 1 and 2 suggest a dynamic influence of temporal attention on prime processing in SP tasks, which increases with increasing PTIs. Importantly, this influence is independent of the visibility of the prime stimuli, thus replicating the previous conclusions of Sumner, Tsai, Yu, and Nachev (2006).

[5] The d' values calculated with incongruent "yes" responses as false alarms amounted to 0.28, 0.09, 0.12, 0.09, and 0.17 (tone) and to 0.06, 0.2, 0.12, 0.12, and 0.27 (no tone), for the PTIs of 17, 34, 51, 68, and 85 ms, respectively. We found no significant d' at any combination of PTI and tone condition. The d' values were larger in Experiment 1 (0.34) than in Experiment 2 (0.15), $t(26) = 1.76$, $p < .05$.

Simulation of the attention effects in the subliminal-priming task

The effects of temporal attention on the SP effect can be formalized with a computational model, which represents a modification of the AM of Vorberg et al. (2003). That modification became necessary, because the AM, despite of its merits in simulating pure PTI effects, could not account for the particular impact of temporal attention on the size of the SP effect (but the modified model can).

In detail, the original AM assumes the existence of independent accumulators collecting sensory evidence from both the prime and the target, which are mapped to the response alternatives of the task. Response activation is accumulated for the prime and the target stimuli with identical accumulation rates, and the longer the PTI, the more the prime information may affect the final motor response, thus leading to an increase of the SP effect with increasing PTIs (Vorberg et al., 2003).

In mathematical terms, the AM relates the size of the SP effect to the specific size of the PTI according to Eq. 1:

$$\text{SP effect(PE)} = \left(\frac{1}{v}\right)\ln\left(2e^{vs}-1\right), \quad (1)$$

where v denotes the rate of accumulated response activation and s represents the time between the prime and target, s = PTI.

Vorberg et al. (2003) successfully applied the AM to simulate a PTI-related influence on the SP effect under those task conditions that allowed for maximum predictability of the time of target presentation. Note that in that study, they used a constant ITI and a large amount of training (nine sessions), which allowed participants to predict the presentation time of the target stimuli.

In the present study, the application of the AM allowed us to simulate the SP effect with sufficient goodness only for the tone condition, in which participants could predict the time of target presentation. This can be seen in Fig. 6, which illustrates the results of a Monte Carlo simulation (one million repetitions) of the present SP effects in Experiment 1 with the AM; the mean fit error[6] between the simulated and empirical data amounted to $M = 2.26$, $p > .05$. The AM failed to fit the data of the no-tone condition. There, the mean fit error, $M = 64.75$, exceeded the critical χ^2 value, suggesting a significant difference ($p < .05$) between the empirical and simulated curves of the SP effect. Probably, this failure originated from the specific property of the AM predicting that the size of the SP effect will be equal to or larger than the amount of the actual PTI (or in any case, not less; see Formula 1 above). As a consequence, the slope coefficient β_e of the regression function relating the SP effect to the PTI should amount to values 1 and larger only. The shaded gray area in Fig. 6b denotes the range of the largest and smallest possible SP effects, according to the predictions of the AM. As can be seen, the empirical data fall outside the gray area, and the slope coefficient ($\beta_e = 0.865$) in the no-tone condition is smaller than 1. We will come back to this issue in the General Discussion.

In order to simulate the observed effect of the accessory tone on the SP effect, we modified the AM by assuming variable, instead of identical, accumulation rates for the prime- and target-related information in the SP task. In the resulting variable accumulator model, called VAM (see Eq. 2), separate parameters λ_P and λ_T describe the different accumulation rates of the prime and the target stimuli. We assumed that temporal attention affects the rate of accumulation of prime-related sensory evidence, and that a higher accumulation rate is present in the tone than in the no-tone condition.

The assumption of a variable accumulation rate under different attention conditions is not new. It has been implemented in recent accumulator models in order to explain the effects of attention on the efficiency of visual stimulus detection (Carrasco & McElree, 2001), of practice on the speed of motor responses in choice RT tasks (Brown & Heathcote, 2005), and of cuing effects on simple RT task performance (Smith & Wolfgang, 2004). In the context of the present experimental situation, an increased accumulation rate for prime-related information (λ_P) increases the particular impact of the prime-related information on the decision-making mechanism in the tone relative to the no-tone condition. This, in turn, increases the influence of the prime information in both the congruent and incongruent conditions, and thus leads to an increased size of the SP effect in the tone as compared to the no-tone condition. See Fig. 7a for an illustration of this mechanism. The mathematical description of the resulting VAM reads

$$\mathrm{PE} = \left(\frac{1}{v}\right)\ln\left(\frac{\lambda_P(-1+e^{-vs})-\lambda_T}{\lambda_P(1-e^{-vs})-\lambda_T}\right), \tag{2}$$

$$\lambda_P(s) = \lambda_T + (\lambda_{P0}-\lambda_T)e^{-rs}, \tag{3}$$

where λ_{P0} denotes the initial accumulation rate of the prime at the time point $s = 0$, and r is a constant restricting the final amount of the prime-related activation that is accumulated under each PTI. The prime-related accumulation rate increases inverse-exponentially with the growth rate r and saturates finally at the accumulation rate of the target. Hence, the growth rate r defines how fast the prime accumulation rate grows. Equation 3 implies that the prime-related accumulation rate grows faster at smaller than at larger s (PTI).

