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Modulating the Masked Congruence Priming Effect With the Hands and the Mouth

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The authors report a series of experiments in which they use the masked congruence priming paradigm to investigate the processing of masked primes in the manual and verbal response modalities. In the manual response modality, they found that masked incongruent primes produced interference relative to both congruent and neutral primes. This finding, which replicates the standard finding in the masked congruence priming literature, is presumed to reflect the conflict that arises between two incompatible responses and, thus, to index the extent of processing of the masked prime. Somewhat surprisingly, when participants were asked to respond verbally in the same task, masked incongruent primes no longer produced interference, but masked congruent primes produced facilitation. These findings are surprising because they suggest that the processing of nonconsciously perceived primes extends to the response level in the manual, but not verbal, response modality. The authors propose that the modulation of the masked congruence priming effect by response modality is due to verbal, but not manual, responses being mediated by the lexical–phonological production system.

Keywords: masked priming, stimulus–response compatibility, response priming, visual awareness, response modality, lexical access in speech production

How extensively are subliminally presented stimuli processed? In a seminal paper in this area of research, Dehaene et al. (1998, p. 599) claimed that their results resolved the issue over the extent of processing of subliminally presented (masked) primes. In their experimental paradigm, participants categorized a visible target stimulus (e.g., EIGHT) as being either larger or smaller than five. Unbeknownst to the participants, the visible targets were preceded by a masked prime stimulus (e.g., three) that fell either on the same side of five as the target (i.e., congruent prime) or on the opposite side of five (i.e., incongruent prime). Participants responded by pressing a "smaller than five" button with one hand and a "larger than five" button with the other hand. Despite participants being unable to detect the presence of the prime stimuli, the primes produced clear behavioral and neurophysiological effects. Behaviorally, Dehaene et al. found that response times in the incongruent condition were significantly slower than in the congruent condition. This behavioral effect, referred to as the *masked congruence effect* (MCE), has been observed in a wide variety of paradigms with nonorthographic stimuli, including meta-contrast masking of arrows (Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003) and spatial locations (Leuthold & Kopp, 1998; Neumann & Klotz, 1994) and pattern masking of arrows (Eimer & Schlaghecken, 1998). Subsequently, the MCE has also been replicated several times with orthographic stimuli (Kunde, Kiesel, & Hoffmann, 2003; Naccache & Dehaene, 2001; Van Opstal, Reynvoet, & Verguts, 2005). It was the neurophysiological findings, though, that led Dehaene et al. to claim to have "resolved the depth of processing of masked primes" (p. 599). These authors found that the masked primes produced detectable modulations in electrical brain activity (event-related potentials) and cerebral blood flow (functional MRI) over the motor cortices. Essentially, when the prime and target corresponded to responses made with opposing hands, more activation was seen over the ipsilateral motor cortex than when both the prime and the target corresponded to a response made with the same hand. It was proposed that participants were unconsciously applying the task instructions to the prime, categorizing it as either smaller or greater than five, and preparing a covert motor response that was appropriate to the prime. As such, Dehaene et al. claimed to have demonstrated that the processing of subliminally presented primes extends all the way down to include the motor system. Subsequently, several researchers have replicated the ERP findings in a range of masked priming paradigms (Eimer & Schlaghecken, 1998; Leuthold & Kopp, 1998; Praamstra & Seiss, 2005).

Although the neurophysiological effects establish the extent of processing of masked primes, these findings do not necessarily reveal the reason for longer response latencies in the incongruent condition. For example, it could be argued that responses are selected at a premotor (amodal) level of representation (Botvinick,

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Cohen, & Carter, 2004; Pashler, 1989) and that the slower response latencies in the incongruent condition reflect the extra time that is needed to select the target representation in the context of an activated, incompatible representation. On this account, the prime-induced activation observed by Dehaene et al. (1998) over the motor cortex could be due to activation cascading down from the semantic system but would not be relevant to the behavioral finding that response latencies are slower in the incongruent condition. Alternatively, and just as plausibly, one could take the prime-induced activation over the motor cortex to be informative with respect to understanding the behavioral effects. Dehaene et al. suggested that the activation over the motor cortex was important in formulating an account of the MCE. On their account, the prime-induced covert motor activation conflicted with the overt motor response required by the target, thereby producing "response competition and hence slower response times relative to congruent trials" (Dehaene et al., 1998, p. 598). According to this view, *response competition* is taken to mean competition between two incompatible motor programs, covert or otherwise.

This latter hypothesis, that the MCE is due to the conflict that arises between incompatible motor responses, has received support from subsequent behavioral studies that have revealed that the MCE is due primarily to interference in the incongruent condition (as opposed to facilitation in the congruent condition). For example, in an experimental paradigm similar to that used by Dehaene et al. (1998), Koechlin, Naccache, Block, and Dehaene (1999; Experiment 2) found that response latencies in the incongruent condition were significantly slower than those in both the congruent and the neutral conditions (the neutral prime was "5"), with no difference between the latter two conditions. Similarly, in a replication of the behavioral findings reported by Dehaene et al., Naccache and Dehaene (2001) found that incongruent trials were significantly slower than neutral trials (the neutral prime was "$") but that congruent and neutral trials were not different from one another. In a similar study, Kunde et al. (2003; Experiment 1) reported that response latencies were slower in the incongruent condition than they were in the neutral condition, with no appreciable difference between the congruent and the neutral conditions. In addition, the error rates in these experiments are generally greater in the incongruent condition than in the congruent condition, suggesting that participants are formulating a motor response to the prime and, on occasion, mistakenly executing that response. This line of findings has been taken as support for the original claim made by Dehaene et al. that the MCE is due to the conflict that arises between two incompatible motor programs, one induced by the prime and one by the target.

More recently, Finkbeiner, Song, Nakayama, and Caramazza (in press) reported a masked congruence priming experiment in which pointing trajectories were the dependent measure. In their study, participants were asked to categorize target stimuli (e.g., BLOOD or CUCUMBER) as either "red things" or "green things." The target stimuli were presented in white letters, and participants responded by pointing to a red square on the left side of the screen or to a green square on the right side of the screen. Unbeknownst to the participants, the target stimulus was preceded by the prime word *red* or *green* or an appropriately matched neutral stimulus. Finkbeiner et al. found that the curvature of participants' pointing trajectories was consistently larger in the incongruent condition than in the neutral and congruent conditions. This finding indicates that participants initiated their motor response on the basis of the masked prime stimulus so that in the incongruent condition, they then had to subsequently correct mid-trajectory. The findings of this kinematic analysis are compelling insofar as they establish that the processing of a masked prime can extend down to include the formulation of an overt motor response.

Given the demonstration that prime-induced activation extends beyond the sensory cortices to include motor cortices (Dehaene et al., 1998) and that this involvement of the motor system is not simply epiphenomenal in nature but is capable of affecting overt motor responses to the target (Finkbeiner et al., in press), it seems reasonable to conclude that interference in the masked congruence priming paradigm is due, at least in part, to the conflict that arises between incompatible motor responses—one engendered by the prime and one by the target. Although this conclusion seems warranted in light of the empirical findings obtained when participants respond manually, there is reason to think that the processing of masked primes may not extend down to the motor level when participants respond verbally and, hence, that interference may not be obtained in the verbal response modality.

In a recent picture–word naming study in which participants named picture stimuli (e.g., dog) while ignoring superimposed distractor words (e.g., WOLF), Finkbeiner and Caramazza (2006) found that categorically related distractor words produced interference when the words were presented visibly but facilitation when they were presented subliminally. Finkbeiner and Caramazza attributed this shift in the polarity of the semantic (categorical) effect as a function of masking to two qualitatively different processes. In the case of interference, a standard finding in the picture–word naming literature, they proposed that visibly presented distractor words obligatorily trigger the formulation of a phonologically well-structured (articulatory) response. This is thought to lead to interference because the mistakenly generated response to the distractor word needs to be rejected or "blocked" so that the target response may be produced over the single output channel.[1] In contrast, no interference is obtained when the distractor stimulus is masked because, it is hypothesized, a masked orthographic prime is unable to trigger the formulation of a phonologically well-structured articulatory response. It is important to note that this hypothesis does not predict that masking blocks phonological priming effects in naming tasks. For example, a prime stimulus may preactivate lexical–phonological representations without leading to the formulation of an articulatory (i.e., motor) response. Thus, although allowing for the possibility that activation from the lexical–semantic system may cascade down onto lexical–phonological representations, the hypothesis put forth by Finkbeiner and Caramazza holds that undetected prime stimuli are unable to engender an articulatory response (which, in turn, could interfere with the articulation of the response engendered by the target stimulus).

