

## Engaging the motor system with masked orthographic primes: A kinematic analysis

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We report two experiments in which participants categorized target words (e.g., BLOOD or CUCUMBER) according to their canonical colour of red or green by pointing to a red square on the left or a green square on the right. Unbeknownst to the participants, the target words were preceded by the prime words “red” or “green”. We found that the curvature of participants’ pointing trajectories was greater following incongruent primes (*green-BLOOD*) than it was following congruent primes, indicating that individuals initiated a response on the basis of the prime and then corrected that response mid-flight. This finding establishes that the processing of masked orthographic stimuli extends down to include the formulation of an overt manual response.

The question of whether perceptual processing is continuous with motor planning is important in distinguishing cognitive models which posit serial and discrete processes (e.g., Sternberg, 1969) from those that posit continuous processing between early and late stages (e.g., Eriksen & Shultz, 1979). Though it has been difficult to tease these two theoretical positions apart, support for the continuity hypothesis has come from studies that employ continuous measures as the dependent variable (e.g., Spivey, Grosjean, & Knoblich, 2005; Tanenhaus, Spivey-Knowlton, Eberhard, &

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Sedivy, 1995). For example, in a recent paper, Spivey et al. (2005) asked participants to use a computer mouse to point to one of two pictures (e.g., “candle”), one on the left and one on the right, and found that participants’ pointing trajectories were more likely to be curved towards the distractor image (e.g., “candy”) when its name shared an initial phoneme with the name of the target. Spivey and colleagues argued that these findings supported the continuity hypothesis because they established that participants began formulating their motor response on the basis of the initial phoneme, well before the disambiguating point in the acoustic-phonetic input.

In similarly motivated research concerning the depth of processing of visually presented distractor information, Coles, Gratton, Bashore, Eriksen, and Donchin (1985) used a continuous measure of participants’ responses in the flanker task (Eriksen & Eriksen, 1974). In this task, participants are asked to respond to a target letter (e.g., “S” with the left hand and “H” with the right hand), which can be presented in the context of compatible distractors (e.g., SSSSS) or incompatible distractors (e.g., HHSHH). Not surprisingly, participants are slower to respond to the centrally presented target letter in the incompatible condition, but it has been difficult to determine if the increased response times reflect difficulty at an early stimulus evaluation stage or if they reflect the conflict that arises between two incompatible motor programmes. Coles et al. sought to resolve this issue by establishing whether or not participants formulated a motor response to the distractor stimuli. They had participants squeeze dynamometers with the left or right hand, depending upon the target letter, and found that participants squeezed the dynamometer with the nontarget hand more often in the incompatible condition. Coles et al. argued that these findings were more informative than response latencies because they revealed that response activation proceeded simultaneously with stimulus evaluation, and that at least one component of the flanker effect could be attributed to the conflict that arises between incompatible motor programmes (but see Mattler, 2005).

It is somewhat surprising to find that in a similar line of research aimed at resolving the depth of processing of masked orthographic primes, previous studies have not made use of a continuous measure of participants’ responses. This may be because already in 1998, Dehaene et al. demonstrated that masked orthographic primes modulated both haemodynamic and electrical activity over the motor cortex. In their experimental paradigm, participants categorized a visible target stimulus (e.g., “EIGHT”) by pressing a “smaller than five” button with one hand and a “larger than five” button with their other hand. Unbeknownst to the participants, the visible targets were preceded by a masked prime stimulus (e.g., “three”), which either fell on the same side of five as the target (i.e., congruent prime)