A Monte Carlo simulation (one million repetitions) with the VAM provided excellent fits between the empirical and the simulated data curves for the tone condition, mean fit error = 0.93, $p > .05$ and for the no-tone condition, mean fit error = 2.37, $p > .05$ (see Table 3 for results for Exp. 1). This reflects a high validity of the VAM to model the variation of the SP effect under different conditions of temporal attention.

We also simulated the influence of temporal attention on the RT data in the present paradigm. For that purpose, we transformed the original equations for calculating RTs given by Vorberg et al. (2003) according to the underlying assumptions of the VAM (see the Appendix). In brief, the resulting VAM equations for calculating the RTs for congruent and incongruent trials read

$$\mathrm{RT}_{\mathrm{cong}} = \left(\frac{1}{v}\right)\ln\left(\frac{\lambda_P(s)(1-e^{-vs})-\lambda_T}{cv-\lambda_T}\right), \tag{4}$$

$$\mathrm{RT}_{\mathrm{incong}} = \left(\frac{1}{v}\right)\ln\left(\frac{-\lambda_P(s)(1-e^{-vs})-\lambda_T}{cv-\lambda_T}\right), \tag{5}$$

where c denotes the response threshold.

When fitting the RT functions for congruent and incongruent trials in the two tone conditions of Experiment 1, we used the same parameter estimates that had been determined earlier during the simulation of the SP effects with Eq. 2, except for c. The threshold value c was estimated separately for each tone condition in each experiment. This specific procedure improved the power of the model's validity testing because it reduced the actual number of free parameters to

[6] Fit errors were estimated by calculating the squared difference between the empirical and the simulated data, weighted by the squared standard errors for the separate PTIs (see Miller & Greeno, 1978, and also Mattler, 2005; but see Ratcliff & Tuerlinckx, 2002). Goodness of fit was tested by comparing the sum of the fit errors over the PTIs against the critical χ^2 value [$\chi^2(df = 4) = 9.49$, $p = .05$], because the fit errors are assumed to be χ-distributed (for details, see Table 3).

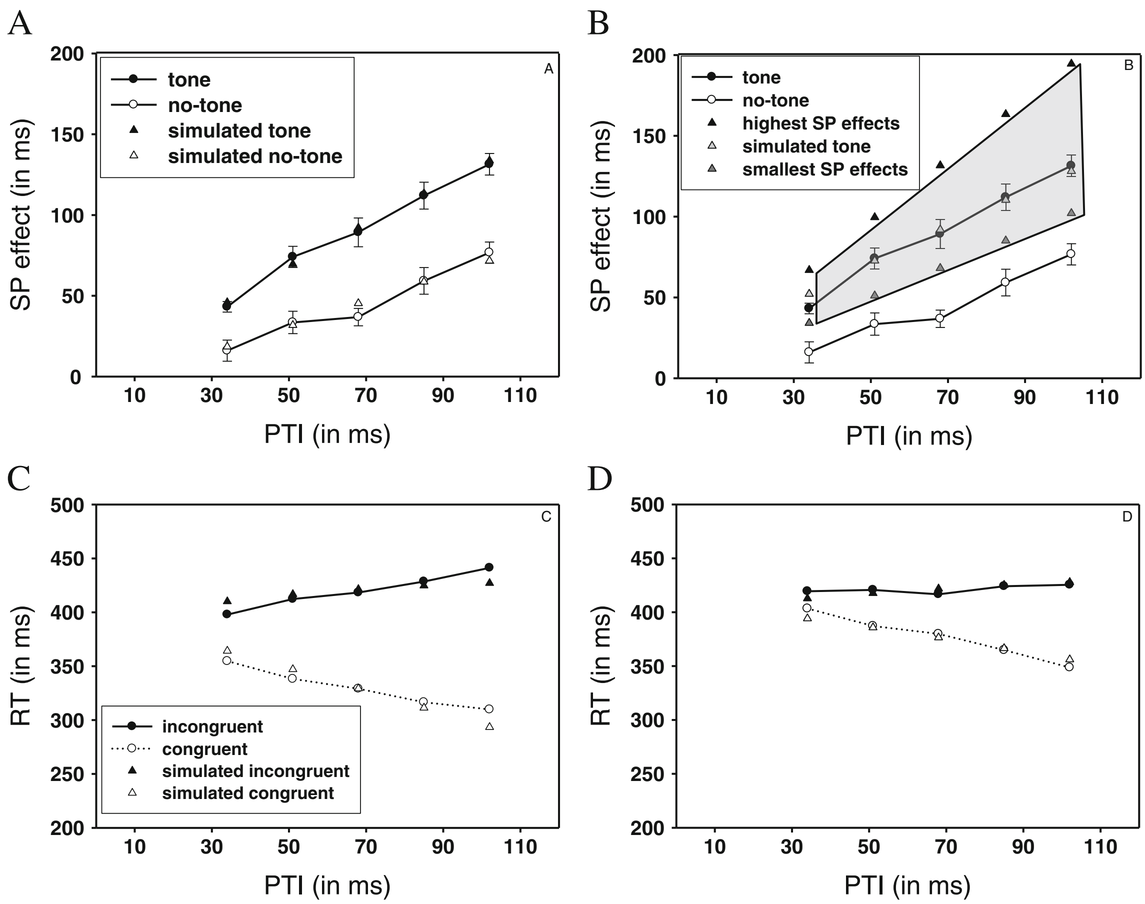

Fig. 6 Simulation of the effects of temporal attention on the subliminal-priming (SP) effect and on the reaction times (RTs) in Experiment 1 with the original accumulator model (AM) and the variable accumulator model (VAM). **a** Empirical data and simulation with the AM of the SP effect in Experiment 1. **b** Empirical data and predictions of the AM for the size of the SP effect. The gray area denotes the range of the theoretically possible sizes of the SP effect predicted by the AM (for explanation, see the text). The next two panels show the simulation by the VAM and the empirically observed RTs in congruent and incongruent trials in the tone (**c**) and the no-tone (**d**) conditions

only one in Eqs. 4 and 5, and in this way penalized its testing (see Roberts & Pashler, 2000, for other possibilities).