[1] It is important to note that Finkbeiner and Caramazza (2006) argued that the speed with which a distractor-engendered response may be rejected is modulated by whatever relevance the nontarget response may have vis-à-vis the task at hand. With respect to the picture–word naming task, this is producing a name for the picture (see also Mahon, Costa, Peterson, Vargas, & Caramazza, 2007; Miozzo & Caramazza, 2003).

With respect to the facilitation effect that was obtained with masked distractor words, Finkbeiner and Caramazza (2006) attributed this to the indirect activation of the target representation by the distractor word through the overlap in the processing of their respective semantic representations. In this case, because the activation engendered by the masked prime is not associated with an alternative response that has to be rejected, its effects on the target response may be facilitatory.

The account that Finkbeiner and Caramazza (2006) put forth to explain the polarity shift in picture–word naming as a function of masking makes a clear, albeit counterintuitive, prediction in the masked congruence priming paradigm. Namely, if, as Finkbeiner and Caramazza suggested, undetected stimuli do not trigger the formulation of an articulatory response, and if interference in the masked congruence priming paradigm is due to the conflict that arises between competing motor-level responses, then it follows that undetected (incongruent) primes should not produce interference when participants respond verbally. This prediction is counterintuitive because, as the review above made clear, it has already been established that masked incongruent primes produce a robust interference effect when participants respond manually. Presently, there is no clear reason to think that the same pattern of performance would not be obtained when participants respond verbally. As such, either the account put forth by Finkbeiner and Caramazza is incorrect, or, as they have suggested, participants cannot formulate an articulatory response to undetected stimuli but, somewhat unexpectedly, can generate a manual response to the same undetected stimuli.

This is an important issue to resolve. If it is found that the interference effect obtained in the masked congruence priming paradigm in the manual modality is not obtained in the verbal modality, this will then suggest that the extent to which a masked stimulus is processed can be modulated by the response modality. This would appear to have important implications for theories of information processing. A standard assumption in information-processing theory is that the processing of information proceeds independently of the particular motor system that is ultimately recruited to execute the appropriate action. With this assumption in mind, it would be surprising to find that the processing of subliminally presented information can be modulated by whether individuals respond with their hands versus their articulators.

In the experiments that follow, we test the hypothesis put forth by Finkbeiner and Caramazza (2006) that undetected prime stimuli do not engender an articulatory response and, hence, do not produce interference in the verbal modality. We do this using the masked congruence priming paradigm in which it has been well established (with manual responses, at least) that undetected primes do produce interference. To anticipate our findings, we find that undetected incongruent primes produce a robust interference effect in the manual response modality, thereby replicating several previous findings (see above). Interestingly for our purposes here, though, we find no interference in the verbal response modality. It is important to note that the lack of interference in the verbal modality is not simply a result of participants being unable to process masked primes when responding verbally because we find that the same masked primes produce facilitation in the congruent condition. We report several follow-up experiments designed to test different possibilities as to why the processing of masked primes would extend down to the motor level in the manual response modality but not in the verbal response modality. These possibilities include differences in the relative difficulty of responding verbally versus manually, the difference in the number of response channels between the two modalities, the possibility that the baseline needs to be calculated differently in the two modalities, and the possibility that the directness of the stimulus–response mapping differs between the two modalities. In each case, we find that undetected incongruent primes produce interference when participants respond manually but not when they respond verbally. Also, in each case, we are confident that the masked primes are processed in the verbal response modality because in this modality congruent primes consistently produce facilitation. We find an important exception to this general pattern of findings when we use a task in which participants are able to precompile their verbal response. Namely, when we use the go–no-go task, in which participants simply release the prepared response when appropriate, we find that masked incongruent primes produce interference in the verbal response modality. This is an important finding as it helps to constrain the possible hypotheses that one may generate in trying to account for how the processing of masked primes could be modulated by the response modality. Our findings suggest that the locus of the modulatory effect by response modality is in the lexical route, which mediates the selection and execution of a response in the verbal modality but, arguably, not in the manual response modality. We conclude by suggesting that these findings constitute the first evidence that the extent of information processing may be modulated by the motor system that is ultimately recruited to produce a response.

Experiment 1: Masked Congruence Priming

The goal of Experiment 1 was to test the hypothesis put forward by Finkbeiner and Caramazza (2006) that undetected primes do not produce interference in the verbal response modality. To develop the strongest test of this hypothesis, we used the masked congruence priming paradigm because it is well established that incongruent primes produce interference in this paradigm. In the interest of exposition, we present three separate pairs of experiments as Experiment 1. The experiments in each pair were identical in every way except that participants responded manually in one and verbally in the other. In the first two pairs of experiments (Experiments 1a–1d), participants categorized target words (e.g., BLOOD, SPINACH) as referring to either "red things" or "green things." In the third pair of experiments (Experiments 1e and 1f), participants categorized target words (e.g., JULY, YELLOW) as either a color or a month. In the manual modality, participants responded by pressing an appropriate button; in the verbal modality, participants responded by saying "red" or "green" (Experiments 1b and 1d) or "color" or "month" (Experiment 1f).

Participants

Ninety-six individuals (16 in each of six experiments) at Harvard University participated for course credit or pay. All participants were native speakers of English and had normal or corrected-to-normal vision.

Materials

The primes and targets used in each of the six experiments are presented in Table 1. In each experiment, the neutral primes were

Table 1
Prime and Target Stimuli Used to Form Congruent, Incongruent, and Neutral Conditions in Experiment 1

Experiment	Congruent and incongruent primes	Neutral primes	Targets
1a&1b	red, green	son, hotel	TOMATO, FIRE, BRICK, BLOOD, STRAWBERRY, LEAF, JADE, PICKLE, CUCUMBER, SPINACH
1c&1d	red, green	boy, mouth	
1e& 1f	april,green	basic, limit	ORANGE, BLUE, PURPLE, BLACK, YELLOW, JANUARY, FEBRUARY, JUNE, JULY, AUGUST

matched to the congruent and incongruent primes on several dimensions, including frequency, length, imageability, and number of orthographic neighbors (Coltheart, Davelaar, Jonasson, & Besner, 1977). In all experiments, target words appeared four times in each condition (congruent, incongruent, and neutral) and once in the 10 practice trials for a total of 130 trials.

Procedure

Participants were asked to indicate either the color of the target word's referent (Experiments 1a–1d) or whether the target word referred to a color or a month (Experiments 1e and 1f). Participants responded by pressing an appropriate button (Experiments 1a, 1c, and 1e) or by saying "red" or "green" (Experiments 1b and 1d) or "color" or "month" (Experiment 1f). In the button-press experiments, a two-button button box was positioned perpendicular to the monitor with the button closest to the monitor corresponding to either the "red" or "color" response and the button closest to the participant corresponding to either the "green" or the "month" response (both buttons were colored identically). Half of the participants pressed the far button with their dominant hand and the close button with their nondominant hand. This mapping was reversed for the other half of the participants. In the naming experiments, a microphone was used to trigger a voice key. The microphone was placed in front of the participant, and responses were recorded digitally and subsequently scored for accuracy.

Participants sat approximately 50 cm from a flat-screen CRT monitor. The software program DMDX (Forster & Forster, 2003) was used to present the stimuli and record the responses. Stimuli were presented in identical fashion in all versions of the experiment (see Figure 1). Each trial began with the word *loading* presented for 500 ms, a blank space of 500 ms, the word *loading* for 500 ms, a blank space of 500 ms, and then a forward mask for 500 ms. Immediately following the forward mask, the prime word was presented for 30 ms, followed by a backward mask for 10 ms, which was followed immediately by the target. The target stimulus was displayed for 2 s or until a response was made, whichever came first. The primes were presented in lowercase letters and the targets in uppercase letters. The backward mask was a randomly generated five-letter consonant string (e.g., KWPDR) and was presented in uppercase (see Figure 1). Response latencies were recorded from the onset of the target stimulus. Each trial began immediately following a response on the previous trial.

Preceding the experimental trials were 10 practice trials, 1 for each target stimulus. The practice trials were congruent and were identical to the experimental trials. The experimental trials were presented in a pseudorandom order such that each successive block of trials included one presentation of each target in each experimental condition. The blocks, and the trials within each block, were presented in a different random order for each participant.

Following the experiment proper, a prime detection task was assessed. Following Kouider and Dupoux (2001, 2004), participants were asked to discriminate between primes that contained real letters (e.g., yckw) and those that contained nonsense symbols (e.g., ЖбЯг). The task consisted of 40 trials with the same temporal characteristics as in the experiment proper. Participants were instructed to press the far button with one hand when they saw the normal letters and the close button with their other hand when they saw the nonsense symbols. Participants were told that half of the trials would have normal letters and half would have nonsense symbols. Two practice trials with clearly visible primes, one with normal letters and one with nonsense symbols, preceded the prime detection task to familiarize participants with the task.