or on the opposite side of five (i.e., incongruent prime). Despite participants being unable to detect the presence of the prime stimuli, Dehaene et al. found that the lateralized readiness potential (LRP) and the “lateralized bold response” revealed increased brain activity (both electrical and haemodynamic) over the ipsilateral motor cortex when the target stimuli were preceded by incongruent primes. These findings led Dehaene et al. to claim to have “resolved the depth of processing of masked primes” (p. 599). Subsequently, several researchers have replicated the LRP findings in a range of masked priming paradigms (Eimer & Schlaghecken, 1998; Leuthold & Kopp, 1998; Praamstra & Seiss, 2005), which, taken together, clearly establish that subliminally presented primes are capable of modulating electrical activity over the motor cortex. But, while it is widely agreed upon that the LRP indexes early motor processes (Coles, 1989; Eimer, 1998; Leuthold, Sommer, & Ulrich, 2004), it is also known that LRPs may be observed in the absence of an overt motor response (de Jong, Coles, Logan, & Gratton, 1990; Osman, Bashore, Coles, Donchin, & Meyer, 1992). Given that LRPs and overt motor responses may be uncoupled, it still remains to be seen if the processing of masked orthographic primes can extend down to include the formulation and/or execution of an *overt* motor response. This is an important issue to resolve because, while it has been established that perceptual processing is continuous with response formulation processes for consciously perceived stimuli (cf. Gold & Shadlen, 2000), it has yet to be determined if the same continuity holds for subliminally presented letter strings. This latter possibility is especially intriguing because letter strings are processed in the ventral stream (cf. Gaillard et al., 2006), and hence are not thought to have direct and immediate access to the visuomotor system (Milner & Goodale, 1995). Thus, evidence indicating that undetected letter strings can be translated into motor programmes in real time would have important implications for theories of response selection as well as visuomotor control.

To determine if the processing of a masked orthographic prime stimulus is continuous with motor programming, we analysed the kinematics of participants’ responses. To our knowledge, there has been only one other study to use movement trajectories as its dependent measure in a masked priming paradigm.<sup>1</sup> Schmidt (2002) used a metacontrast masking procedure to mask coloured disks in a pointing task in which participants had to point to an annulus (backward mask) with a prespecified colour. Schmidt varied

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<sup>1</sup> Eimer and Schlaghecken (2001) used eye movements as a dependent measure in a masked priming paradigm, but because their study was designed to investigate the subsequent suppression of prime-induced responses, or the so called negative compatibility effect, they used a masking procedure that is very different from (and difficult to compare to) the procedures used to investigate the masked congruence effect (MCE).

the interstimulus interval (ISI) between prime (e.g., red disk) and target (e.g., green annulus) in both the congruent and incongruent conditions from 10 to 60 ms and found that manipulating the ISI had a dramatic effect on the magnitude of the congruence effect. Essentially, the longer participants had to process the prime stimulus, the more their pointing trajectories curved initially towards the nontarget annulus. While this finding would appear to provide support for the claim that masked primes are capable of engaging the motor system directly, this result is undermined by the fact that participants could identify the colour of the primes at even the shortest ISI. In light of this, the results of Schmidt's study do not provide compelling evidence that undetected stimuli are capable of driving overt motor responses. Furthermore, because we are interested in determining the depth of processing of masked stimuli that share only an arbitrary relationship with the target response, we chose to use orthographic stimuli as opposed to colours or arrows.

In our study, we used a pattern masking procedure that, beginning with Forster and Davis (1984), has been demonstrated by a long line of researchers to be successful in preventing visual awareness of the prime stimulus (cf. Dehaene et al., 1998; Finkbeiner, Forster, Nicol, & Nakamura, 2004; Grainger, Diependaele, Spinelli, Ferrand, & Farioli, 2003; Kouider & Dupoux, 2004). Using this masking procedure, we find, to anticipate our results, that the curvature of participants' pointing trajectories was consistently larger in the incongruent condition. This finding indicates that participants were able to programme their initial motor response on the basis of the prime stimulus, which, in the incongruent condition, they then had to correct mid-flight. These behavioural findings extend upon the original claim made by Dehaene et al. (1998) by revealing that the processing of masked primes is not limited to early stages of processing (e.g., lexical orthographic or semantic), but that it can extend all the way down to include the formulation of an *overt* motor response.

## EXPERIMENT 1

### Participants

Seven right-handed participants recruited from the Harvard University community categorized target words that were presented in white on a black background (e.g., BLOOD or CUCUMBER), according to their canonical colours of red or green by pointing to an appropriately coloured square. Unbeknownst to the participants, the target words were preceded by the subliminal primes "red" or "green".

## Materials

Ten target words were selected, five with green referents (*leaf, cucumber, pickle, lime, spinach*) and five with red referents (*tomato, lava, brick, blood, fire*). The prime words were *red* and *green*. The neutral primes *boy* and *mouth* were matched to the critical primes on several variables, including length (letters), frequency, number of orthographic neighbours, and imageability. The prime words never appeared as visible targets, thereby preventing the formation of stimulus–response mappings that could be executed without at least some rudimentary semantic analysis (cf. Damian, 2001). Target words appeared four times in each condition (congruent, incongruent, and neutral) for a total of 120 experimental trials and once in each condition in an initial block of 30 practice trials.