As can be seen, the summed fit errors[7] amounted to $M = 6.51$ and 1.33 in the tone and the no-tone conditions, respectively [critical $\chi^2(8) = 15.5$, $p < .05$] (see Table 3). The related values of the observed and of the simulated RT data for the tone and the no-tone conditions of Experiment 1 are presented in Figs. 6c and d, respectively.

For comparison purposes, the RT functions were also simulated with the equations proposed by the original AM, not incorporating assumptions about the attentional modulation of the accumulation rates (Vorberg et al., 2003). As can be seen in Table 3, the simulated RT curves for congruent and incongruent trials matched the pattern of the empirical RTs badly. The same pattern of results can be obtained through simulation of the findings of Experiment 2.

General discussion

The time course of the influence of temporal attention

We investigated how temporal attention affects the size of the SP effect at various PTIs in an SP task because earlier studies focused on the impact of either temporal attention or of the PTIs on the SP effect but not on their combined effect (e.g., Fischer et al., 2007; Vorberg et al., 2003). Temporal attention was modulated by presenting an accessory stimulus with constant foreperiod before the target in the tone condition as compared to the no-tone condition. The findings showed that

[7] Fit errors between the empirically observed and simulated RT data were calculated separately for the congruent and incongruent conditions via the procedure described for the SP effect. For the subsequent goodness-of-fit test, we summed the fit errors and the resulting χ^2 values over both conditions. The results of the Monte Carlo simulations separately for the congruent and incongruent conditions yielded good fits between the simulated RT functions and the corresponding empirical data in the tone and the no-tone conditions.