Results

In this and all of the following experiments, incorrect responses were discarded, and outliers were treated by setting them equal to cutoffs established 2 standard deviation units above and below the overall mean for each participant. In the naming experiments, errors included wrong responses, voice key failures, and disfluencies. For each comparison of interest, two analyses of variance were performed, one treating participants as a random effect (F_1), the other treating items as a random effect (F_2). In the first analysis, a repeated measures analysis of variance (ANOVA) was used to determine whether the factor prime type (congruent, in-

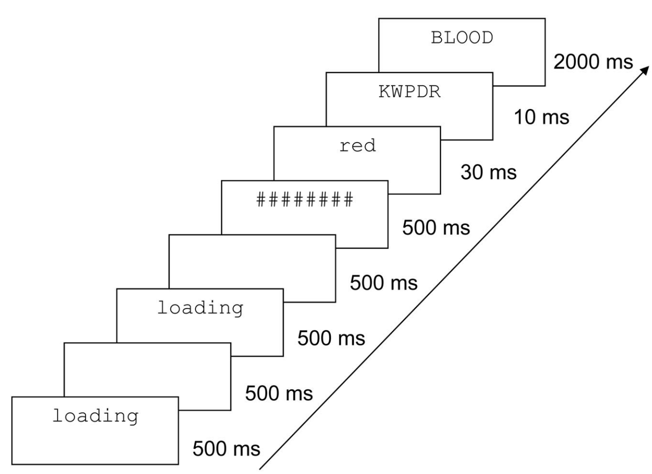

Figure 1. Trial structure used in Experiment 1 (congruent "red" trial is depicted). Each trial was preceded by a 2-s interval during which the word *loading* blinked on and off. This was followed by the forward mask for 500 ms, the prime stimulus for 30 ms, the backward mask for 10 ms, and then the target stimulus for 2 s or until a response was registered.

congruent, or neutral) was reliable. To know whether the masked congruence effect was due to facilitation or inhibition, we also performed post hoc comparisons against the neutral prime condition. When multiple *t* tests were necessary, we controlled for the false discovery rate using the procedure described by Benjamini and Hochberg (1995). In all cases, *t* tests were two tailed.

Omnibus Analysis

In the overall analysis of Experiments 1a–1f, we conducted a 2 (response modality) × 3 (experiment) × 3 (prime type) ANOVA with response modality and experiment as between-groups factors and prime type as a within-group factor. This ANOVA revealed main effects of response modality, $F_1(1, 90) = 23.5$, $p < .01$, $\eta_p^2 = .21$, and $F_2(1, 234) = 541.7$, $p < .01$, $\eta_p^2 = .71$; experiment, $F_1(2, 90) = 2.41$, $p = .09$, $\eta_p^2 = .05$, and $F_2(2, 234) = 54.93$, $p < .01$, $\eta_p^2 = .32$; and prime type, $F_1(2, 180) = 16.89$, $p < .01$, $\eta_p^2 = .16$, and $F_2(2, 468) = 18.52$, $p < .01$, $\eta_p^2 = .07$. The three-way interaction was not reliable ($F_1 < 1$) but, important for our purposes here, the interaction between response modality and prime type was reliable, $F_1(2, 180) = 4.05$, $p = .02$, $\eta_p^2 = .04$, and $F_2(2, 468) = 4.39$, $p = .01$, $\eta_p^2 = .03$. This interaction indicates that the masked congruence priming effect patterned differently as a function of the response modality. To look at this possibility further, we analyze manual and verbal responses separately below.

Experiments 1a, 1c, and 1e: Button-Press Responses

In Experiment 1a, the mean response latencies were 549 ms, 549 ms, and 558 ms in the congruent, neutral, and incongruent conditions, respectively. In Experiment 1c, the mean response latencies were 534 ms, 534 ms, and 552 ms, and in Experiment 1e, the mean response latencies were 533 ms, 527 ms, and 549 ms in the congruent, neutral, and incongruent conditions, respectively. A repeated measures ANOVA with the factors experiment (between subjects) and prime type (within subjects) revealed a main effect of prime type, $F_1(2, 90) = 11.08$, $p < .01$, $\eta_p^2 = .20$, and $F_2(2, 234) = 13.42$, $p < .01$, $\eta_p^2 = .11$. There was no effect of experiment ($F_1 < 1$), nor was there an interaction between the two factors ($F_1 < 1$). Because of this, the data were collapsed across the experiment factor and post hoc *t* tests were run over the collapsed data set (see Figure 2a). These analyses revealed an effect of congruence (congruent was faster than incongruent), $t(47) = -4.26$, $p < .01$, and interference (incongruent was slower than neutral), $t(47) = 3.94$, $p < .01$, but not of facilitation (congruent was not faster than neutral).

In Experiment 1a, the mean error rate was 2.65%, 1.41%, and 3.43% in the congruent, neutral, and incongruent conditions, respectively. In Experiment 1c, the mean error rate was 2.18%, 2.34%, and 4.22%, and in Experiment 1e the mean error rate was 6.76%, 6.16%, and 8.11% in the congruent, neutral, and incongruent conditions, respectively. The repeated measures ANOVA over the error rates revealed an effect of experiment, $F_1(2, 90) = 7.61$, $p < .01$, $\eta_p^2 = .25$, and $F_2(2, 234) = 21.94$, $p < .01$, $\eta_p^2 = .27$, and prime type, $F_1(2, 90) = 6.39$, $p < .01$, $\eta_p^2 = .12$, and $F_2(2, 234) = 5.17$, $p < .01$, $\eta_p^2 = .04$, but no interaction between the two factors. Post hoc *t* tests over the data collapsed across the experiment factor revealed a significant effect of congruence (more errors in the incongruent condition than in the congruent condition), $t(47) = -2.23$, $p = .03$, and interference (more errors in the incongruent condition than in the neutral condition), $t(47) = 4.83$, $p < .01$. There was no difference in the error rates between the congruent and neutral conditions.

Experiments 1b, 1d, and 1f: Verbal Responses

Experiments 1b, 1d, and 1f were identical to those reported above except that the responses were made verbally rather than manually. In Experiment 1b, the mean response latencies were 634 ms, 646 ms, and 651 ms in the congruent, neutral, and incongruent conditions, respectively. In Experiment 1d, the mean response latencies were 597 ms, 607 ms, and 609 ms, and in Experiment 1f the mean response latencies were 579 ms, 587 ms, and 590 ms in the congruent, neutral, and incongruent conditions, respectively. A repeated measures ANOVA with the between-subjects factor experiment and the within-subjects factor prime type revealed a main effect of prime type, $F_1(2, 90) = 9.66$, $p < .01$, $\eta_p^2 = .18$, and $F_2(2, 234) = 9.19$, $p < .01$, $\eta_p^2 = .07$. There was no effect of experiment ($F_1 = 2.33$, $p = .11$), nor was there an interaction between the two factors ($F_1 < 1$). Hence, again, the data were collapsed across the experiment factor and post hoc *t* tests were run over the collapsed data set (see Figure 2b). These analyses revealed a reliable effect of congruence (congruent was faster than incongruent), $t(47) = -4.05$, $p < .01$, and facilitation (congruent was faster than neutral), $t(47) = -4.40$, $p < .01$, but no interference effect, $t(47) = 1$, $p > .3$.

The mean error rates were 2.5%, 3.13%, and 3.13% in Experiment 1b; 3.59%, 3.91%, and 3.28% in Experiment 1d; and 5.01%, 7.66%, and 4.56% in Experiment 1f in the congruent, neutral, and incongruent conditions, respectively. The repeated measures ANOVA revealed no effect of prime type or experiment.

Analysis of prime detectability. In the prime detection task, *d′* was calculated by treating the presence of the letters (e.g., yckw) as the signal and the presence of nonsense symbols (e.g., ЖбЯг) as noise. The mean *d′* value was −0.16 in Experiment 1a, −0.15 in Experiment 1b, 0.01 in Experiment 1c, 0.0 in Experiment 1d, 0.06 in Experiment 1e, and −0.07 in Experiment 1f. In no case did *d′* differ from the null mean. These results are consistent with those reported by Kouider and Dupoux (2001, 2004), who also found that participants were unable to discriminate letter strings from nonletter strings under similar masking conditions (e.g., 30-ms presentation duration with both forward and backward masking).