## Procedure

Participants sat at a table with a fixed Plexiglas screen positioned approximately 50 cm in front of them. The screen was darkened and an LCD projector was used to project the word stimuli onto the centre of the screen in white letters. Throughout the experiment, a red square and a green square were constantly projected to the left and right sides of the screen respectively. Participants were instructed to indicate the colour of the target word's referent by reaching out and touching the appropriate square as quickly as they could.

Each trial began with participants placing their right forefinger on a centrally located starting position in front of the Plexiglas screen. Hand movements were tracked with a Fastrak electromagnetic position and orientation measuring system (Polhemus Inc.) with a 120 Hz sampling rate. A small position-tracking sensor ( $0.89 \times 0.50 \times 0.45$  inches) was attached to the index fingertip of the right hand. The starting position ( $3 \text{ cm} \times 3 \text{ cm}$ ) was aligned with the body midline and marked on the table approximately 20 cm in front of the participants. The tracking system was calibrated at the beginning of the experiment and again after each block of 40 experimental trials. Movement data were transmitted to a Power Mac G4 by Vision Shell library for off-line analysis.

Each trial consisted of a forward mask (#####) for 500 ms, followed by the prime word (e.g., *red*) for 30 ms, a backward mask (e.g., *KMDKS*) for 10 ms followed by the target word (e.g., *BLOOD*), which was presented for 2 s or until a response was made, whichever occurred first. Each stimulus in the sequence followed immediately after the other. There was an ISI of 2 s, during which the word “loading” blinked on and off.

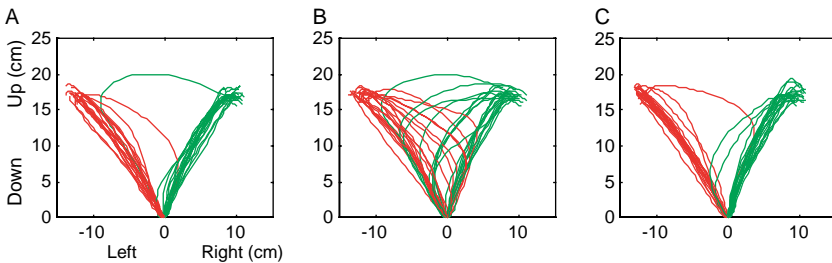
Following the experiment proper, a bias free measure of prime awareness ( $d'$ ) was determined by replacing the primes with “abcd”, which was treated as the signal, and “efgh”, which was treated as noise. Participants were told to press the “j” key upon detecting “abcd” and the “k” key upon detecting “efgh”. Eighty total trials were presented, forty with “abcd” and forty with “efgh”.

## Results

In the following analyses, *reaction time* was defined as the point at which hand velocity exceeded a threshold of 10 cm/s and *total time* was defined as the interval between target onset and the end of pointing movements. *Maximum curvature* was defined as the ratio of the largest deviation (perpendicular distance) of the trajectory from the straight line connecting the start and end points (target position) of the movements to the length of this line (Atkeson & Hollerbach, 1985; Smit & van Gisbergen, 1990).

Incorrect responses were discarded (4%), as were trials with initial latencies shorter than 100 ms (< 1%).

The pointing trajectories of a representative participant (MK) are presented in Figure 1. As is clear from this figure, trajectories were more curved in the incongruent condition than they were in either the congruent or neutral condition. A repeated measures ANOVA confirmed that there was a significant effect of prime type on maximum curvature,  $F(2, 12) = 15.36$ ,  $p = .0005$ . The contrast analyses indicated that the incongruent condition showed a greater maximum curvature than the neutral,  $t(6) = 3.73$ ,  $p = .01$ , and congruent conditions,  $t(6) = 4.23$ ,  $p = .005$ . However, there



**Figure 1.** Manual-pointing trajectories from a representative participant (MK; Experiment 1) in congruent (A), incongruent (B), and neutral (C) conditions. Trajectories associated with each target location are depicted by two distinct colours: red (left target) and green (right target). Trajectories are three-dimensional, but for clarity we only show the X and Y dimensions where the greatest difference between trajectory types is most evident. To view this figure in colour, please see the online issue of the Journal.

was no significant difference between the congruent and neutral conditions,  $t(6) = 1.21$ ,  $p = .27$ . All seven participants exhibited this same pattern of performance.