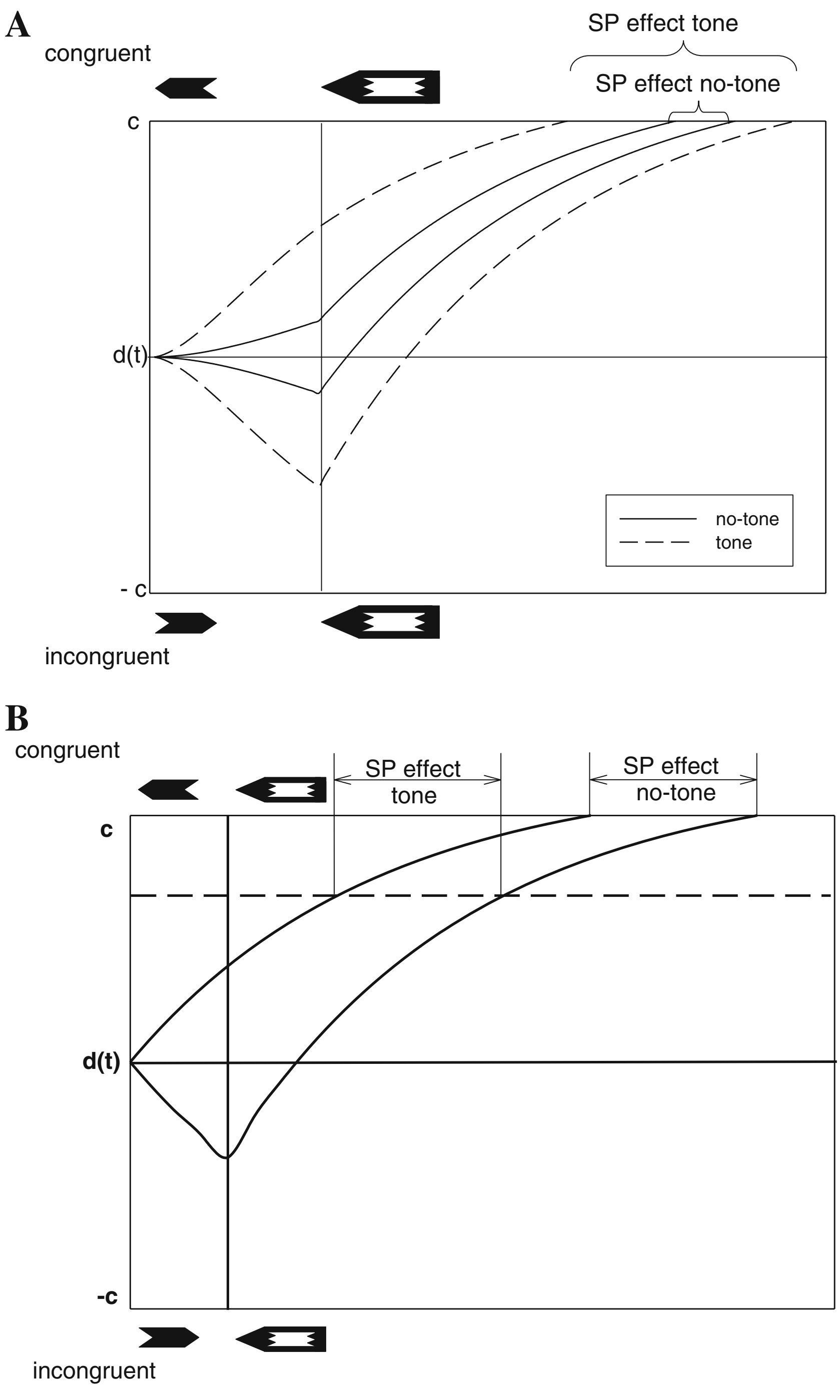

Fig. 7 Accumulation of evidence in the tone and no-tone conditions according to the VAM. In congruent conditions, the prime and target are related to the same motor responses—for example, here with a left-finger response. In incongruent cases, the prime and target are related to opposite responses. In congruent conditions, response activation grows after prime presentation in the direction of the response threshold for the correct response *c*, whereas in incongruent conditions, response activation grows after prime presentation in the direction of the incorrect response threshold –*c*. In the latter case, response activation turns in the direction of the correct response after target presentation. The upper panel (**a**) illustrates the assumption that the accumulation of prime-related evidence is already elevated under conditions of a short PTI and, in addition, grows with higher speed in the tone than in the no-tone condition, which subsequently leads to an increased size of the subliminal-priming effect. The priming effect denotes the difference between the points in time at which the response activation intercepts the *c* line in the congruent and incongruent cases. The lower panel (**b**) illustrates the predictions regarding the reaction times on congruent and incongruent trials and the resulting SP effect, assuming that the presentation of the tone leads to a lowered response threshold, which is depicted by the dashed horizontal line. As can be seen, the presentation of the tone leads to a decrease in the time needed to reach the response threshold *c*, as compared to the no-tone condition. However, the amount of the decrease is the same for both congruent and incongruent trials, thus leaving constant the relation between the two types of trials—that is, the size of the priming effect

Table 3 Simulation parameters and mean fit errors between the simulated and the empirically observed data in Experiment 1

Model	Parameter					Mean Fit Error				
	Condition	ν	Λ_{P0}	r	c	SP Effect	Sign.	Mean RT Congruent	Mean RT Incongruent	Sign.
AM	Tone	0.0249	–	–	40.034	2.26	n.s.	20.85	14.5	s.
	No tone	6.95	–	–	0.09	64.75	s.	3,521.21	4,261.15	s.
VAM	Tone	0.01	0.5	0.033	60.65	0.93	n.s.	3.50	3.01	n.s.
	No tone	0.02	0.067	0.011	48.00	2.37	n.s.	0.77	0.60	n.s.

AM, VAM = original accumulator model (see Vorberg et al. 2003) and new variable accumulator model of subliminal priming (SP); RT = reaction times. The parameters λ in the AM and λ_T in the VAM were fixed to 1. During the Monte Carlo simulations (see the text and note 6) of the SP effect (simulated values), the parameters v, λ_{P0}, and r were determined to be in the range of 0 to 10. The obtained values were used when simulating the RTs for congruent and incongruent trials according to the corresponding equations (see the text). The threshold c was determined in the range of 0 to 100. The mean fit error was determined by the mean of the fit errors across the five PTI conditions. To obtain the fit error of each separate PTI condition, the squared difference between the predicted (simulated) and the empirical data weighted by the squared standard error was calculated (Miller & Greeno, 1978). Goodness of fit was tested against the critical χ^2 values, χ^2 ($df = 4$) = 9.49, $p = .05$, and χ^2 (8) = 15.5, $p = .05$, for the SP effects and for the RTs summed over congruent and incongruent conditions, respectively. s. = significant difference between the empirical and simulated data according to the critical χ^2. n.s. = no significant difference according to χ^2

the allocation of temporal attention to the time of target presentation increased the size of the SP effect, which replicated the findings of Fischer et al. (2007) and Naccache et al. (2002).

The attention-related increase of the SP effect was observed for the whole range of the PTIs that varied randomly between 17 and 102 ms across Experiments 1 and 2. This suggests that the attention window spans at least 102 ms before the presentation of the target stimulus in conditions with a predictable time of target presentation. Naccache et al. (2002) did also report an effect of temporal attention for a PTI condition of 100 ms. However, in that investigation the authors used only one fixed PTI of 100 ms in the predictable condition and the size of the observed SP effect was very small (15 ms). Therefore, on the basis of these findings one cannot be sure whether the observed size of the SP effect reflects a rather decreased size of the SP effect, as compared to that at shorter PTIs, or whether this size results from an enhancing interaction of PTI and temporal attention. The present study allows tracking the influence of temporal attention across the whole range of PTIs between 17 and 102 ms. Within this period the PTI and the temporal attention exert an interactive and enhancing influence on the SP effect; the longer the PTI the greater the impact of temporal attention on the SP effect.

The findings rule out that the presentation of the accessory stimulus has led to a narrowed and sharply bounded attention focus around the presentation time of the target stimulus. In that case, we would have expected that when a prime falls near to the time point of target presentation then the effect of the temporal attention on the SP effect would be large, as compared to a situation in which the prime was presented at the outer boundaries of the attention focus. This would be in analogy to what is known from research on spatial attention. The authors reported evidence about a spatial gradient, in which stimuli that were presented closer in space to the attended position were processed better than stimuli that were more far away (Downing & Pinker, 1985; Erickson & St. James, 1986; LaBerge, 1983). For the case of temporal attention we did not find evidence for such a gradient-like pattern of the impact of temporal attention, with stronger effects near the time of target presentation and smaller effects at outer positions.