Distribution analysis. We followed up our analysis of mean reaction times (RTs) and error rates by examining the magnitude of the masked congruence effect in each response modality as a function of response latency. We did this by constructing cumulative density functions and corresponding delta plots. This was done to explore a possibility raised recently by Ridderinkhof (2002; see also Bub, Masson, & Lalonde, 2006). Ridderinkhof has suggested that suppression of an irrelevant response may be modulated by the latency of the response and that delta plots are able to reveal the differential effects of suppression as a function of response latency. This possibility is relevant for the findings we have reported here because on the assumption that the effect of suppression accrues over time, it may explain why we observed interference in the fast (manual) response modality but not in the slow (verbal) response modality. That is, in the case of the button

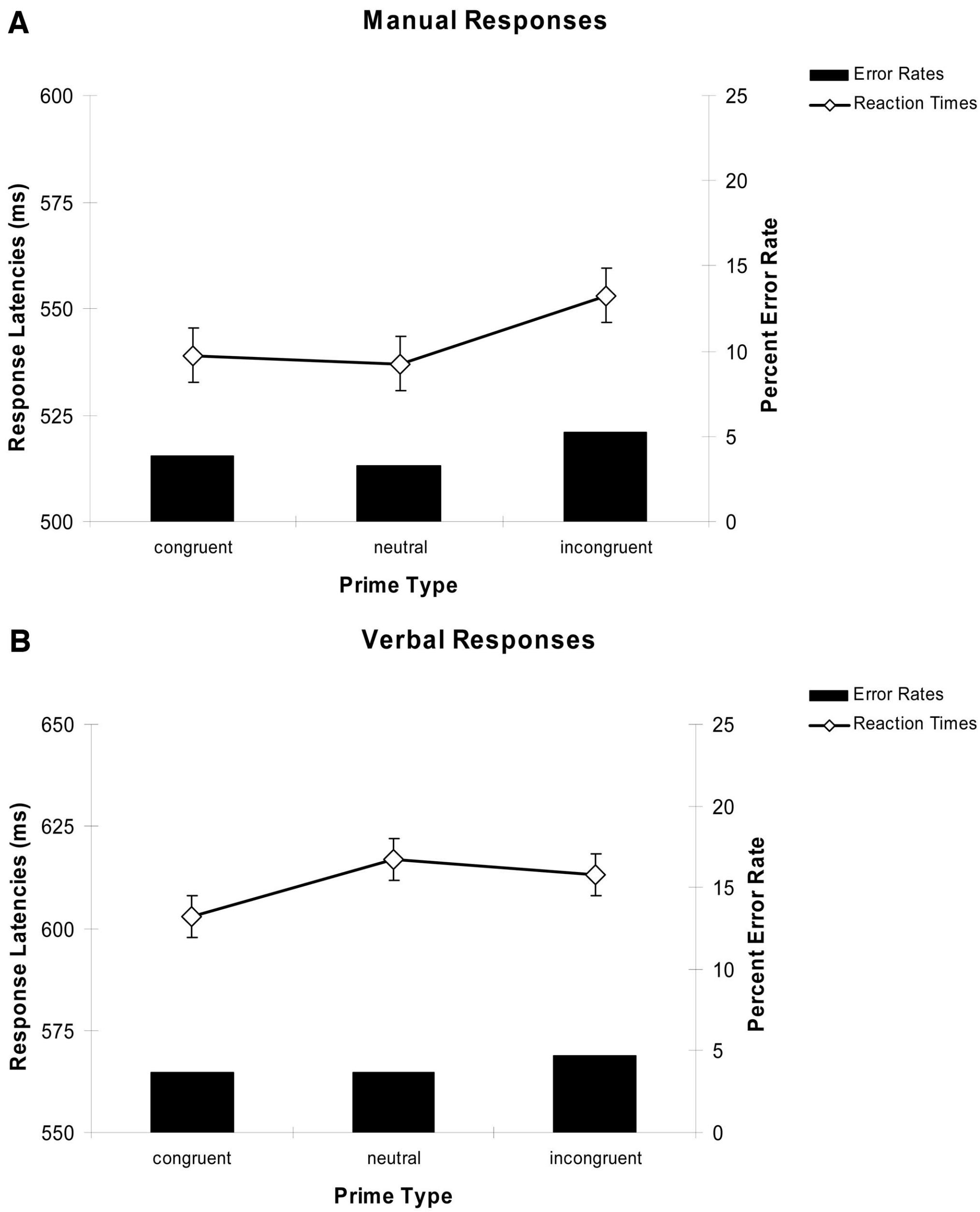

Figure 2. Responses from Experiment 1 as a function of prime type. Response latencies (lines) are plotted on the left *y* axis and error rates (bars) are plotted on the right *y* axis. A: manual responses; B: verbal responses. Error bars represent 1 standard error.

presses, responses may have been made before suppression could "knock down" the activation produced by the incongruent prime, thereby resulting in interference. Essentially, the faster a response is made in the incongruent condition, the more likely it is that the formulation of that response will be influenced (negatively) by the prime-induced activation along a competing dimension. In the case of relatively slow verbal responses, though, it could be that there is sufficient time to suppress the activation produced by the incongruent prime and, hence, prevent interference. We explore this possibility by constructing delta plots, which plot the size of the interference effect as a function of response latency. On the possibility that slowly accumulating suppression of irrelevant information is responsible for the lack of interference with the relatively slow verbal responses, we should find in both response modalities that the magnitude of the interference effect diminishes as response latencies increase.

The delta plots were constructed from the cumulative density functions in the following way (cf. Ridderinkhof, 2002). Each participant's correct RTs were rank ordered by condition (congruent, incongruent, or neutral), and then five successive bins of equal size were formed. The mean of each quintile was calculated for each individual participant and then entered into the group mean.

This yielded five conditional group means, the first of which represented the fastest 20% of the distribution, the second of which represented the next fastest 20% of the distribution, and so on. These means are plotted against the cumulative probabilities in Figure 3. The delta plots were derived from the cumulative density functions by calculating the difference between each participant's quintile mean in the relevant conditions. This was done twice for each response modality, once to determine the interference effect size (incongruent–neutral) and once to determine the facilitation effect (neutral–congruent). The mean difference for each quintile was then calculated by averaging across participants; the resulting delta plots are presented as insets in Figure 3.

Two things are apparent in Figure 3. First, looking at the cumulative density functions, it is clear that the effect of interference in the manual modality and facilitation in the verbal modality is stable across the full range of response latencies. This is most clear in the delta plots (insets in Figure 3). Second, it is also clear that the magnitude of the interference effect does not diminish as response latencies increase. In the manual response modality, the magnitude of the interference effect reached a peak in the third quintile (M = 17.0 ms), but the magnitude of the interference effect does not exhibit the systematic relationship with increasing response latencies that is typically indicative of a suppression mechanism: The size of the interference effects in the first (M = 11.4 ms) and fifth quintiles (M = 10.7 ms) does not differ, $t(47) < 1$. In the verbal response modality, there is virtually no interference at any point in the RT distribution. Thus, it does not appear that we can appeal to a slow-acting suppression mechanism to explain the lack of interference in the relatively slow verbal modality and the presence of interference in the relatively fast manual modality. Remember, if the reason there was no interference in the verbal response modality was because verbal responses were delayed long enough for suppression to inhibit activation along the irrelevant dimension, then in both modalities we should have observed an inverse relationship between the magnitude of the interference effect and response latencies—as response latencies increase, the magnitude of the interference effect should diminish. Instead, we observed virtually no effect of response latency in either the manual or the verbal response modality.

Discussion

Several important findings were obtained in this experiment. First, we replicated the standard finding in this paradigm in which masked incongruent primes produce interference when participants respond manually (cf. Finkbeiner et al., in press; Koechlin et al., 1999; Kunde et al., 2003; Naccache & Dehaene, 2001). This effect appears to be very robust and, as revealed in the cumulative distribution analysis, is stable across the full range of response latencies. Second, consistent with the hypothesis that undetected primes do not trigger the formulation of a covert articulatory response and, hence, do not produce interference, no interference

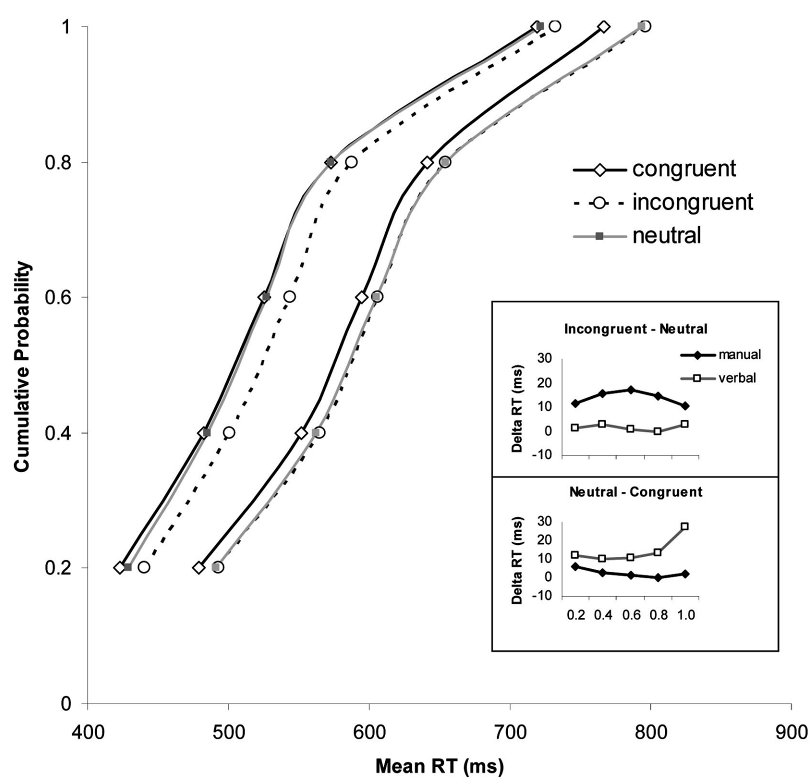

Figure 3. Cumulative density functions for manual and verbal responses in Experiment 1. The insets are the delta plots derived from the cumulative density functions for manual and verbal responses. In the top inset, the magnitude of the interference effect is plotted; in the bottom inset, the magnitude of the facilitation effect is plotted. RT = reaction time.