Just as with the analysis of maximum curvature, the analysis of total times revealed a significant effect of prime type,  $F(2, 12) = 10.41$ ,  $p = .002$ , but the analysis of reaction times did not ( $F < 1$ ). With respect to the total times, the contrast analyses indicated that responses were slower in the incongruent condition (794.5 ms) than they were in the neutral (778.3 ms),  $t(6) = 3.10$ ,  $p = .02$ , or congruent conditions (769.6 ms),  $t(6) = 5.52$ ,  $p = .001$ . However, there was no significant difference between the congruent and neutral conditions,  $t(6) = 1.31$ ,  $p = .24$ . There was no speed-accuracy tradeoff as the accuracy rates in the congruent (95%), incongruent (93%), and neutral (95%) conditions were not statistically different,  $F(2, 12) = 0.32$ ,  $p = .73$ .

The prime-discrimination task yielded a mean hit rate of 62% and a mean false-alarm rate of 57%. The individual  $d'$  scores were entered into a one-sample  $t$ -test, which revealed that  $d'$  ( $M = 0.128$ ) did not differ significantly from zero,  $t(6) = 1.20$ ,  $p = .27$ .

While these findings are compelling in revealing the depth of processing of masked orthographic primes, it is important to establish that these findings can be replicated with a more stringent prime-discrimination measure. We do this in the following experiment.

## EXPERIMENT 2

This experiment differs from the previous one in that we parametrically manipulated the duration of the prime stimulus from 10 ms to 40 ms in 10 ms increments, both during the experiment proper and the prime-discrimination task. The rationale for this manipulation is straightforward. If manipulating prime duration within this range modulates the magnitude of the congruence effect (as indexed by the curvature measure) but has no effect on participants' prime-discrimination measures, then we can be relatively confident that the masked congruence effect is not dependent upon prime awareness. We tested this possibility in the present experiment.

Seven right-handed participants were recruited from the Macquarie University community (Sydney) to perform the identical task described in Experiment 1, with the following exceptions. In this case, a CRT monitor was used to present the stimuli and participants responded by moving an electronic pen across a tablet (Wacom), which was positioned on a slight incline between the participant and the monitor. The display on the monitor was identical to the display used in Experiment 1. Affixed to the

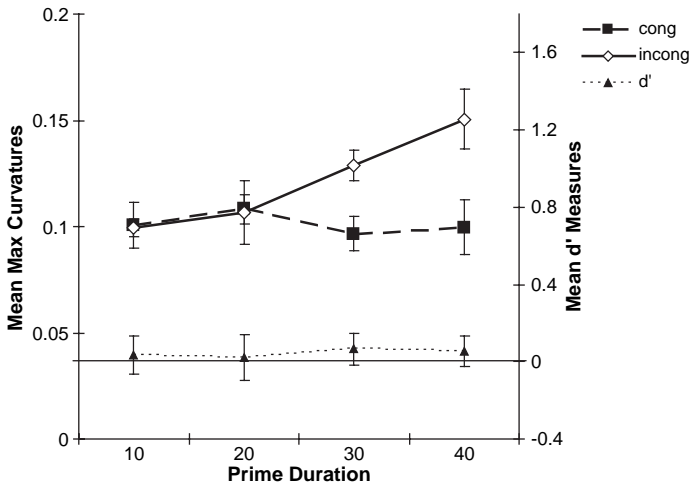
tablet were three foam stops, one corresponding to the start position in the bottom-centre of the tablet (closest to the participant) and one in each of the top corners (closest to the monitor). The top-left foam stop corresponded to the red square depicted on the monitor screen and the top-right foam stop corresponded to the green square. Participants initiated a trial by sliding the pen into the “start” foam stopper and then responded by sliding the pen across the tablet and into the appropriate stop in either the top-left or top-right corner. No cursor was presented on the screen, but after just a few trials participants were able to hit the target foam stops without looking at the tablet. Because the position of the target foam stops corresponded closely to the position of the coloured squares on the monitor, the subjective experience of “reaching” from the start position towards one of the two coloured squares was similar across the two experiments. Presentation software (Neurobehavioral Systems) was used to present the stimuli and record the xy coordinates of the pen at a sampling rate of 200 Hz.

One additional difference between the two experiments was in the number of trials. Both the experiment proper and the prime discrimination task consisted of 240 total trials, 30 congruent and 30 incongruent at each of the four prime durations. A neutral prime was not included.