In contrast the effect of temporal attention on the size of the SP effect increased with increasing size of the PTI—that is, from the smallest to the largest PTI. This indicates that the PTI-dependent influence of temporal attention on the SP effect reflects an increasing efficiency of the nonconscious prime processing, which benefits with increasing degree from the allocation of temporal attention on the target over the range of the PTIs (see also Brown & Heathcote, 2005; Smith & Wolfgang, 2004).

Temporal attention and the time window

The observation of a time window spanning at least 102 ms is in accordance with proposals of studies with other paradigms. Olivers and Meeter (2008) and Shih (2000, 2008) estimated the size of the attention window by analyzing the detection performance in the RSVP paradigm. An impaired detection performance of the second stimulus under conditions of short lag to the first stimulus points to a restricted duration of the attention window, which can be estimated by mathematical modeling (Shi, 2000, 2008). Although, the estimated durations vary depending on factors like stimulus saliency, presentation rate of stimuli, instruction, etc., the authors proposed durations from about 150 ms (Shi, 2008) and more (Olivers & Meeter, 2008). For the case of RSVP, the assumption of an attention window holds that the onset of the first visible target in the RSVP stream triggers the opening of an attention window. The window lasts for some further period in which the existing sensory information is gated with increased efficiency to later processing stages—that is, the consolidation in working memory (see also Chun & Potter, 1995; Dell'Acqua, Dux, Wyble, & Jolicœur, 2012).

For the case of SP tasks the attention window is triggered by the anticipation of the time of target presentation and its opening improves the processing of prime information that is presented *prior to* the target. Studies with other paradigms show that such an extension of the attention window for the interval even before the time of target presentation is conceivable. For example, Wright and Fitzgerald's (2004) estimated the size of the attention window by asking participants to assess time characteristics of auditory stimuli, which were presented at different expected and unexpected points in time. Best performance was achieved under conditions of a time interval covering from about 150 ms *before* the expected time and up-to 100–200 ms *after* the expected time. Probably, an operation of the attention window in the interval before the expected time ensures ecological robustness of the attention allocation in noisy situations with relatively uncertain stimulus presentation times (Wright & Fitzgerald, 2004). While the findings from different paradigms and situations converge to the possible temporal duration of the time window that covers a range of up-to 200–300 ms, the present findings show that the time window in SP task situations covers at least an interval of not less than 100 ms before the target is presented. During that time period the temporal attention leads to an enhancing effect of the prime information on target processing, which results from improved gating of sensory to motor information. Further studies may investigate whether temporal attention enhances the prime influence on target processing even for still larger PTIs or for negative PTIs—that is, in situations in which the prime is presented after the target.

An important issue relates to the question how the attention is allocated across the time window—that is, with or without a gradient. According to Shih (2008), the assumption of a constant allocation of attention across the time window allows appropriate simulations of the performance of participants during rapid serial visual presentation tasks. For the present findings, the assumption of a constant allocation—that is, without any gradient—allowed us for a good approximation of the observed temporal attention effect on prime processing in the SP task.

Accumulation of sensory evidence and decision making

The results of the present simulation part illustrate a possible mechanism by which temporal attention may affect the processes in the SP task and, as a consequence, influences the SP effect. We locate the impact of the temporal attention on the decision stage of the SP task in accord with studies of Hackley and Valle-Inclán (1998, 1999, 2003) and others who suggested that accessory stimuli affect early pre-motor stages and not the late motor execution in choice RT tasks. Consistent with these views, the present data were simulated in the framework of accumulator models formalizing the human-choice decision making in RT tasks (Hanes & Schall, 1996; Smith & Ratcliff, 2004).

The simulation results are consistent with the assumption that the accumulation rates for the prime- and for the target-related response information may differ from each other in an SP task. This assumption is basic to the VAM and represents an extension to the AM of Vorberg et al. (2003) that successfully covers the increase of the SP effect with increasing PTI but fails to account for the attentional modulation of the SP effect. Contrary to the AM, the VAM, therefore, allows for a specification of assumptions about how temporal attention may modulate the SP effect.

A successful simulation of the data with the VAM was possible when assuming that the prime-related accumulation rate is greater in the tone than in the no-tone condition. In case of a larger prime-related accumulation rate the influence of the prime on the processing of the target information becomes greater in congruent and in incongruent trials. Although in the congruent condition this leads to a faster achievement of the response threshold, it leads to a delayed achievement of the response threshold in the incongruent condition and, as a resulting net effect, to an increasing SP effect.

The validity of the VAM and of the corresponding assumptions is signified by several observations. First of all, we achieved excellent fits between the theoretically predicted by the VAM and the empirical observed values of the SP effect at the various PTIs under the tone and the no-tone conditions. The same holds true for a simulation of the pure RT functions, which follow different dynamics across the PTI in the tone and the no-tone conditions. Contrary to the VAM, the AM failed to predict the empirical data of the SP effect and of the RT functions especially in the no-tone conditions. In our view, this is because the no-tone condition in the present study reflects a situation with an insufficient supply of attentional resources and the AM was not originally developed to model data in a situation with lacking temporal attention on target processing. Note that in the study of Vorberg et al. (2003) there was a regular ITI with a minimal temporal uncertainty of 70 ms (Exp. 1; due to the random PTI); this and the high degree of training (nine sessions) enabled the participants in the study of Vorberg et al. to predict precisely the presentation time of the target stimuli and to allocate temporal attention accordingly. In contrast, in the present study we administered a highly variable ITI manipulation in both tone conditions in order to prevent that participants could predict the target presentation by the timing of the trials. This was achieved by incorporating a random variable time period in the ITI, which was distributed exponentially around a mean of 800 ms. The failure of the AM to simulate the data of the no-tone conditions on one hand and its appropriateness for simulating the tone data on the other hand, indicate that its predictions are valid rather for the special case of optimal target anticipation; on the contrary, the VAM represents a more general accumulator model suitable for a simulation of the SP performance under different conditions of attentional resources.

