



Unconscious and out of control: Subliminal priming is insensitive to observer expectations



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ABSTRACT

We asked whether the influence of an invisible prime on movement is dependent on conscious movement expectations. Participants reached to a central target, which triggered a directional prime–mask arrow sequence. Participants were instructed that the visible arrows (masks) would most often signal a movement modification in a specific (biased) direction. Kinematic analyses revealed that responses to the visible mask were influenced by participants' intentional bias, as movements were fastest when the more probable mask was displayed. In addition, responses were influenced by the invisible prime without regard to its relationship to the more probable mask. Analysis of the time of initial trajectory modifications revealed that both primes influenced responses in a similar manner after accounting for participants' bias. These results imply that invisible stimuli automatically activate their associated responses and that unconscious priming of the motor system is insensitive to the conscious expectations of the participant making the pointing movements.

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1. Introduction

Visual masked priming can be used to explore visuomotor processing in the absence of conscious awareness. In a typical masked priming experiment, participants are instructed to make a speeded response based on a feature of a visible target shape (*mask*): for example, to press a left or right key in response to the direction of a centrally presented large arrow (see Vorberg, Mattleer, Heinecke, Schmidt, & Schwarzbach, 2003). Unbeknownst to the participants, an arrow shape (*prime*) precedes the mask shape, pointing in either the same or opposite direction as the subsequent mask. Even though the prime is rendered invisible to consciousness as a result of metacontrast masking (for reviews see Breitmeyer, 1984; Breitmeyer & Ogmen, 2000; Enns & Di Lollo, 2000; Kahneman, 1968), response times to the mask are dependent on prime–mask congruency. In particular, response times are facilitated when the prime shares attributes critical to the correct response (congruent trial) and delayed when it shares attributes critical to the alternative response (incongruent trial) (Ansoorge, Heumann, & Scharlau, 2002; Dehaene et al., 1998; Neumann & Klotz, 1994; Schmidt, 2002; Taylor & McCloskey, 1990, 1996).

To explain how subliminal primes influence action, Kiesel, Kunde, and Hoffmann (2007) and Kunde, Kiesel, and Hoffmann (2003) have proposed the Action-Trigger Hypothesis (ATH), an elaboration of Neumann's (1990) theory of Direct Parameter Specification. According to the ATH, the ability of a subliminal stimulus to influence action is governed by one's intentions. Specifically, the model proposes that action triggers are established based on task demands, such that task relevant stimuli

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are mapped to appropriate responses. After establishing action triggers, stimulus processing is then restricted to determining whether an incoming stimulus is associated with an action trigger. If a match is obtained, the related action trigger is activated automatically, independent of participants' conscious awareness, with the potential to evoke a response. In particular, as suggested by Vorberg et al.'s (2003) accumulator model of priming, a response will be initiated when the accumulated neural evidence for one response alternative (or action trigger) vs. the opposite response alternative (the second action trigger) achieves a critical value. Thus, processing of a subliminal prime leads to activation of its associated response, driving the difference in accumulators towards the response associated with the prime.

In support of the ATH, electrophysiological indices of motor-related cortical activation and behavioural results have demonstrated that invisible primes activate their corresponding responses. In general, electrophysiological studies have derived lateralized readiness potentials (LRPs) from motor-related cortical activity during the reaction time interval of metacontrast masking experiments (e.g., Dehaene et al., 1998; Eimer & Schlaghecken, 1998; Jaskowski, Skalska, & Verleger, 2003; Leuthold & Kopp, 1998; Vath & Schmidt, 2007). Vath and Schmidt (2007) have shown that, in addition to obtaining the expected prime–mask congruency effects outlined above, the time-course and shape of the LRP indicate that the masked primes can activate the corresponding response at the level of the motor cortex.

Behavioural results from Schmidt et al. have demonstrated that even early phases of a movement can be governed by a prime (Schmidt, 2002; Schmidt, Niehaus, & Nagel, 2006; Schmidt & Schmidt, 2009, 2010; Schmidt & Seydell, 2008). In Schmidt's paradigms, participants were instructed to initiate a movement in a direction dictated by a mask stimulus. By analyzing the kinematics of the resulting movements, Schmidt found that the time of movement onset and direction was influenced by the prime, independent of the subsequent mask. Consistent with these results, Cressman, Franks, Enns, and Chua (2007) showed that an invisible prime stimulus can activate its associated response even when its presentation occurred during an already initiated action, demonstrating that a prime not only influences response selection or initiation processes but can also take over on-line control of one's movements.

In the paradigm by Cressman et al. (2007), participants were given the fixed movement goal of completing a rapid movement to a central target location. On the majority of trials a neutral prime–mask sequence was presented in the central target after movement initiation. On a small percentage of trials, the neutral sequence was replaced with a directional prime–mask arrow sequence. The directional mask was the signal for participants to change their pointing direction from the central target and move toward either a left or right eccentric target location, as specified by the direction of the mask arrow. Although participants were not conscious of the primes, kinematic analyses revealed that movement trajectories deviated in the direction of the prime (left or right) before deviating in the direction of the visible mask.

Although the ATH (Kiesel et al., 2007; Kunde et al., 2003) proposes automatic activation of established action triggers, the detailed content of these action triggers is not specified. Recent results by Jaskowski et al. (2003), Wolbers et al. (2006) and Ansoorge et al. (2002), suggest that one is able to strategically mediate a prime's influence on response initiation. Jaskowski et al. (2003) manipulated the percentage of congruent and incongruent prime–mask trials between blocks of trials, reporting that a prime's influence was greater when there was a higher percentage of congruent trials. Jaskowski concluded that this action modification arose strategically, as a function of participants observing their own overt errors. While this study implies that the prime's influence on movement may be modified under certain circumstances, it remains unclear if consciously manipulating the probability of a mask-related response will lead to changes in how action triggers are established and hence affect automatic prime-related processing.

In the present study we tested whether the probability of making a movement in one direction or another has an influence on these prime-evoked directional responses. Specifically, we asked whether action triggers are established equally for low and high probability responses. To address this question, we manipulated the baseline probability of the directional masks that participants saw and responded to on each trial. Specifically, we modified the protocol of Cressman et al. (2007) such that on 80% of trials in which a mask arrow was presented, it pointed in a particular direction (either right or left). Participants were instructed of this bias and their experience in the testing session confirmed that one directional mask appeared with much greater frequency than the other mask.