effect was obtained in the incongruent condition in the verbal response modality. Third, we observed a facilitation effect for masked congruent primes in the verbal response modality. This effect also appears to be very robust and stable across the full range of response latencies. This finding reveals that the lack of an interference effect in the verbal modality cannot simply be due to an inability to process masked primes when responding verbally.

Why is it that masked incongruent primes produce interference when responding manually but not verbally? We explored one possibility that follows from Ridderinkhof's (2002) suggestion that suppression operates over the activation that is produced along a competing or irrelevant dimension. Because some time is needed before suppression can be fully effective along this dimension, the benefit conferred by suppression will increase as response latencies increase. In other words, as response latencies increase, the magnitude of the interference effect should decrease. We investigated this possibility by constructing cumulative density functions and plotting the magnitude of the interference effect against RT, both for manual and verbal response modalities. We found that the magnitude of the interference effect was not modulated at all by response latency in the manual response modality and, if anything, slightly increased with greater RTs in the verbal modality. As such, there is no compelling evidence in our data to suggest that a slow-acting suppression mechanism was responsible for the modulation of the MCE as a function of response modality in Experiment 1.

Another possibility that we addressed indirectly with the "color–month" experiments in Experiment 1 (Experiments 1e and 1f) is that incongruent primes *do* engage the articulators directly but that we failed to detect this because the amount of interference produced by the neutral prime was equal to the amount of interference produced by the incongruent prime. This possibility follows from the hypothesis that orthographic primes are encoded directly into covert articulatory responses, regardless of the strength of the masking procedure, and that interference arises as a function of the difference between the articulatory gestures engendered by the prime and the target. On this account, an incongruent prime (e.g., *green*) and a neutral prime (e.g., *hotel*) produce similar amounts of interference because the articulatory gestures corresponding to these primes are equally distinct from the gesture required to produce the target response (e.g., *red*). Although this account would call into question the interpretation of the results in the "red–green" experiments, this account does not generalize to the "color–month" experiments. In Experiment 1f, the primes were *april, green, basic,* and *limit,* none of which overlap with the target responses "color" and "month." Thus, it seems reasonable to attribute the facilitation effect observed in Experiment 1f to priming at the premotor (semantic) level, not to interference in both the incongruent and the neutral conditions. Below we report a cross-language experiment that was designed to investigate this possibility further. In Experiment 2, we recruited Chinese–English bilingual individuals to participate in a replication of the red–green experiment in which we replaced the English prime words with the Chinese translation-equivalent characters. Because the Chinese characters were phonologically unrelated to the English target responses, we reasoned that any facilitation produced by these primes should be attributed to the premotor (semantic) level of processing.

Experiment 2: Is Facilitation in Naming Because of Priming or an Equal Amount of Interference in the Incongruent and Neutral Conditions?

Participants

Sixteen Chinese–English bilingual individuals were recruited from the Harvard University community. All participants were native speakers of Chinese and were highly proficient readers of Chinese characters. All individuals had normal or corrected-to-normal vision.

Materials and Procedure

The materials and procedure were the same as described above for Experiment 1b except that the masked primes (i.e., *red, green, son, hotel*) were replaced with their Chinese translation-equivalent characters (e.g., (红[red], pronounced "hong," and 绿[green], pronounced "lu"). In all other aspects, Experiment 2 was identical to Experiment 1b. Participants responded verbally in English (e.g., "red" or "green") as quickly as they could; participants were not informed of the presence of the prime words and were not aware that Chinese characters were presented during the course of the experiment.

Results

Errors and outliers were treated in the same way as described above. Just as in the unilingual naming experiments reported above, a reliable effect of facilitation was obtained in the present bilingual experiment. Mean response latencies were 796 ms, 813 ms, and 817 ms in the congruent, neutral, and incongruent conditions, respectively (see Figure 4). A repeated measures ANOVA revealed a significant effect of the factor prime type, $F_1(2, 30) = 5.94$, $p < .01$, $\eta_p^2 = .28$, and $F_2(2, 78) = 4.58$, $p = .01$, $\eta_p^2 = .11$. Post hoc t tests revealed a significant facilitation effect (congruent condition was faster than the neutral condition), $t(15) = -2.17$, $p = .04$, and congruence effect (congruent condition was faster than the incongruent condition), $t(15) = -3.4$, $p < .01$, but no interference effect.

The mean error rate was 2.05%, 1.89%, and 1.26% in the congruent, neutral, and incongruent conditions, respectively. The repeated measures ANOVA revealed no effect of prime type ($F < 1$).

Analysis of Prime Detectability

The same items used in the experiment proper were reused in a forced-choice prime-discrimination task. Participants were informed of the Chinese characters as primes and asked to discriminate between 红(red) and 绿(green). Discriminability (d') was calculated by treating the presence of one character (红) as the signal and the presence of the other character as noise. The mean d' value was 0.18 and did not differ reliably from the null mean, $t(15) = 1.87$, $p = .08$.

Discussion

The motivation for the present experiment was to investigate the possibility that the apparent facilitation effect obtained in the verbal modality in Experiment 1 was actually the result of two

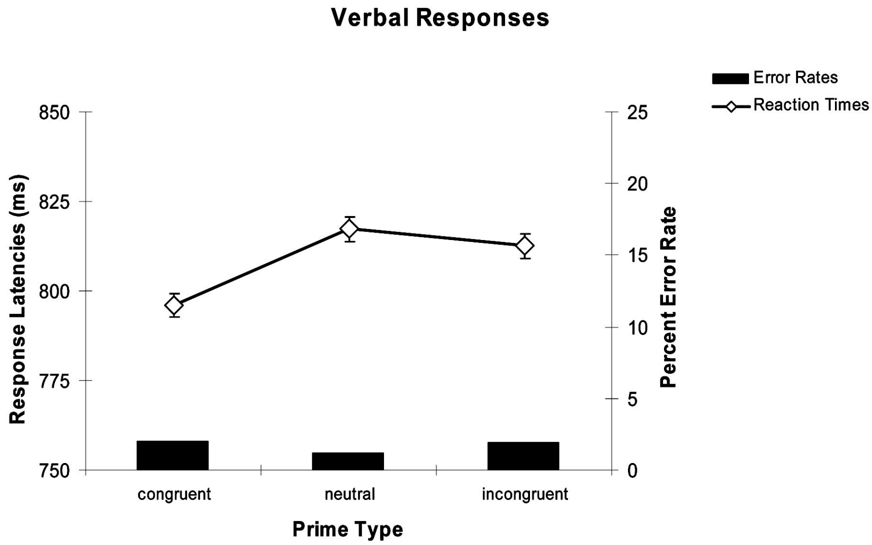

Figure 4. Response latencies (lines) and error rates (bars) from Experiment 2 as a function of prime type.

interference effects of equal magnitude in the incongruent and neutral conditions. According to this possibility, interference arises as a function of the mismatch in the articulatory gestures engendered by the prime and the target responses. To assess this possibility, we replaced the English primes with their Chinese translation equivalents, all of which were phonologically unrelated to their English equivalents. If, as hypothesized, interference arises as a result of an articulatory mismatch, then the Chinese primes should have produced an equal amount of interference in all three conditions (congruent, incongruent, and neutral). Inconsistent with this hypothesis, Chinese–English bilingual participants produced the same pattern of effects (facilitation and no interference) with masked Chinese characters as primes as that we obtained in the verbal response modality in Experiment 1. As such, it appears that the facilitation effect obtained in the verbal modality is prearticulatory (presumably semantic) in nature. These findings are also consistent with the hypothesis put forth by Finkbeiner and Caramazza (2006), which posits that undetected primes do not trigger the formulation of an articulatory response and, hence, do not produce interference.