Despite of its overall good fit to the data, we need to discuss possible limitations of the present VAM. The model makes quantitative claims about the size of the SP effect at different PTIs and about its relation to the amount of the prime-related accumulation rate under tone and no-tone conditions. The model does not specify the particular mechanisms by means of which temporal attention leads to an increase of the accumulation rate under conditions of the tone as compared to the no-tone condition.

In addition, the present VAM simulations may be complemented by additional assumptions in future studies. For example, one might incorporate an assumption that temporal attention affects the accumulation rate of the target in addition to the prime-related accumulation rate. The incorporation of such an assumption would be an important further step toward a unified conceptual understanding of temporal attention effects on both the prime and the target information in SP tasks. However, for the present state of the simulation analysis, such an additional assumption would not be favorable, because it would increase the number of free parameters in the VAM and, consequently, decrease the power of the model fitting (Roberts & Pashler, 2000). For the present study, the number of free model parameters does not represent a problem as we penalized the VAM when simulating the RT functions by using parameter estimates that were determined during the simulation of the SP effects. This procedure reduced the number of free VAM parameters to only one and ensured sufficient power when testing the fit.

Further factors that may be important are related to temporal aspects of prime presentation (Scharlau & Neumann, 2003). For example, it is conceivable that the prime stimulus itself has a temporal warning effect for the presentation of the target stimulus. That warning effect should have been strongest in the no-tone condition because in the tone condition, the auditory signal would have predicted the target occurrence with highest certainty. That assumption may explain why we found a decrease of the RTs in the neutral condition with increasing PTI in Experiment 1 and 2. The present VAM does not consider such effects of an increased accumulation rate of the target or of an additional warning influence of the prime for target processing; the implementation of such effects in the VAM maybe a fruitful program for further research just as the consideration of individual distributions of the RTs. Note that Kinoshita and Hunt (2008) provided evidence that response speed may represent a further factor for determining the final size of the SP effect, with smaller SP effects in situations with larger response times. The present model may explain such patterns when assuming that a high response threshold leading to large RTs is accompanied by a small prime-related accumulation rate leading to a small difference between incongruent and congruent conditions. The likelihood of such a coincidence is high under conditions of large overall mean RTs that are usually accompanied by larger RT variability (Wagenmakers & Brown, 2007).

Although the model provides the opportunity to illustrate such influences, its specific tailoring for such purposes should be subject for future studies. The present simulation represents rather a first step for a formalization of temporal attention effects in masked prime processing. The results show that the VAM together with the assumption of a tone-related increase of the prime-related accumulation rate can successfully simulate the dynamics of the mean SP effects across the PTIs and under different conditions of temporal attention.

A different assumption needs to be discussed about how the accessory stimulus may affect the decision stage in choice tasks. Coles, Gratton, Bashore, Eriksen, and Donchin (1985) proposed that the accessory stimuli affect the response process nonspecifically (which is different to the current assumption of a prime-specific effect; see below). The nonspecific effect may be accomplished by shortening the time for the decision either by lowering the response thresholds nonspecifically for *both response alternatives* or by nonspecifically increasing the initial activation level of *all response alternatives*. In both of these situations the distance of the actual response activation level to the threshold would be reduced and the RTs would be decreased, as compared to a condition without an accessory stimulus. Although this assumption may explain a general reduction of the RTs due to the accessory stimulus the model cannot explain the observed dynamics of the SP effect across the PTI in the present two tone conditions. For the case of the VAM, the simulation of the tone influence on the SP effect requires us to assume that the accessory tone affects specifically those response activation processes that are tight to the specifically presented prime information in the current trial. That is if a left-pointing prime is presented then temporal attention increases specifically the accumulation rate for the left response accumulator and vice versa for a right-pointing prime. Given this assumption, the VAM can successfully simulate the increasing difference between the SP effects across the PTI in the tone and the no-tone conditions. By contrast, as can be seen in Fig. 7b, the VAM would not allow to simulate the present findings when assuming that the response threshold is nonspecifically reduced in the tone relative to the no-tone condition; in that case, the model predicts equal decreases of RTs for both congruent and incongruent trials in the tone as compared to the no-tone condition, with a constant difference between the two types of RTs (i.e., the SP effect). Figure 7b illustrates that the assumption of a lowered response threshold (*c*) would predict the same decrease of RTs in the tone and no-tone conditions for congruent and for incongruent trials and does not allow for simulating the changing size of the SP effect under the tone conditions. The same pattern of the SP effect would result if one assumes an unspecific increase of the response activation level due to the accessory tone.