Given that participants had both conscious knowledge and specific experience to support the expectation that one direction of movement modification would be more likely than another direction, we expected them to bias their movements intentionally. We anticipated that this bias would lead to faster responses when the more probable mask was displayed compared to the less probable mask (Blackman, 1972; Hawkins, MacKay, Holley, Friedin, & Cohen, 1973; LaBerge, Legrand, & Hobbie, 1969; Heuer, 1982; Schlaghecken & Eimer, 2001). Taking this conscious tuning of the response system into account (Bertelson & Barzelee, 1965; Gehring, Gratton, Coles, & Donchin, 1992; Laming, 1969; Miller, 1998), we then looked to determine whether action triggers were established equally for the two directional primes by asking two questions: (1) Does prime–mask congruency influence responses to the mask independent of the mask displayed? (2) Do the two directional primes automatically trigger their associated motor responses? If the influence of prime–mask congruency is similar across spatial–temporal movement parameters, independent of the mask probability (and thus the probability of making one response over the other), it would suggest that action-relevant stimuli are mapped to their respective responses, without any record of their relative probability. Alternatively, if the two primes differ in their influence on action under these conditions, it would imply that automatic movement modifications in response to unseen visual shapes are influenced by conscious expectations and tuning of the motor system. The implication of such a result for the ATH is that action triggers store information about response probability.

Two experiments are reported. In Experiment 1 we examined the influence of primes in the face of differential expectations about two movement possibilities. In this experiment the visibility of the primes was assessed by asking participants at the end of the speeded pointing task whether they noticed any of the prime shapes. In Experiment 2 we repeated the priming task with a new group of participants, but in this case they were also asked on each trial to make a discrimination of which prime shape had been presented.

2. Experiment 1: the influence of primes on biased motor responses

2.1. Method

2.1.1. Participants

Twelve right-handed university students (mean age = 22.3 ± 4.8 years) with normal or corrected-to-normal visual acuity participated in this study. Participants were paid \$20 for their involvement. All participants gave informed consent, and the study was conducted in accordance with the ethical guidelines set by the University of British Columbia.

2.1.2. Stimuli and apparatus

Shapes were presented in white on a black background (19" monitor, 70 Hz refresh), oriented 15° from the horizontal. A central home position for the hand (a 12 mm circle) was at the bottom of the display and all stimuli were presented in a central square target (3.3 cm^2), 27 cm above the home position. Two additional squares (3.3 cm^2), serving as left and right targets, were separated horizontally by 7 cm (centre-to-centre distance) from the centre target. Participants viewed the display from a distance of approximately 60 cm, with their head movements restricted by a chin-rest that aligned their heads with the centre of the display, and their right hand holding a stylus.

Prime shapes ($4 \text{ mm} \times 9 \text{ mm}$) consisted of left and right pointing arrows, as well as a neutral shape formed from the superimposition of the two arrows. Masks consisted of larger ($23 \text{ mm} \times 28 \text{ mm}$) versions of the same shapes as the primes, with a central cutout as shown in Fig. 1. The outer contour of the prime stimuli fit exactly within the inner contour of the masks. Primes were presented for 14 ms and the prime–mask stimulus-onset asynchrony (SOA) was set at 56 ms.

Position of the stylus tip was monitored in three dimensions using an OPTOTRAK (Northern Digital, Waterloo, Ontario) motion analysis system (spatial resolution 0.01 mm). The stylus tip was equipped with a microswitch that provided a signal indicating whether or not the stylus was in contact with the surface of the display. The 3D stylus position and microswitch status were sampled at 500 Hz. Movement time was measured from stylus lift-off to stylus contact with the display.

2.1.3. Procedure

On each trial, following the onset of the three target squares, participants initiated a pointing movement from the home position to the central square target. A breakdown of the number of trials completed by each participant is provided in

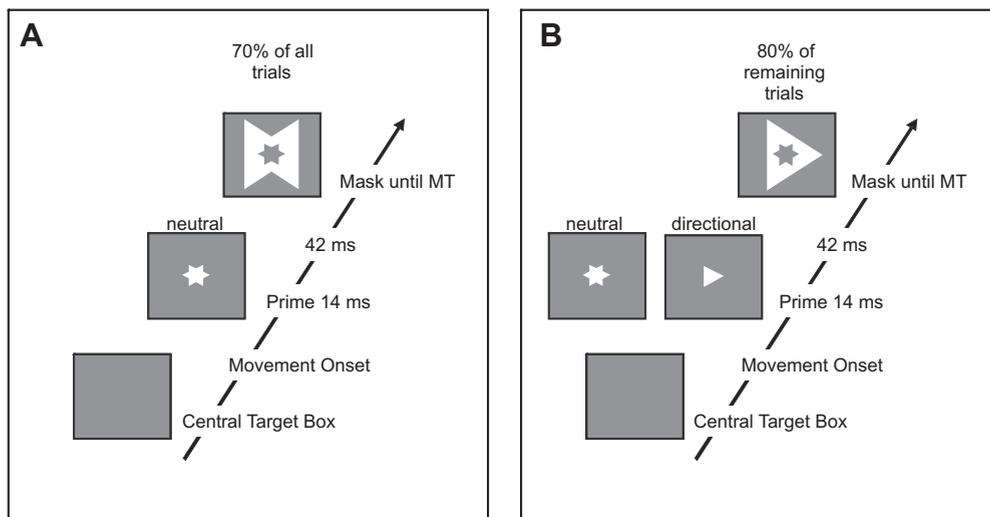


Fig. 1. Temporal sequence of a direct pointing trial (A) and a perturbed pointing trial (B). In the pointing task, 70% of the trials were direct pointing trials in which participants were cued to move to the central target (neutral prime + neutral mask). On the remaining 30% of trials (perturbed trials), participants had to modify their final movement goal in the direction specified by the mask (left or right). On the majority of perturbed trials (80%) a specific directional mask was presented (e.g., right). The directional masks were preceded by neutral or directional primes. On all trials the prime–mask sequence was displayed upon movement onset.

Table 1

Number of trials completed for each prime–mask combination for participants who completed the Mask Pointing task in Experiment 1 (Point) and the Mask Pointing + Perceptual Discrimination task in Experiment 2 (Point + Dis.). In Experiment 1 the neutral mask was always preceded by the neutral prime (N). In Experiment 2, the neutral mask was preceded by all primes with equal probability (neutral prime (N), prime congruent (C) with high probability mask (HPM), prime incongruent (I) with high probability mask).