Having established that the processing of masked primes is modulated by the response modality, we now consider different possibilities for this phenomenon. In the following experiment, we consider the possibility that there is an interaction between the number of response channels and the decision process. For example, it may be that interference arises in the manual modality but not in the verbal modality because in the manual modality responses were executed over two separate response channels. To test this possibility, we ran Experiment 1 again, but this time had participants respond with their right index finger only.

Experiment 3: Testing the Number-of-Response-Channels Hypothesis

This experiment is identical to Experiment 1a except that participants indicated whether the targets were “red things” or “green things” by using their right index finger only.

Participants

Eighteen individuals recruited from the Harvard University community participated for course credit or pay. All participants were native speakers of English and had normal or corrected-to-normal vision.

Materials and Procedure

The materials and procedure were identical to those of Experiment 1a except that participants responded with one finger as opposed to two hands. This was accomplished by replacing the button box with the keyboard and having participants press the “1” button on the number pad if the target referred to a red object and the “3” button if it referred to a green object. In an effort to ensure that participants began each trial with their index finger in a middle location, participants initiated each trial by pressing the “2” button.

Results

Just as in the previous experiments in which responses were made manually, a robust interference effect was observed. Mean response latencies were 545 ms, 548 ms, and 559 ms in the congruent, neutral, and incongruent conditions, respectively (see Figure 5). A repeated measures ANOVA revealed a significant effect of the factor prime type, $F_1(2, 34) = 4.38$, $p = .02$, $\eta_p^2 = .21$, and $F_2(2, 78) = 4.97$, $p < .01$, $\eta_p^2 = .11$. Post hoc *t* tests revealed a significant interference effect (incongruent condition was slower than the neutral condition), $t(17) = 2.47$, $p = .02$, and a significant congruence effect (congruent condition was faster than the incongruent condition), $t(17) = 2.36$, $p = .03$, but no facilitation effect.

The mean error rate was 1.53%, 2.08%, and 2.78% in the congruent, neutral, and incongruent conditions, respectively. No effect of prime type was revealed in the repeated measures ANOVA, $F_1(2, 34) = 1.3$, $p > .2$.

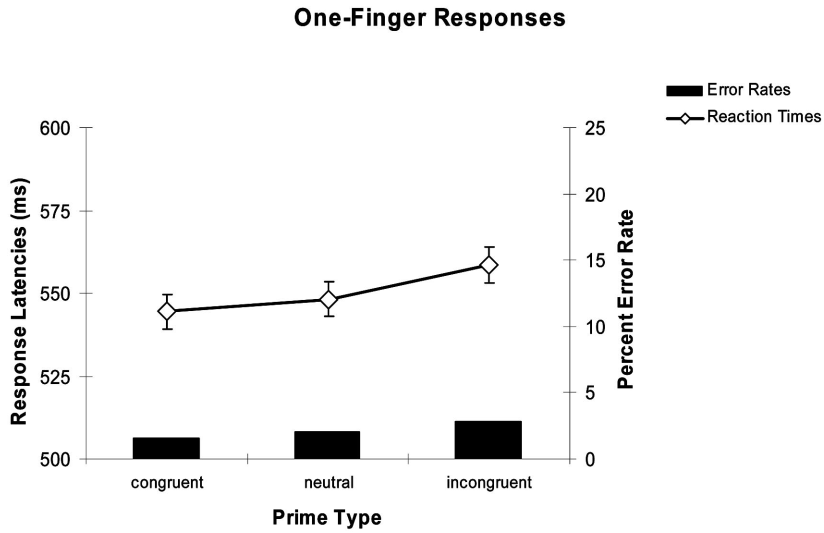

Figure 5. Response latencies (lines) and error rates (bars) from Experiment 3 as a function of prime type.

Analysis of Prime Detectability

The prime detection task was identical to that of Experiment 1. The mean d' value was -0.14, which did not differ from the null mean.

Discussion

The purpose of this experiment was to test the possibility that the critical difference between the manual and the verbal response modalities is the number of channels over which a response may be executed. In the button-press experiments reported above, participants made one response with their left hand and the other response with their right hand. In the verbal modality, both possible responses were necessarily produced over the same channel. To determine whether this architectural constraint was responsible for the difference in the processing of masked primes, we equated the number of response channels between the manual and verbal response modalities by having participants make both possible responses with just their right index finger. We found that reducing the number of response channels in the manual response modality had no effect on the processing of masked primes in this modality. Just as when participants respond with two hands, incongruent primes produced an interference effect when participants respond with just one finger. It does not appear to be the case, then, that the difference in the number of response channels between the verbal and the manual response modalities is critical to whether the prime is processed down to the motor level in the masked congruence priming paradigm.

Below we consider the possibility that the relative difficulty of responding verbally versus manually is critical to the extent of processing of masked primes. To address this possibility, we increased the level of difficulty of executing a manual response by increasing the number of possible responses that participants could make from two to four. In the following experiment, participants had to indicate whether the target word referred to something that is red, green, yellow, or orange.

Experiment 4: Testing the Relative-Difficulty-of-Responding Hypothesis

Participants

Sixteen individuals recruited from the Harvard University community participated for course credit or pay. All participants were native speakers of English and had normal or corrected-to-normal vision.

Materials and Procedure

The materials and procedure differed slightly from those of the previous experiments insofar as this experiment made use of four different response categories. Participants were asked to categorize target orthographic stimuli (always presented in black ink) as "red things," "orange things," "yellow things," or "green things". The target stimuli were BLOOD, TOMATO, CARROT, PUMPKIN, LEMON, BANANA, LEAF, and SPINACH. Participants responded with the middle and index fingers of the left and right hands by pressing the "Z" key for "red things," the "X" key for "green things," the ">" key for "orange things," and the "?" key for "yellow things." The prime words in the congruent and incongruent conditions were *red, orange, yellow,* and *green*. The neutral primes were consonant strings (e.g., wrlndgy). To ensure full masking of the prime stimuli, the length of the forward and backward masks were increased to eight characters in this experiment. Each target was presented five different times in each of the three prime conditions (congruent, incongruent, and neutral) for a total of 120 trials. Unlike the previous experiments, which had only 10 practice trials, this experiment was preceded by 40 practice trials. The practice trials were all congruent trials. In the experiment proper, incongruent primes always corresponded to the same finger on the opposite hand. For example, if the target response was to be made with the middle finger of the left hand, the incongruent prime corresponded to the middle finger of the right

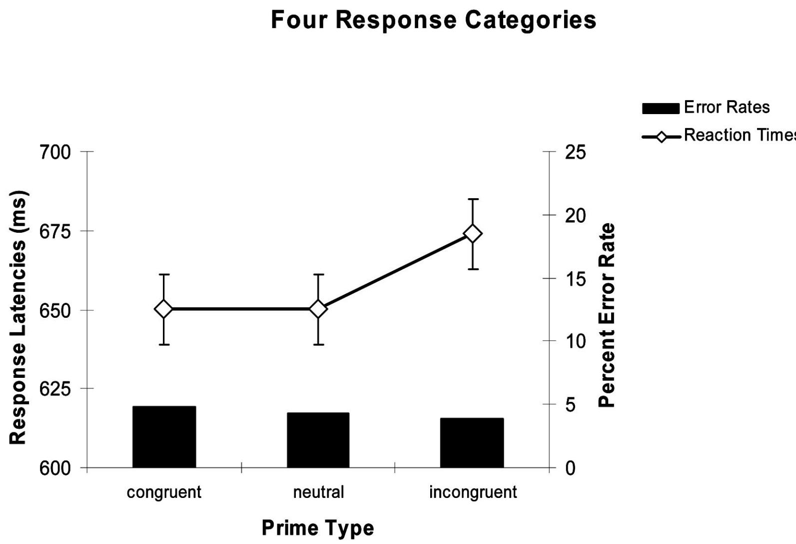

Figure 6. Response latencies (lines) and error rates (bars) from Experiment 4 as a function of prime type.

hand. All other aspects of the stimulus presentation and procedure were identical to those of Experiment 1.

Results

As is clear in Figure 6, increasing the number of response alternatives had the intended effect of increasing the difficulty of executing a manual response (as indexed by the increase in response latencies) but no effect on the overall pattern of effects by prime condition. Just as in the previous experiments in which responses were made manually, a robust effect of interference was observed but no effect of facilitation. Mean response latencies were 650 ms, 650 ms, and 674 ms in the congruent, neutral, and incongruent conditions, respectively. A repeated measures ANOVA revealed a significant effect of the factor prime type, $F_1(2, 30) = 4.89$, $p = .02$, $\eta_p^2 = .25$, and $F_2(2, 78) = 6.52$, $p < .01$, $\eta_p^2 = .14$. Post hoc *t* tests revealed a significant interference effect (incongruent condition was slower than the neutral condition), $t(15) = 2.79$, $p = .01$, and a marginal effect of congruence (congruent condition was faster than the incongruent condition), $t(15) = 2.23$, $p = .04$,[2] but no facilitation effect. The mean error rate was 4.83%, 4.33%, and 3.83% in the congruent, neutral, and incongruent conditions, respectively. No effect of prime type was revealed in the repeated measures ANOVA, $F_1(2, 30) < 1$.