Other authors have located the effects of neutral warning signals (or accessory stimuli) primarily on the motor stages of choice RT tasks. For example, Posner (1978) proposed that the presentation of auditory warning signals leads to a phasic burst of the motor readiness, which shortens especially the motor execution during choice RT tasks (see also Tandonnet, Burle, Vidal, & Hasbroucq (2003) for neurophysiological evidence). According to a motor execution account the presentation of the accessory stimulus may have led to a general increase of motor readiness shortly below the motor threshold, as compared to a no-tone condition. The presentation of the primes then would add the lacking amount of activation that is necessary to exceed the motor threshold. However, a motor execution account may explain only part of the present findings namely the observation that the RTs are generally shorter in the tone than in the no-tone condition. However, it cannot explain the dynamics of this effect across the PTIs, and, more importantly, it cannot explain why we get even a stronger increase—that is, a prolongation—of the incongruent RTs in the tone relative to the no-tone condition. In order to explain this pattern of findings one must assume that the accessory stimulus does affect the decision stage of the tasks.

The locus of the temporal attention effect and the subliminal-priming paradigm

An assumption needs to be discussed, according to which, in the present paradigm, the temporal attention effect was not directed on the target but on the prime processing. This objection may be raised if taking into account that in the present experiments the PTI manipulation was paralleled by the manipulation of another time interval—the interval between the accessory stimulus and the prime. We call this latter interval the API. The API varied in opposite direction to the variation of the PTI; when the PTI was large then the API was short (and the tone effect was largest) and when the PTI was short then the API was long (and the tone effect was smallest). Therefore, theoretically, it could be that the accessory tone had directly affected the processing of the prime stimulus and the varying time of the API was responsible for the observed manipulation of the SP effect and not the allocation of attention on the target. Importantly, in that case the accessory stimulus should have improved the processing efficiency of the prime stimulus mostly under the condition of the shortest API—that is, the longest PTI—as compared to the longest API—that is, the shortest PTI. However, such a view seems not plausible because of the findings of an additional experiment, which tested the efficiency of prime processing under a condition that attention had directly been allocated to the prime stimulus. Briefly, in that additional experiment we presented the prime stimulus as a visible black-colored left or right pointing arrow by omitting the masking target stimulus; the accessory stimulus was presented with random intervals before the "prime" stimulus, which equalized the APIs in Experiments 1 and 2; the intervals were calculated as 250 ms minus size of the PTI and amounted to 148, 165, 182, 199, and 233 ms. Participants responded as fast as possible on the black arrows (with spatially corresponding motor responses [the neutral prime was omitted]). As a result the accessory stimulus decreased more strongly the reaction times on the "prime" stimulus the longer the API, $F(4, 64) = 9.4$, $p < .001$. That is the processing of the "prime" stimulus benefited most under the condition of the longest API, which is opposite to the direct prime influence view; in the condition without accessory stimulus, we found no effect of the API on the reaction times ($p < .71$).

Temporal attention and prime visibility

A further issue, which needs consideration, is whether temporal attention might have affected the size of the SP effect by improving prime visibility. The possibility that the anticipation of target presentation may affect the SP effect due to improved prime visibility was recently investigated in a study by Sumner et al. (2006).

In our view, the present findings are not consistent with an assumption that the effect of the accessory tone on the SP effect was mediated by an enhancement of the representation of the prime. Whereas in Experiment 1 we found increased values of prime visibility under condition of a prime duration of 34 ms, the prime visibility was not different from zero under conditions of short prime duration (17 ms) in Experiment 2. Importantly, despite these differences in prime visibility across experiments, we found the same pattern of an influence of the accessory tone on the size of the SP effect. This, in particular, rules out that prime visibility was the decisive factor for the tone-dependent modulation of the SP effect. In addition, the amount of prime visibility was not affected by the accessory tone condition in Experiment 1 nor in Experiment 2, which suggests that the allocation of temporal attention did not cause any main effects on the conscious representation of the prime stimuli.

Nevertheless, one might argue that not prime visibility in general has caused the observed findings but changes in masking strength across different PTIs in combination with the presentation of the accessory tone. Indeed, several studies have shown that masking strength depends on factors like the interval between prime and mask, the duration of stimuli and masks just as stimulus luminance (Breitmeyer, Ogmen, &

Chen, 2004; Enns & Di Lollo, 2000; Francis, 1997). For the case of the particular arrow stimuli applied in the present study, Vorberg et al. (2003) have shown that prime visibility was strongly increased, as compared to chance performance, and changed with PTI under conditions of mask durations (14 and 42 ms) and for primes with a duration of 14 and 42 ms, respectively. However, most importantly, for experimental conditions resembling the present timing conditions most closely—for example, a prime duration of 14 ms and a mask duration 140 ms—Vorberg et al. (2003) have shown that prime recognition performance did not vary with PTI and did not differ from chance performance. This is consistent with the prime visibility data of the present Experiment 2 in which the prime lasted 17 ms and the mask 150 ms and in which we did not find any changes in prime visibility across the PTIs in both the tone and the no-tone condition. Although, one cannot exclude an impact of changing prime visibility across PTIs on the findings in Experiment 1, the combined findings of Experiments 1 and 2 exclude a masking strength interpretation of the present data. If varying masking strength at different PTIs had been responsible for the attention-related influence on the SP effect, then we would expect such an effect especially in Experiment 1 and not in Experiment 2, and this prediction is not supported by the present findings.

Summary

The present work suggests that the effect of temporal attention on the size of the SP effect interact with the time duration of prime processing. Moreover, we find that the longer the time for the prime processing, the stronger the influence of temporal attention on size of the SP effect. This holds for a PTI range varying between 17 and 102 ms. The resulting dynamics in the size of the SP effect due to temporal attention can be accounted by an accumulator model—the VAM proposed in this work. According to that model the accumulation rates for prime- and target-related response information differ from each other. The assumption that the allocation of temporal attention increases the accumulation rate for the prime-related response information allows a simulation of the temporal dynamics of the SP effects under different conditions of the allocation of temporal attention with sufficient goodness of fit.