Prime	Neutral mask			High probability mask (HPM)			Low probability mask (LPM)		
	C with HPM	I with HPM	N	C	I	N	C	I	N
Point	0	0	350	40	40	40	10	10	10
Point + Dis.	120	120	120	36	36	36	12	12	12

Table 1. On 70% of the trials (direct pointing), movement of the stylus initiated the appearance of the neutral prime shape (14 ms) in the central box followed by a neutral mask shape (SOA = 56 ms). On the remaining 30% of trials (perturbed pointing), the prime was one of three shapes (displayed with equal probability: left arrow, right arrow, or neutral shape) and the mask in the central box was either a left or a right pointing arrow. Participants were not told of the primes. The mask arrow was the signal for participants to change their pointing direction towards the eccentric target indicated by the arrow. Participants were told that on the majority of the perturbed trials (80% of the perturbed trials) a right (or left) arrow would appear, and that it was their signal to move to the target indicated by the arrow. On the remaining 20% of the perturbed trials a left (or right) arrow would appear and participants were to move to the target indicated by the arrow. Participants were given a movement time goal of 300–500 ms and movement time feedback was provided verbally by the experimenter following all direct pointing trials.

Participants completed two 1 h testing sessions on separate days. Each testing session began with 20 practice trials of direct pointing, followed by 250 test trials. In the test trials the direction of the biased mask (e.g., right (or left) mask arrow displayed on 80% of perturbed trials) was counterbalanced across participants, such that half of the participants were instructed that the right (or left) mask would be displayed on the majority of trials. Participants completed all trials with the same instructional bias across the two testing days.

2.1.4. Analysis

Raw data from all pointing responses were collected by the OPTOTRAK and converted into 3D coordinates. These data were then digitally filtered using a second order dual-pass Butterworth filter with a low-pass cutoff frequency of 10 Hz.

In order to determine the motor influence of the primes, we compared individual perturbed trials in which participants moved to the correct eccentric target to an average spatial trajectory computed from the direct pointing trials. On average, participants adjusted their pointing movements and landed at the correct eccentric target on the majority of perturbed trials (mean corrected trials = 83.6% ± 14.7 SD). With respect to the direct pointing trials, the average spatial trajectory in the 2D plane was calculated for all direct pointing trials for each participant. The points in this average trajectory were obtained by deriving the mean lateral spatial position in the x - y plane for every 2 mm of forward movement progression. If a trajectory did not have a position value at the exact spatial location required, one was obtained by linear interpolation from the closest data points. In addition, the standard deviation of the mean position in the x -direction was calculated. The resulting mean spatial trajectory, together with its 2 standard deviation (SD) bandwidth, then became the standard against which pointing movements on perturbed trials were assessed (see Cressman et al., 2007).

We examined the temporal and spatial characteristics of the perturbed trials by analyzing movement times (MTs) as determined by the status of the microswitch in the stylus, the time of final trajectory modifications to the mask, the time of initial trajectory modifications to the prime, and the lateral distance travelled during movement completion, across the different prime–mask sequences in comparison to the standard for direct pointing trials. In Fig. 2, we provide example trajectories showing how these dependent measures were derived. For each perturbed pointing trial, the time of final trajectory modification was defined as the point in time at which displacement in the horizontal axis of the movement reached a maximal value and showed a reversal toward the appropriate eccentric target. The time of initial trajectory modification was defined as the point in time at which displacement in the lateral movement axis first reached a reversal point in the trajectory such that following this reversal point the movement fell outside of the 2 SD bandwidth of the direct pointing trials. It was expected that participants would only modify their movements once on perturbed trials in which a neutral or congruent prime was displayed. In these cases, the initial and final trajectory modifications would have the same value. The lateral displacement made in completing the pointing movement to the correct eccentric target was defined as the distance travelled from the point in the trajectory corresponding to the final trajectory modification to the eccentric target. Regardless of the direction of trajectory modification, data were categorized according to the mask presented (high probability mask vs. low probability mask) and the prime's direction relative to the mask displayed (congruent (same direction), incongruent (opposite direction), or neutral). Data were then analyzed using a 2 Bias Direction (left mask displayed on the majority of perturbed trials vs. right mask displayed on the majority of perturbed trials) × 2 Mask (high probability mask vs. low probability mask) × 3 Prime Congruency (congruent, incongruent, neutral) analysis of variance (ANOVA) with repeated measures on the last two factors. Tukey's Honestly Significant Difference (HSD) post hoc tests were administered to determine the locus of these differences ($\alpha = .05$).