Discussion

This experiment was designed to address the possibility that the extent of processing of masked primes is somehow modulated by the difficulty of executing a response. According to this possibility, it could be that masked primes are not processed down to the motor level when participants respond verbally because of the difficulty of executing a verbal response relative to that of executing a manual response. To test this possibility, we increased the number of response categories from two to four. On the assumption that response latencies index response difficulty, we were successful in equating the response difficulty of manual responses to that of verbal responses. In fact, the response latencies in the present experiment were slightly longer than the response latencies in the verbal modality in Experiment 1. Nevertheless, this increase in difficulty had no appreciable effect on the nature of the masked congruence effect. Despite the increased response latencies, interference was still obtained in the incongruent condition, and no facilitation was obtained in the congruent condition. This finding suggests that the processing of masked primes is modulated more by the modality of the response than it is by the so-called difficulty of executing a response. Of course, there are several possible ways in which difficulty may arise. It could be, for example, that the difficulty of formulating the articulatory response “red” to the stimulus BLOOD is different in kind from the difficulty of having to select one of four different response categories.

In the previous experiments, we established that the processing of masked primes is modulated by the response modality such that undetected primes are processed down to the response level in the manual response modality but not in the verbal response modality. Follow-up experiments have revealed that the modulation by response modality cannot be reduced to differences in the number of response channels between the two modalities or to the so-called difficulty of responding verbally versus manually. In the following experiment, we investigate the possibility that differences in the nature of the stimulus–response mapping between response modalities may have contributed to the contrasting pattern of findings that we have observed in the two modalities. By virtue of our participants being highly proficient readers, it may be that the orthographic stimuli used in the previous experiments map directly (and perhaps obligatorily) onto a verbal response, and this may have created unforeseen difficulty in the verbal response modality. For example, when presented with the target stimulus BLOOD,

[2] This comparison reached standard levels of significance ($p < .05$) in the paired-samples *t* test, but failed to do so when controlling for the false discovery rate.

participants may not be able to avoid verbalizing that letter string, thereby producing “blood” covertly. Furthermore, the verbalization “blood” may then conflict with the intended target response “red,” and this may have created difficulty in the verbal modality that is not present in the manual modality. When responding manually, the stimulus BLOOD does not map naturally onto a particular manual response other than the one that the participant has learned in the context of the experiment. This difference in the nature of the stimulus–response mapping between the two response modalities may be critical to whether or not one finds evidence of the masked prime being processed down to the response level. With this possibility in mind, we used pictures as primes and targets in the following experiment. The advantage of using pictures is that the stimulus–response mapping should be equally arbitrary in both the speech and the manual response modality.

Experiment 5: Masked Congruence Priming With Pictures

In this experiment, individuals were asked to indicate whether a target picture depicted a face or a tool. As with the previous experiments, the target pictures were preceded by a masked prime stimulus that elicited a response either congruent or incongruent with the target picture. A fundamental difference between this experiment and the previous experiments was that in this experiment no neutral stimulus was used. Instead, we parametrically manipulated the prime duration from 10 ms to 60 ms in 10-ms increments. Because no effect is expected for primes that are presented for only 10 ms, we used response latencies in the 10-ms prime duration as our baseline.

A primary motivation for manipulating the prime duration in this way was to test explicitly the claim made by Finkbeiner and Caramazza (2006) that undetected primes do not engender an articulatory response, but that detected primes do. In the previous experiments, we did not test this claim directly because we used only a 30-ms prime duration, which renders the primes undetectable. In the present experiment, we put this claim to the test by varying prime durations from those that are very short and undetectable to those that are longer and detectable. According to the hypothesis put forth by Finkbeiner and Caramazza, undetected primes should not produce interference in the verbal modality but detected primes should. On the basis of the findings reported above, and on the masked congruence priming literature, detectability of the prime stimulus should not modulate the interference effect in the manual modality.

A secondary motivation for manipulating the prime duration was to address the possibility that our baseline condition in the previous experiments was not appropriate. It could be, for example, that masked (neutral) primes are more likely to engage the articulators than the hands and, hence, do not constitute an appropriate neutral stimulus. Determining the appropriate baseline in experiments of this type is difficult, but one solution for which there is some consensus is to use only congruent and incongruent primes and to parametrically manipulate the presentation duration of the primes (Ziegler et al., 2000). This procedure allows one to plot the effect size of each prime type (congruent and incongruent) as a function of the opportunity that participants are given to process the prime stimulus. At the shortest presentation duration (10 ms), there is not sufficient opportunity to process the prime, and so little to no effect of prime type is expected. Because primes presented for only 10 ms do not produce an effect, the mean response latencies in this condition can be taken as the baseline. As primes are presented for increasingly longer durations, there is an increased opportunity to process the primes and, hence, an increased likelihood of observing an effect of the prime stimulus on target responses. To determine the direction and magnitude of the prime effect obtained with longer presentation durations, the response latencies in these longer presentation conditions are compared with the response latencies in the 10-ms (baseline) condition.

Participants

Six individuals recruited from the Harvard University community participated for pay. All participants were naïve to the purpose of the experiment, were native speakers of English, had normal or corrected-to-normal vision, and were strongly right handed. Handedness was assessed using the Edinburgh Handedness Inventory (Oldfield, 1971), which yields a laterality quotient that ranges from 1.0 (extreme right handedness) to -1.0 (extreme left handedness). The mean laterality quotient for the participants was .88.

Materials

Ten black-and-white photographs, 5 of faces and 5 of tools, were selected and used as target stimuli. Two additional pictures were selected and used as prime stimuli. The prime stimuli never appeared as target stimuli or vice versa. The tool prime was a hand saw. The target tool stimuli consisted of a hatchet, drill, hammer, file, and wrench. All tool stimuli were presented in an orientation that afforded a left-handed grip. The face stimuli were emotionally neutral female faces selected from the Harvard Faces Database. The faces were cropped vertically from just above the eyes to just below the lips and horizontally from the left to right outermost edges of the eyes. Both the faces and the tools were presented in 20% uniformly distributed noise (see Figure 7 for an example).

The prime picture was both preceded and followed by complementary black-and-white checkerboard pattern masks. All stimuli were the same size (approximately 3.5° of visual angle) and were presented centrally at fixation.

Design and Procedure

Participants were tested in five separate 1-hr sessions, one session per day, within a 10-day period.

Sessions 1 and 2: Determining the Effect of Priming

In the first two sessions, participants were not informed of the primes and were simply asked to respond to the target stimulus as quickly as they could. Half of the participants responded manually in their first session and verbally in their second session, with the order reversed for the remaining participants.

Sessions 3 and 4: Prime Detection

The experimental files used in Sessions 1 and 2 were again used in Sessions 3 and 4, with two changes: (a) The question “Did you see a prime?” was appended to each trial and (b) 20% of the primes in each display condition were replaced with blank spaces (half

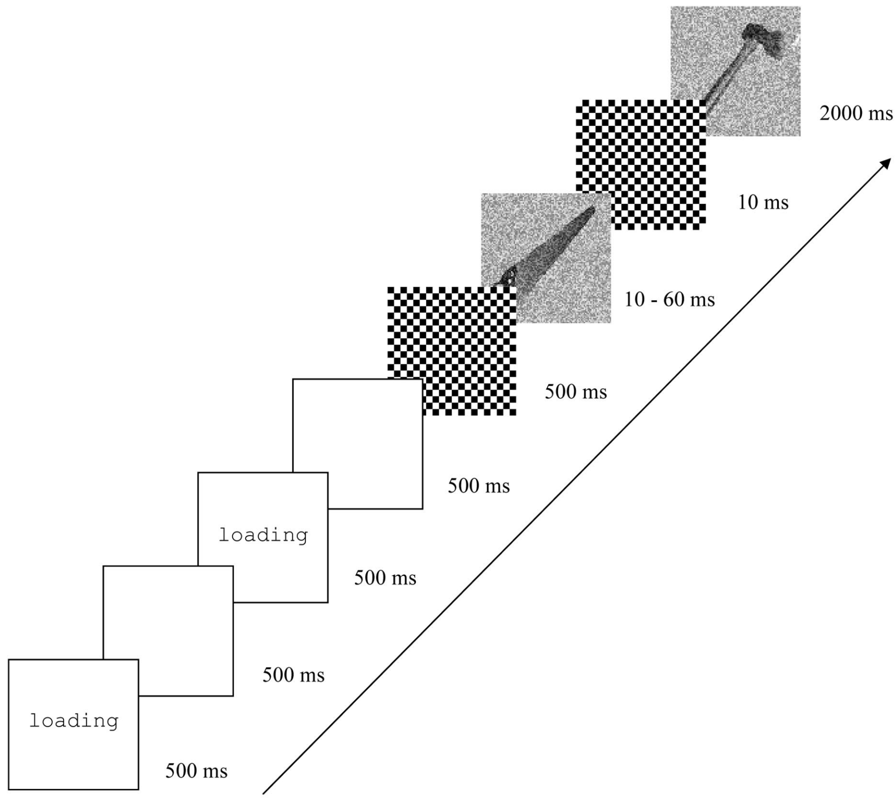

Figure 7. Trial structure in Experiment 5 (congruent tool trial is depicted). Each trial was preceded by a 2-s interval during which the word *loading* blinked on and off. This was followed by the forward mask for 500 ms, the prime stimulus for 10 to 60 ms, the backward mask for 10 ms, and then the target stimulus for 2 s or until a response was registered.