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Appendix I

The original AM and the modified VAM assume two accumulators whose activations obey a stochastic immigration–death process. To illustrate this process, we may think of a waiting queue, at which people queue up at a constant immigration rate λ and leave the queue at a rate that is proportional to a death rate v and the number of people in the queue. Then the Immigration–Death process with parameters λ and v describes mathematically the length of the queue, which in turn corresponds to the activation of the accumulator. To be more specific mathematically, the mean activation of an accumulator at time t is given by

$$n = \left(\frac{\lambda}{v}\right)(1-e^{-vt}) + n(0)e^{-vt},$$

where $n(0)$ denotes the initial activation at time $t = 0$.

In our model, the response of each hand of the subject is related to an accumulator with mean activity

$$n_j = \left(\frac{\lambda_j}{v}\right)(1-e^{-vt}) + n_j(0)e^{-vt}, 0\leq t\leq s, \tag{A1}$$

between the prime and the target presentation with the variables n_L, λ_L, n_R, and λ_R for the left and right hands, respectively. Here, the decay rate v is the same for both accumulators and s represents the time point of the target presentation—that is, s = PTI. The corresponding mean activation of the accumulators after the target stimulus is given by

$$n_j = \left(\frac{\lambda_j}{v}\right)\left(1-e^{-v(t-s)}\right) + n_j(s)e^{-v(t-s)}, s\leq t. \tag{A2}$$

Importantly, we point out that the parameters λ_L, λ_R in Eq. A2 are different from the parameters λ_L, λ_R in Eq. A1 in the VAM, whereas they are identical in the original AM. In other words, the VAM presumes different immigration rates before and after the target presentation. Considering the latter activations, the participant responds to the stimuli if the difference of both activations $d(t) = n_L(t) - n_R(t)$ exceeds the threshold value c. Consequently, the reaction time (RT) of the participant is determined implicitly by

$$d(s + \mathrm{RT}) = c. \tag{A3}$$

This means that one has to invert mathematically the function d in order to gain the RT.

In the following paragraphs, we discuss the model for the specific experimental conditions. Without loss of generality and for simplicity, the paragraphs show the model for left-arrow prime stimuli. A similar treatment is possible for right-arrow prime stimuli.

The congruent condition

In this condition, the mean activation of the accumulators is modeled by Eq. A1 and the parameters $\lambda_L = \lambda_P + \lambda_b$, $\lambda_R = \lambda_b$ between the prime and the target presentations, whereas the mean activation of the accumulators after the target presentation is defined by Eq. A2 and $\lambda_L = \lambda_T + \lambda_b$, $\lambda_R = \lambda_b$. Here, λ_b denotes the background activation rate, which is independent of the stimuli.

We observe that, under the present condition of a left-arrow prime stimulus, the accumulation rate of the right hand λ_R is smaller than the rate of the left hand λ_L at all times. Moreover, the different accumulation rates λ_P and λ_T before and after the target presentation, respectively, are presumed in the proposed VAM, with $\lambda_P < \lambda_T$. This contrasts to the AM of Vorberg et al. (2003), which assumes identical accumulation rates $\lambda_P = \lambda_T$. In addition to this extension, the accumulation rate λ_P increases exponentially for increasing PTIs with rate r:

$$\lambda_P(s) = \lambda_T + (\lambda_{P0} - \lambda_T)e^{-rs}. \quad \text{(A4)}$$

Hence, the values of λ_P change between the lowest value λ_{P0} and the maximum value λ_T. This variable accumulation rate is missing in the AM of Vorberg et al. (2003), as well. Then, taking into account Eq. A3 in order to gain the RT, we find

$$RT_{cong} = \left(\frac{1}{v}\right)\ln\left(\frac{\lambda_P(1-e^{-vs}) - \lambda_T}{(cv - \lambda_T)}\right), \quad \text{(A5)}$$

with λ_P taken from Eq. A4.

The incongruent condition

In this condition, the mean activation of the accumulators is modeled by Eq. A1 and the parameters $\lambda_L = \lambda_b$, $\lambda_R = \lambda_P + \lambda_b$ for the time interval between the prime and target presentations, whereas the mean activation of the accumulators after the target presentation is defined by Eq. A2 and the parameters $\lambda_L = \lambda_T + \lambda_b$, $\lambda_R = \lambda_b$, which are the same as in the congruent condition. Comparing the latter parameters with the parameters in the congruent condition, now the accumulation rate of the left hand λ_L is smaller than the rate of the right hand λ_R between the prime and target presentations. Moreover, the accumulation rates of prime and target λ_P and λ_T are different in the proposed model, a situation similar to the congruent condition.

Then, applying Eq. A3, we gain the RT

$$RT_{incong} = \left(\frac{1}{v}\right)\ln\left(\frac{-\lambda_P(1-e^{-vs}) - \lambda_T}{(cv - \lambda_T)}\right), \quad \text{(A6)}$$

with λ_P taken from Eq. A4.

The priming effect

Finally, the priming effect represents the difference of the RTs in the incongruent and congruent conditions, given by Eqs. A5 and A6, respectively, and we gain

$$SP = RT_{incong} - RT_{cong} = \left(\frac{1}{v}\right)\ln\left(\frac{\lambda_P(-1 + e^{-vs}) - \lambda_T}{\lambda_P(1 - e^{-vs}) - \lambda_T}\right). \quad \text{(A7)}$$

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