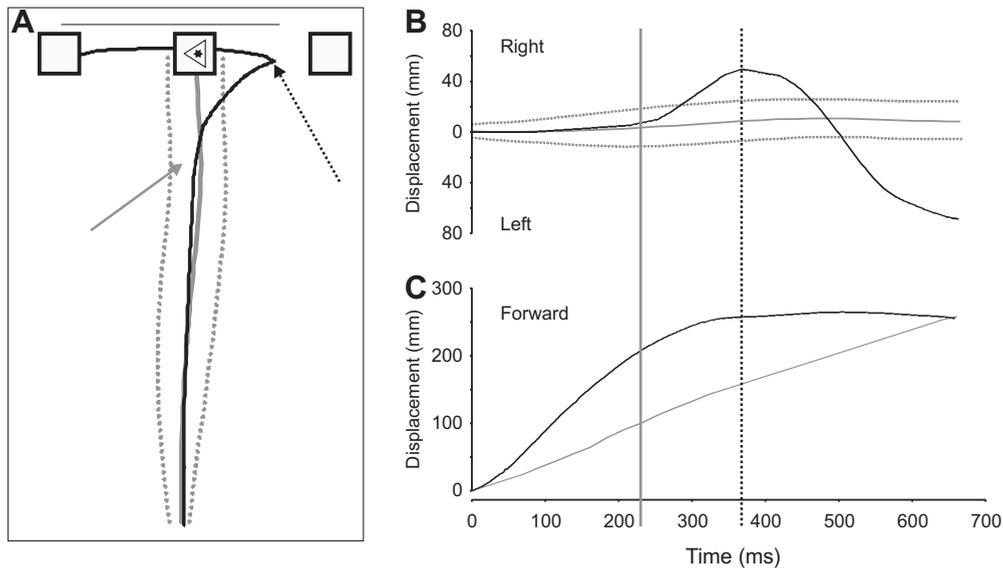


Fig. 2. Schematic illustrating how the different dependent measures were determined. In (A) we show an individual perturbed trial in which a prime pointing in the same direction as the high probability mask preceded the low probability mask (solid black line). This perturbed trial was compared to the participant's mean spatial trajectory for the direct pointing trials (grey solid line) with its 2 standard deviation (SD) bandwidth (dashed grey lines). The eccentric and central target boxes are displayed, with a left mask arrow (low probability mask in this instance) being presented in the central target box. For this perturbed trial, the trajectory is first modified in the direction of the prime (falling outside the 2 SD bandwidth of the direct pointing trials), and is then corrected in the direction of the mask. In order to quantify the priming effects, we examined the time at which these modifications occurred. In (B) and (C) we plot the changes in horizontal and vertical displacement as a function of time respectively. Displacement for the perturbed trial is shown as the solid black line. Displacement for the mean direct pointing trials is provided as a guideline (grey solid line with its 2 SD bandwidth shown in (B) as dashed grey lines), extended across the time taken to complete the perturbed trials. In general, movements were completed much faster in the direct pointing trials compared to the perturbed trials. The first trajectory modification was taken as the point in time at which displacement in the lateral movement axis first reached a reversal point in the trajectory such that following this reversal point the movement fell outside of the 2 SD bandwidth of the direct pointing trials (indicated by the grey arrow in (A), which corresponds to the grey line in (B) and (C)). The time of final trajectory modification was defined as the point in time at which displacement in the horizontal axis of the movement reached a maximal value and showed a reversal toward the appropriate eccentric target (indicated by the black arrow in (A), which corresponds to the dashed black line in (B) and (C)). The lateral displacement made in completing the pointing movement to the correct eccentric target was defined as the distance travelled from the point in the trajectory corresponding to the final trajectory modification to the eccentric target (black horizontal line displayed above the trajectories in (A)).

2.2. Results

When asked whether they were aware of the smaller prime shapes shown in advance of the larger mask target shapes, all participants indicated they were completely unaware of the presence of the primes. The motor influence of these prime shapes was examined in analyses of mean movement times and the times of trajectory modifications to the correct eccentric target.

2.2.1. Movement time is influenced by probability of movement direction, but prime–mask congruency has no additional influence

On direct pointing trials, participants were quite successful in completing their movements in response to the visible mask within the required time window of 300–500 ms (mean MT = 412 ms + 18.1 SD). On perturbed pointing trials, movement times increased as shown in Table 2 and summarized in Fig. 3a. MT was shorter for the high probability mask (mean

Table 2

Mean (SE) movement times (ms), times of final trajectory modification to the mask (ms), lateral displacement to the correct eccentric target (mm), and response times to the primes (ms) for participants who completed the Mask Pointing task in Experiment 1 (Point) and the Mask Pointing + Perceptual Discrimination task in Experiment 2 (Point + Dis.). Primes were congruent (C), incongruent (I) or neutral (N) with respect to the mask.

Prime	Participant group	High probability mask (HPM)			Low probability mask (LPM)		
		C	I	N	C	I	N
Movement time (ms)	Point	551 (17)	584 (14)	603 (17)	587 (17)	625 (17)	631 (17)
	Point + Dis.	573 (30)	631 (36)	616 (27)	627 (48)	686 (67)	684 (46)
Modification to the mask (ms)	Point	299 (6)	337 (5)	342 (6)	329 (5)	360 (5)	361 (6)
	Point + Dis.	300 (19)	354 (26)	345 (17)	336 (41)	389 (46)	374 (27)
Lateral displacement	Point	68.2 (4.2)	71.2 (3.4)	68.9 (2.7)	69.0 (3.7)	80.1 (7.3)	69.6 (2.7)
Modification to the prime (ms)	Point	299 (6)	322 (4)	342 (6)	329 (5)	314 (9)	361 (6)

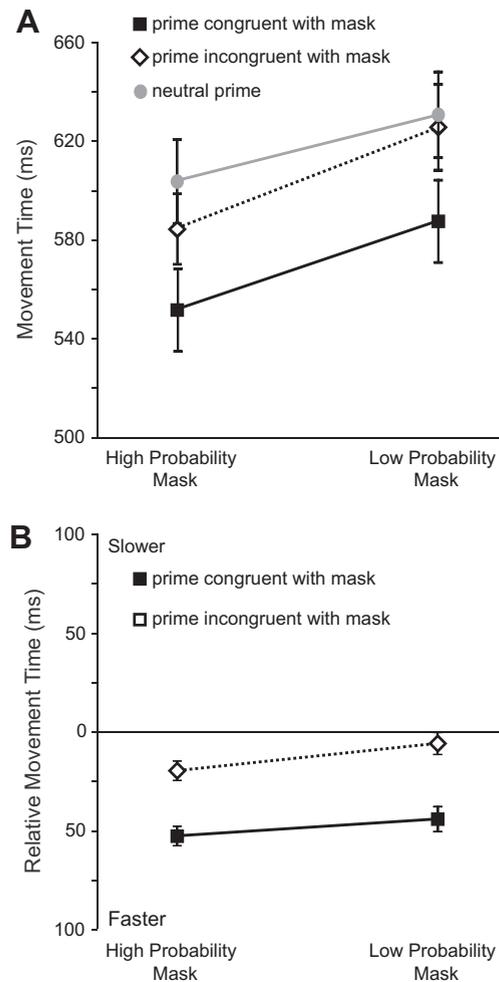


Fig. 3. Effect of the prime–mask sequence on (A) movement time (ms) and (B) movement time relative to trials in which a neutral prime preceded a directional mask (ms). Results are displayed with respect to the prime’s relation to the high (left symbols) and low probability mask (right symbols) (e.g., congruent (black squares), incongruent (white diamonds) or neutral (grey circles)). Error bars denote standard errors. Participants completed their movements earlier on trials in which the prime and mask pointed in the same direction, regardless of the directional prime displayed.

MT = 579 ms) compared to the low probability mask (mean MT = 614 ms), $F(1, 10) = 27.646$, $p < .001$.¹ MT also differed significantly depending on which invisible prime was presented. Specifically, MT was shortest for congruent primes (mean MT = 569 ms), intermediate for incongruent primes (mean MT = 604 ms), and slowest for neutral primes (mean MT = 617 ms), $F(2, 20) = 71.720$, $p < .001$.