In the prime-discrimination task, participants used their left hand to indicate whether the prime stimulus was the word “red” by pressing the “Z” key or “green” by pressing the “X” key. Stimulus presentation in this task was identical to that of the experiment proper. Here, though, participants were asked to emphasize accuracy over speed. To encourage an emphasis on accuracy (cf. Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003), participants were asked not to respond until the target stimulus was replaced with a question mark, which occurred 1 s after target onset.

## Results

Again, incorrect responses were discarded (2.3%), as were responses with initial latencies shorter than 100 ms (< 1%). As can be seen in Figure 2, the maximum curvature of participants’ responses increased in the incongruent condition as a function of prime duration. This was confirmed in a 2 (prime type)  $\times$  4 (prime duration) repeated-measures ANOVA, which revealed a significant effect of prime type,  $F(1, 6) = 11.67, p = .01$ , no effect of duration,  $F(3, 18) = 1.29, p > .1$ , but, importantly, a reliable interaction between the two factors,  $F(3, 18) = 6.12, p = .005$ . The contrast analyses revealed a significant congruence effect (incongruent > congruent) at both the 30 ms duration,  $t(6) = 4.57, p = .004$ , and the 40 ms duration,  $t(6) = 3.55, p = .012$ .



**Figure 2.** Mean maximum curvatures and  $d'$  measures in Experiment 2 as a function of prime duration. The error bar represents between-participants standard error.

The error analysis did not reveal significant effects of prime type or prime duration, but did reveal an interaction between the two factors,  $F(3, 18) = 4.64$ ,  $p = .02$ . The post hoc comparisons revealed more errors in the incongruent condition (5.2%) than in the congruent condition (1%) at the 30 ms duration,  $t(6) = 3.58$ ,  $p = .01$ , but no differences at the other durations (all  $ps > .2$ ).

The analysis of reaction times revealed no differences ( $F < 1$ ) but the analysis of total times mirrored the analysis of maximum curvatures. There was a significant effect of prime type,  $F(1, 6) = 7.05$ ,  $p = .04$ , but not of prime duration ( $F = 1.1$ ), and a reliable interaction between the two factors,  $F(3, 18) = 3.94$ ,  $p = .02$ . The contrast analyses revealed that total times were slower in the incongruent condition (702 ms) than they were in the congruent condition (670 ms) at the 40 ms duration,  $t(6) = 3.90$ ,  $p = .008$ , but not at the other prime durations (all  $ps > .1$ ).

Four separate  $d'$  measures, one per prime duration ( $N = 60$ ), were calculated for each participant. These were then entered into four separate one-sample  $t$ -tests, one for each prime duration. The mean  $d'$  measures were 0.03, 0.02, 0.06, and 0.05 at the 10 ms, 20 ms, 30 ms, and 40 ms durations respectively. At no duration was  $d'$  found to be different from 0 (all  $ps > .45$ ). Furthermore, a comparison of each participant's  $d'$  measure with that participant's effect size (difference in maximum curvature between congruent and incongruent conditions) failed to reveal any reliable correlations at any prime duration. Thus, just as in Experiment 1, these findings

establish that participants are able to formulate an overt motor response on the basis of an undetected orthographic prime stimulus.

## DISCUSSION

Can the processing of masked orthographic stimuli extend down to include the formulation and/or execution of overt motor responses? The findings that we have reported here provide compelling evidence in favour of this possibility. In our paradigm, participants had to point to a green square on the right or a red square on the left depending upon the target stimulus (e.g., CUCUMBER or BLOOD). Just prior to the onset of the target word, the prime word “red” or “green” was presented subliminally. Despite the unavailability of the prime stimulus to visual awareness, we found that the congruity of the prime stimulus with the target stimulus had a significant effect on participants’ pointing trajectories. For example, when the prime “red” preceded the target LEAF, participants’ trajectories were initially more curved in the direction of the red square than they were when the prime was “green”. This indicates that participants initiated their pointing response on the basis of the prime stimulus (e.g., towards the red square) and then changed direction mid-flight in order to finish their response by landing on the other square.

These findings establish the depth of processing of masked orthographic primes by revealing that the processing of subliminally presented orthographic stimuli can extend down to include the formulation of an overt motor response. Thus, just as with the processing of spoken language (Spivey et al., 2005) or visible distractors in the flanker task (Coles et al., 1985), the processing of subliminally presented orthographic information appears to be contiguous with the very latest stages of response activation and preparation. These findings have important implications for theories of information processing, and, in particular, for models of response selection and visuomotor control.

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