However, prime–mask congruency had no additional influence on movement time. As shown in Fig. 3a, the differences in MT between congruent, incongruent and neutral primes trials were similar for both the high probability and low probability mask conditions, such that there was no Mask \times Prime Congruency interaction, $F(2, 20) = 1.970$, $p = .166$. This additive relationship indicates that the influence of the invisible prime was not affected by the probability expectation associated with the visible mask. Most notably, participants even completed their movements faster when the neutral prime was followed by the high probability mask compared to the low probability mask (high probability mask: mean MT = 603 ms vs. low probability mask: mean MT = 631 ms). This difference could not have arisen due to changes in subliminal processing, as on these trials the same neutral prime was presented. Rather, the difference in results between the neutral prime trials reflects

¹ Statistical analysis also revealed a significant Bias Direction \times Mask interaction ($F(1, 10) = 15.856$, $p = .003$), and post hoc analyses indicated that significant differences in MT between responses to the high probability vs. low probability mask were only present for participants who responded more often to the right mask (i.e., the right mask was biased). Differences in MT between the high probability vs. low probability mask were likely not seen for participants who responded more often to the left mask due to differences in one’s ability to perform ipsilateral (corresponding to movements in the low probability direction for these participants) vs. contralateral reaches (corresponding to movements in the high probability direction for these participants). Specifically, ipsilateral (rightwards) reaches are typically completed more rapidly than contralateral reaches (Fisk and Goodale, 1985).

differences in visuomotor processing of the visible masks as a consequence of the instructions provided, revealing participants' intentional response bias.

To factor out participants' intentional biases from their responses to the primes, Fig. 3b plots only the differences in MT between the two directional primes and the neutral prime for both masks. These times were similar regardless of mask probability ($F(2,20) = 0.304, p = .742$), implying that the directional primes led to faster movements when they were congruent with the following mask, independent of participants' intentional bias.

Although the preceding analysis documented the influence of the invisible primes on movement trajectories, independently from participants' response biases, it did not provide any information on the temporal or spatial course of these priming effects. In the following analyses we determined the influence of both mask probability and prime–mask congruency on final adjustments made to movements (in response to the visible mask) and on initial movement modifications (in response to the invisible prime).

2.2.2. Responses to the mask are influenced by probability of movement direction, but prime–mask congruency has no additional influence

Fig. 4 shows the average time of final trajectory modifications towards the target indicated by the visible mask for the factors of mask probability and prime–mask congruency. These data show that participants were faster to modify their movements in response to the high probability mask, $F(1,10) = 83.853, p < .001$. They also show faster responses to the mask when congruent primes were displayed compared to incongruent or neutral primes, $F(2,20) = 56.054, p < .001$, with post hoc tests indicating that the only significant differences were between the congruent prime and the other two conditions ($p < .05$). But as in the previous analysis of movement time, prime congruency had a similar influence on final trajectory modifications to both high and low probability masks (Mask \times Prime Congruency interaction: $F(2,20) = 1.076, p = .360$). There was no significant main effect, or any significant interaction, involving the factor of Bias Direction ($p > .05$). This suggests that the prime–mask sequence displayed had a similar effect on final trajectory modifications, regardless of the direction in which the movement was biased.

Thus far, the results shown in Fig. 4 indicate that (1) participants modified their movements earlier towards the correct target indicated by the more probable mask, reflecting the influence of participants' intentional bias, and (2) participants modified their movements earlier when the mask was preceded by a congruent prime, regardless of the mask's probability. This second finding suggests that each directional prime influenced action, regardless of the conscious expectation of movement direction associated with it.

In the next section, we turn our attention to the ability of the primes to trigger their associated responses directly. To determine if participants modified their movements in the direction cued by the primes, we focused on incongruent prime–mask trials, as it was only on these trials that we could potentially distinguish between initial responses to the prime and final responses to the mask (i.e., responses would be in opposing directions). As we indicated earlier, movement trajectories would only be expected to be modified once on congruent or neutral prime–mask trials. The potential interaction of participants' conscious influence on movement trajectories (i.e., due to intentional biases) and the subliminal influence of the primes leads us to somewhat complex predictions. Even if action triggers were established for both primes and they were processed through the system in a similar manner, the expression of their direct motor influence could nevertheless be shaped by participants' intentional bias. In particular, we reasoned that because a participant's intentional bias favoured

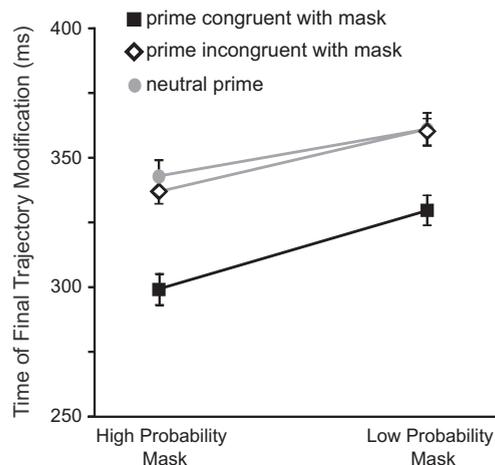


Fig. 4. Effect of the prime–mask sequence on the time of final trajectory modifications in the direction of the correct eccentric target (ms). Results are displayed with respect to the prime's relation to the high (left symbols) and low probability mask (right symbols) (e.g., congruent (black squares), incongruent (white diamonds) or neutral (grey circles)). Error bars denote standard errors. Participants modified their trajectories earlier on trials in which the prime and mask pointed in the same direction, regardless of the directional prime displayed.

the motor system to respond in a particular direction, this response bias would influence the ability of the prime to influence action. Thus, we expected to find a greater number of early overt responses to the prime pointing in the same direction as the high probability mask compared to the prime pointing in the same direction as the low probability mask. The prime pointing in the direction of the low probability mask would first have to counteract participants' intentional biases, before triggering its associated response.

2.2.3. Initial priming effects

2.2.3.1. Early trajectory modifications are seen more often in response to the prime pointing in the more probable response direction

As expected, it was only on incongruent trials that we found evidence of initial trajectory modifications that were later corrected (i.e., the first modification was in the direction of the invisible prime and the second was in the direction of the visible mask (see Fig. 5)), leading to a greater lateral distance that had to be traversed towards the final target. Moreover, as expected, we observed more overt movement modifications when the prime was pointing in the same direction as the high probability mask compared to when the prime was pointing in the same direction as the low probability mask. Based on our criteria, we distinguished initial responses in the direction of the prime on 34% of incongruent prime–mask trials when the prime pointing in the more probable response direction was followed by the low probability mask. We detected initial responses on only 8% of incongruent trials when the prime pointing in the less likely response direction was followed by the higher probability mask.

The apparent difference in the magnitude of the two directional primes' influence on movement trajectories was also reflected in the mean lateral distance made in completing pointing movements to the correct eccentric target after final trajectory modifications (see Table 2). ANOVA revealed a significant main effect for Prime Congruency ($F(2,20) = 27.997$, $p < .001$), and post hoc comparisons indicated that the greatest lateral distances were achieved on incongruent trials compared to the other prime–mask combinations (which did not differ from each other). However, ANOVA also revealed a significant Mask \times Prime Congruency interaction ($F(2,20) = 13.320$, $p < .001$), and post hoc analysis indicated that participants had a significantly greater lateral distance to travel to the correct eccentric target when the prime pointing in the more probable mask direction preceded the low probability mask (as shown in Fig. 5 and reported in Table 2, mean displacement = 80.1 mm) compared to all other prime–mask trials, which did not differ from each other. No other main effects or interactions were significant ($p > .05$). Thus, it appears that the prime pointing in the same direction as the high probability mask had a greater overt influence on action, such that it was able to take over control of participants' movements and change the trajectories to a greater extent than the prime pointing in the direction of the low probability mask.

2.2.3.2. Onset of initial priming is influenced by probability of movement direction and prime–mask congruency

While spatial trajectories demonstrated that the prime pointing in the same direction as the high probability mask had the greatest overt influence on movement, we found that the prime pointing in same direction as the low probability mask still triggered its associated response such that movements were modified in the direction of the prime on a small percentage of trials. Moreover, as shown in Fig. 6A, the times at which trajectories were first modified were dependent on the mask presented ($F(1,10) = 12.867$, $p = .005$), and prime congruency ($F(2,20) = 50.004$, $p < .001$). ANOVA did not reveal any significant effects or interactions involving the factor of Bias Direction ($p > .05$). Movement trajectories were modified earlier when

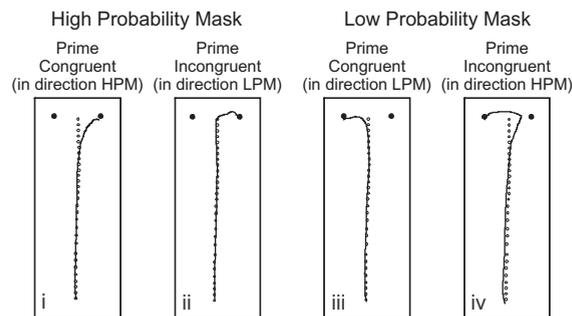


Fig. 5. Examples of mean direct spatial trajectories (open circles) and individual perturbed spatial trajectories (solid lines) when a directional prime was displayed. For this participant, the right mask was biased. In the two panels on the left, examples of trials are shown when the high probability (right) mask was displayed and preceded by a prime that was either (i) congruent with the mask (i.e., pointing in the same direction as the high probability mask and hence in the more likely (right) response direction) or (ii) incongruent with the mask (i.e., pointing in the same direction as the low probability mask and hence in the less likely (left) response direction). In the two panels on the right, examples of trials are shown when the low probability (left) mask was displayed and preceded by a prime that was either (iii) congruent with the mask (i.e., pointing in the same direction as the low probability mask and hence in the less likely (left) response direction) or (iv) incongruent with the mask (i.e., pointing in the same direction as the high probability mask and hence in the more likely (right) response direction). The centre of the eccentric target boxes are indicated by annuli (the centre target box is not visible). For this participant the right mask was displayed on the majority of trials (80%). Note the early trajectory modifications in the direction of the prime on trials in which the prime pointed in the same direction as the high probability mask (i.e., a right prime was displayed: first and last panel).

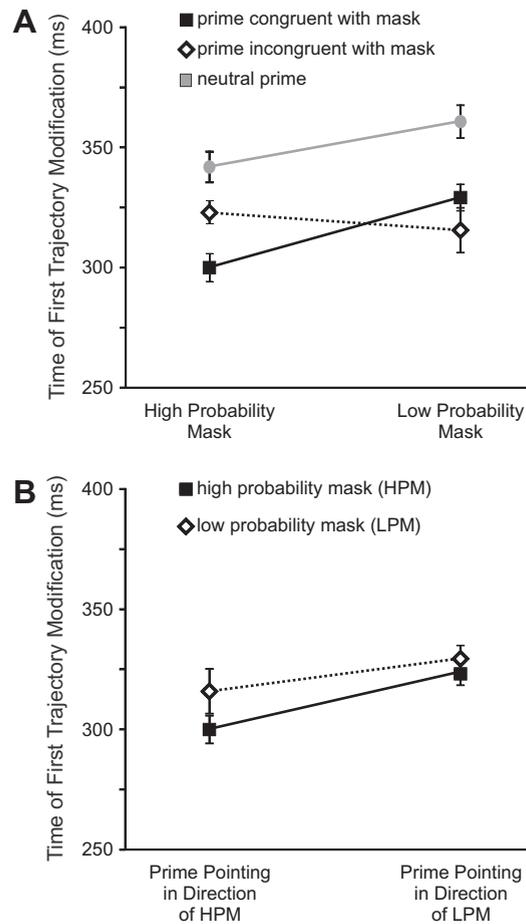


Fig. 6. (A) Effect of the prime–mask sequence on the time of the first trajectory modification from the central target (ms). Results are displayed with respect to the prime's relation to the high (left symbols) and low probability mask (right symbols) (e.g., congruent (black squares), incongruent (white diamonds) or neutral (grey circles)). (B) A subset of the data shown in (A), now illustrating the influence of the mask on the different primes (prime pointing in the same direction as the high probability mask (HPM: left symbols) and prime pointing in the same direction as the low probably mask (LPM: right symbols)) on first trajectory modifications when the high probability (black squares) and low probability mask (white diamonds) were displayed. Error bars denote standard errors. Participants' initial responses were influenced by the direction of the prime, independent of the following mask.

the high probability mask was displayed. More importantly however, with respect to prime congruency, post hoc analysis revealed that the latest modifications came on trials in which the neutral prime was displayed, and there was no difference in timing between congruent and incongruent trials, suggesting that both directional primes had an earlier influence on movements than the neutral primes.

To show that these triggered responses were indeed dependent on the prime presented, we re-plotted the data in Fig. 6B to show the time of initial movement modifications for both masks with respect to the directional primes displayed (prime pointing in the same direction as the high probability mask and prime pointing in the same direction as the low probability mask). These times were then analyzed in a 2 Bias Direction (left mask displayed on the majority of perturbed trials vs. right mask displayed on the majority of perturbed trials) \times 2 Mask (high probability mask vs. low probability mask) \times 2 Prime Direction relative to the high probability mask (same direction vs. opposite direction) ANOVA with repeated measures on the last two factors. Critically, we found that the times of initial trajectory modifications were similar regardless of the mask displayed ($F(1, 10) = 4.536, p = .06$)² and bias direction (ANOVA did not reveal any significant effects or interactions involving

² This p -value of .06 is small, potentially providing the impression that initial trajectory modifications were dependent on the subsequent mask displayed. The time of initial trajectory modifications was defined as the time in the trajectories at which displacement in the lateral movement axis first reached a reversal point in the trajectory such that following this reversal point the movement fell outside of the 2 SD bandwidth of the direct pointing trials. Thus there is the potential that a response may have been initiated to the prime, but because the response did not result in a lateral displacement that fell outside the 2 SD bandwidth criteria, the initial modification was taken as the later point in time at which participants responded to the mask. The 2 SD bandwidth criteria results in a very conservative estimate of participants' initial responses to the prime, potentially leading to many trajectory modifications to the prime going undetected. If we use a less conservative bandwidth (e.g., responses falling outside a 1 SD bandwidth of the direct pointing trials), analysis reveals a much greater p -value ($p = .225$), providing further support that participants responded in a similar manner to the prime regardless of the subsequent mask displayed.

the factor of Bias Direction ($p > .05$). Responses were modified earlier when the prime was pointing in the same direction as the high probability mask compared to when it was pointing in the same direction as the low probability mask ($F(1, 10) = 20.253$, $p = .001$), independent of the mask displayed (Mask \times Prime Direction interaction: $F(1, 10) = 0.813$, $p = .388$). Thus, even with our conservative 2 SD spatial criterion to determine initial trajectory modifications, we find that early responses were dependent on the prime presented, independent of the following mask. Taken together, these findings suggest that while one can intentionally bias their expectation of an upcoming change in pointing direction, subliminal stimuli are processed in an automatic manner, such that they begin to activate their associated responses regardless of their relationship to the more likely mask and hence response direction.

3. Experiment 2: masked priming and prime discrimination

In this experiment we conducted a more stringent test of the visibility of the primes by having participants perform both the speeded pointing task under differential expectations about movement direction and a prime discrimination task.

3.1. Method

Six new participants completed the same speeded movement task as in Experiment 1. What differed was that this time, participants were instructed that primes would be presented on each trial before starting the testing session. Specifically, participants were shown the three prime shapes and told that on each trial, prior to the mask, one of the three primes would be displayed with equal probability. After completing each reach, participants indicated which prime they thought had been presented.

In order to present the three primes with equal probability across all trials, we modified the type and number of trials of each prime–mask combination from Experiment 1. Participants now completed three blocks of 168 trials (the total number of trials completed by participants for each prime–mask combination are provided in Table 1). Within each block, the neutral mask was still displayed most often (71.4% of all trials, or 360 trials out of the 504 total trials) and participants were made aware that on the majority of trials in which a directional mask appeared (i.e., perturbed trials), it would be either a right (or left) arrow. The same right (or left) mask arrow remained more probable across all three testing blocks. The high probability directional mask was displayed on 75% of all perturbed trials. In order to ensure that all three primes were presented with equal probability in all conditions, directional primes were now also presented in advance of the neutral mask (making the percentage of direct pointing trials in which a neutral prime was followed by a neutral mask 24% of all trials).

3.2. Results

3.2.1. Prime discrimination was at chance

The percentages of correct responses for the different perturbed trials are reported in Table 3. Given that the 3 primes were displayed with equal probability, chance performance was 33%, and participants were at or below this level for directional primes. When neutral primes were presented, accuracy rose to 87%. Regarding these as “correct” responses is misleading, however, because participants showed a strong bias to report the prime as neutral when they were uncertain (see the second row of Table 3). On average, participants reported that a neutral prime had been presented on 70% (23% SD) of all perturbed trials. Taken together, these results imply that although participants may have been a little better at discriminating the neutral primes from the directional primes, they were effectively unable to discriminate the directional primes from one another.

3.2.2. Reaching movements were influenced by subliminal primes regardless of their relationship to the expected movement direction

Despite the different task demands in this experiment, participants performed their reaches in much the same way as participants in Experiment 1. That is, participants completed their movements to the centre target when the neutral prime–mask sequence was displayed within the goal movement time (mean MT = 467 ms \pm 29 SD). Similar to the previous participants, and as shown in Table 2, MT increased on perturbed pointing trials. As well, MT was shorter when the high probability mask (mean MT = 607 ms) was displayed compared to the low probability mask (mean MT = 666 ms) and MT

Table 3

Prime identification performance on trials in which a directional mask was displayed. Primes were congruent (C), incongruent (I) or neutral (N) with respect to the mask. The top row indicates the mean percentage of trials in which participants correctly identified the prime presented and the bottom row indicates the mean percentage of trials in which participants indicated that a neutral prime had been presented.

Prime	High probability mask (HPM)			Low probability mask (LPM)		
	C (%)	I (%)	N (%)	C (%)	I (%)	N (%)
% of Correct responses	30	29	82	24	22	91
% of Neutral responses	57	59	82	69	63	91

was influenced by prime congruency, such that movements were completed faster on congruent prime–mask trials compared to incongruent prime–mask trials or neutral prime trials, which did not differ from each other.

Finally, to further demonstrate that both directional primes influenced all participants' movements in a similar manner, independent of whether or not they were aware of the primes, we analyzed the time at which all participants modified their movements in the direction cued by the mask (high vs. low probability mask). Included in the analysis were the factors of Group (Experiment 1 participants who completed the Pointing task vs. Experiment 2 participants who completed the Pointing + Perceptual Discrimination task), Bias Direction (left mask displayed on the majority of perturbed trials vs. right mask displayed on the majority of perturbed trials), Mask (high probability mask vs. low probability mask) and Prime Congruency (congruent (same direction), incongruent (opposite direction), or neutral). Similar to the results of Experiment 1, there were significant main effects for Mask ($F(1, 14) = 18.283, p < .001$), and Prime Congruency ($F(2, 28) = 41.224, p < .001$), and a non-significant Mask \times Prime Congruency interaction ($F(2, 28) = 0.618, p = .564$). ANOVA did not reveal any significant effects or interactions involving the factor of Group or Bias Direction ($p > .05$), suggesting that the prime–mask sequence displayed had a similar effect on final trajectory modifications, independent of whether participants were aware of the primes or the direction in which the movement was biased. These results again indicate that participants were faster to modify their initial movements from the central target in response to the high probability mask (in the more probable response direction) compared to the low probability mask and suggest that the two directional primes had a similar influence on movement.

4. Discussion

This study investigated whether the automatic influence of subliminal stimuli on action is influenced by conscious expectations regarding the probability of movement direction. To do this, we manipulated the probability of two movement directions in the context of a masked shape priming task (Cressman et al., 2007). Analysis of movement kinematics revealed that although the directional primes were invisible to participants, they influenced the speeded reaches with a similar time course, regardless of the large differences in the probability of a particular mask being displayed and hence corresponding movement required. In particular, differences between congruent, incongruent and neutral prime trials were similar for both directional masks. The ability of the primes to influence movements overtly (i.e., take over control of the action to the point of changing the movement trajectory) was influenced by its relationship to the more probable mask, but as discussed below we suggest that this is due to biases in the motor system, established at the beginning of the task as a result of conscious movement expectations.

4.1. Evidence for automatic visuomotor guidance regardless of differential expectations about two movement possibilities

According to the Action-Trigger Hypothesis (ATH), (Kiesel et al., 2007; Kunde et al., 2003), processing of a task-relevant subliminal stimulus leads to the automatic activation of the associated response. In accordance with this proposal, research has demonstrated that when participants have to modify their movements to the left and right equally often, both directional primes take over control of the action even though they are not visible to participants (Cressman et al., 2007; Schmidt, 2002). According to the ATH, the activation from such masked primes is sufficiently large that a motor activation threshold can be achieved and the associated response triggered outside of the participant's awareness.

When we examined the spatial trajectories of movements triggered by masked primes in the present study, we found that the primes influenced movements regardless of the participant's intentional bias. We also found that when a prime pointed in the same direction as the high probability mask, participants modified their pointing responses in the direction of the prime on a greater percentage of trials and to a greater extent. Conversely, processing of the prime pointing in the direction of the low probability mask did not result in as large a change in trajectory. Moreover, typically only one change in trajectory was observed on these trials and that was in the direction of the subsequent mask. Thus, based on these trajectory results, it is unclear if both directional primes, those congruent and incongruent with the more probable mask, were processed in a similar manner, such that they influenced movements automatically. Perhaps when a prime pointing in the same direction as the low probability mask was presented, it merely prepared participants' for an upcoming change in trajectory, as opposed to triggering its associated response.

To examine visuomotor processes associated with the prime pointing in the same direction as the low probability mask, we examined our temporal results in light of the influence of task instructions on performance. In addition to finding that both directional primes influenced movement time and the times at which trajectories were modified in the direction indicated by the mask, we also found that on trials in which a neutral prime was presented and participants responded to the visible mask, motor output was dependent on the mask presented. Specifically, participants were faster to complete their movement and modify their movements from the centre when the neutral prime was followed by the more probable mask compared to when the neutral prime was followed by the less probable mask. These results indicate that participants biased one response over the other, such that they favoured modifying their trajectories in the more probable response direction compared to the less probable response alternative, and are in accordance with previous findings demonstrating that responses to a higher probability event are faster compared to the less likely response alternative (see Blackman, 1972; Hawkins et al., 1973; LaBerge et al., 1969; Heuer, 1982; Schlaghecken & Eimer, 2001). To explain these benefits in response times, Miller (1998) has argued that the higher-probability response was prepared prior to stimulus onset (see also Bertelson &

Barzeele, 1965; Gehring et al., 1992; Laming, 1969), biasing the system such that one response was favoured over the other at the time of stimulus presentation. We note that the same pattern of results would be expected, regardless of whether the motor bias arose because of differences in the initial response levels of activation between the response alternatives or if different response thresholds were established for the two response alternatives.

With the assumption that consciously accessible expectations caused differences in the initial response activation for the two response alternatives (i.e., the difference in accumulator activation was biased in the more probable response direction), we then looked to predict the latencies at which the primes would be expected to influence action in our pointing task if the primes triggered their associated responses in the same automatic manner. As suggested above, the predisposition for a particular mask and its associated response should pre-set the system to favour responding in one direction (i.e., the more likely direction). This should cause movements to be initiated earlier in the more likely response direction when the masks were presented alone or preceded by a neutral prime. Furthermore, this threshold difference between the two response alternatives should also influence responses to directional primes. Namely, primes pointing in the same direction as the high probability mask should benefit from this advanced preparation; primes pointing in the same direction as the low probability mask would need to counteract this advanced preparation before the alternative response could be released. Thus, a greater amount of motor activity would need to accumulate when the prime pointed in the direction of the low probability mask, and so this response trigger might not reach its threshold level before input from the mask began to activate its associated response (in accordance with the rapid chase model (Schmidt et al., 2006; Vath & Schmidt, 2007)). On this account, we would not expect responses to be influenced as greatly by the prime pointing in the direction of the low probability mask, even though it had activated its associated response in a similar manner as the prime pointing in the same direction as the high probability mask.

The account outlined above is consistent with the temporal (and spatial) characteristics of the pointing trajectory modifications observed in the present experiment when the prime pointed in the high probability response direction. Movement modifications on these trials occurred early and were at a similar latency, regardless of the subsequent mask direction. However, the predictions from this account were *not* consistent with results obtained when the prime pointing in the same direction as the low probability mask. Recall that on these trials (incongruent trials for the high probability mask), there should be longer response latencies and movement times than on trials in which the neutral prime was followed by the high probability mask. This is because on neutral prime trials the system would still be biased in the high probability mask direction. Contrary to this prediction, we observed earlier modifications on the directional prime trials in comparison to neutral prime trials. These results suggest that the prime pointing in the same direction as the low probability mask had already prepared the system for a change in trajectory.

The result that the prime pointing in the same direction as the low probability mask had an effect on action indicates that it was processed. Furthermore, trajectories were first modified at a similar latency on all trials in which a prime pointing in the same direction as the low probability mask was displayed, regardless of the subsequent mask. If the prime merely indicated an upcoming change in trajectory and did not activate its associated response, we would expect to see a similar pattern of results on these directional prime trials as on the neutral trials (for example, a later response on trials in which a mask pointing in the less probable response direction was displayed compared to when the mask pointing in the more probable response direction was presented). Because we did not observe any differences in response times between the two different mask trials, we take this as evidence that in addition to preparing the system for an upcoming change in trajectory, the prime automatically triggered its associated response.

In conclusion, we interpret the temporal and spatial characteristics of the pointing trajectory modifications observed in the present experiment as evidence that directional primes were processed in a similar, automatic manner, regardless of their associated response probabilities. This implies that action triggers do not take into account or store information about response probability. Instead, once a visual stimulus has been mapped to a given response, all stimuli within the task set are processed in a similar manner. Specifically, a task-relevant prime is processed automatically by the system, independent of its relationship to the more probable mask, such that it begins to activate its associated response (i.e., accumulator). The consciously mediated biasing of the response system then determines the motor output associated with a particular subliminal prime (i.e., whether or not a trajectory is modified overtly in the direction of the prime). Furthermore, in addition to activating a response, the subliminal primes can also serve as a cue to the system that an upcoming change in trajectory is required, and the movement is not to be completed to the original target.

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