congruent trials and half incongruent trials). Participants were informed of the primes and asked to make two responses on each trial. Participants' first response was to the target, just as it had been in Sessions 1 and 2; following their response to the target stimulus, participants were asked to indicate whether a prime stimulus had been presented before the target stimulus. Prime detection responses were made manually, regardless of whether the response to the target stimulus had been made manually or verbally. Just as with the first two sessions, the order of participation in manual and verbal sessions was counterbalanced across participants.

Session 5: Prime Identification

In Session 5, participants were asked to identify the prime by pressing an appropriate button, one for face primes and another for tool primes. In an effort to prevent "unconscious" responses to the prime, participants were cued to respond, and the response cue was delayed for a period of 1 s following the offset of the prime stimulus. This was done by presenting the target stimulus for 500 ms, a blank space for 500 ms, and then the instruction to respond.

Each session began with 10 practice trials in which each target stimulus was presented once. In the experiment proper, each target stimulus ($N = 10$) appeared five times in each condition (five times with a congruent prime and five times with an incongruent prime) in each of the six display conditions (prime duration) for a total of 600 trials. The six different display conditions corresponded to the six different prime durations, which ranged from 10 ms to 60 ms in 10-ms increments (see Figure 7). Just as with the previous experiments, stimuli were presented in a different pseudorandom order for each participant, with the only constraint being that each successive block of 120 trials included one presentation of each target stimulus in each display condition and prime condition. Both the blocks of trials and the trials within the blocks were fully randomized for each participant. Experimental trials were presented continuously with a run length of 50. After every 50 trials, participants were given the opportunity to take a break and were asked to initiate the next run of trials by pressing a foot pedal.

Results

Errors and outliers were treated in the same way as in the previous experiments.

Prime Detection and Identification

To test the hypothesis that prime detectability determines whether interference is obtained in the verbal modality, we first determined the prime durations for which detection occurred and those for which detection did not occur. To do this, the mean d' measure was calculated for each participant in each response modality, prime duration, and task (prime detection and prime identification). The resulting d' measures were then entered into one-sample *t* tests (not corrected for multiple comparisons). Figure 8 displays the resulting d' measures as a function of prime duration, response modality, and task. Interestingly, in both the prime detection and the prime identification tasks, d' measures reached significance at the 40-ms prime duration. In Figure 8, the d' measures above the dashed line are reliably greater than the null mean, and those below the dashed line do not differ statistically from 0.

Verbal Responses

As is clear in Figure 9, effects of both prime type and prime duration were obtained in the verbal response modality. This was confirmed in a repeated measures ANOVA that revealed a main effect of prime type, $F_1(1, 5) = 12.55$, $p = .02$, $\eta_p^2 = .72$, and $F_2(1, 49) = 73.16$, $p < .01$, $\eta_p^2 = .60$, and a marginal effect of prime duration, $F_1(5, 25) = 1.95$, $p = .12$, $\eta_p^2 = .28$, and $F_2(5, 245) = 6.56$, $p < .01$, $\eta_p^2 = .12$. As is also clear in Figure 9, there was a robust interaction between the two factors, $F_1(5, 25) = 5.39$, $p < .01$, $\eta_p^2 = .52$, and $F_2(5, 245) = 11.14$, $p < .01$, $\eta_p^2 = .19$. The nature of this interaction is clear: Incongruent primes produced an interference effect, and congruent primes produced a facilitation effect, the magnitude of which increased as a function of prime duration.

To investigate the hypothesis that the processing of undetected primes does not extend down to the response level (i.e., produce interference) but that the processing of detected primes does, we separated the item means from the incongruent prime condition into "detected" and "undetected" groups. Item means in the undetected group corresponded to the trials with prime durations of 10, 20, and 30 ms (see prime detection results above); item means in the detected group corresponded to the trials with prime durations of 40, 50, and 60 ms. These incongruent item means were then entered into a 2 × 3 repeated measures ANOVA with the factors

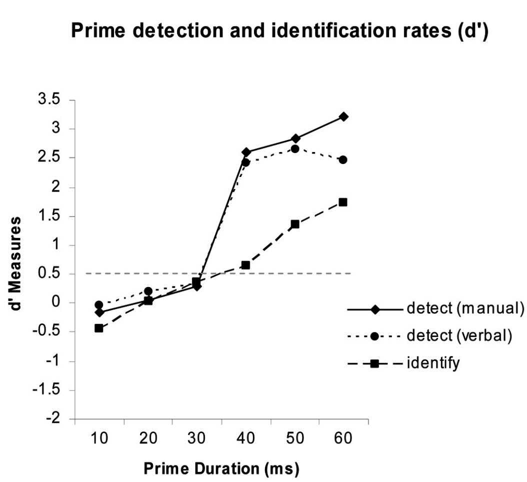

Figure 8. Prime detection and identification rates (d') in Experiment 5 as function of prime duration, response modality and task.

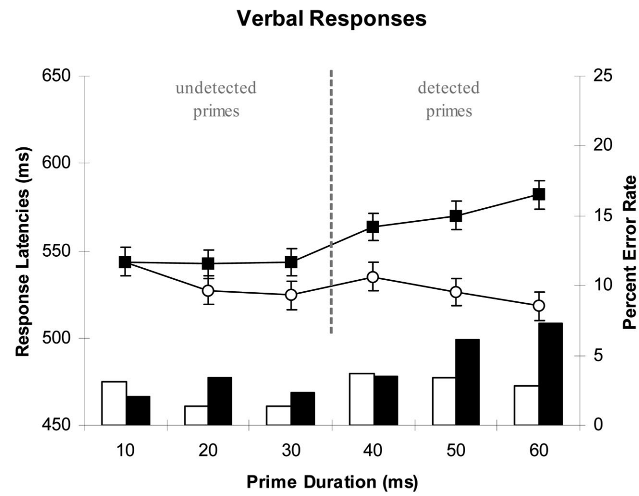

Figure 9. Verbal responses in Experiment 5. Response latencies (lines) are plotted against the left *y* axis and error rates (bars) are plotted against the right *y* axis. Incongruent trials are depicted with filled squares in the line graph and filled bars in the bar graph; congruent trials are depicted with open circles and open bars. The error bars represent 95% confidence intervals calculated on the basis of pooled error terms as described in Masson and Loftus (2003) for two-factor, within-subject designs.

detectability and prime duration. This analysis revealed a main effect of detectability, $F(1, 49) = 80.3$, $p < .01$, $\eta_p^2 = .62$, and prime duration, $F(2, 98) = 4.6$, $p = .01$, $\eta_p^2 = .09$. It is important to note that the interaction between these two factors was reliable, $F(2, 98) = 6.06$, $p < .01$, $\eta_p^2 = .11$. This interaction reveals that the interference effect produced by incongruent primes as a function of prime duration was different for detected and undetected primes. Namely, detected primes produced an interference effect but undetected primes did not. The same analysis with response latencies from the congruent prime condition revealed a main effect of prime duration, $F(2, 98) = 4.4$, $p = .02$, $\eta_p^2 = .08$, but no effect of detectability and no interaction (*F*s < 1). This pattern of results is clear in Figure 9. In the verbal response modality, interference occurs only for detected primes; facilitation, however, occurs for both undetected and detected primes. This was confirmed in a series of post hoc *t* tests (that, again, controlled for the false discovery rate; see Table 2) in which the mean response latencies in each prime condition and duration were compared with the baseline condition (mean response latencies at the 10-ms prime duration); these contrasts revealed reliable effects of facilitation beginning with 20-ms primes. However, as predicted, reliable interference effects were obtained for detected primes only.

In the analysis of the error rates, there was a reliable effect of prime type, $F_1(1, 5) = 4.65$, $p = .08$, $\eta_p^2 = .48$, and $F_2(1, 49) = 7.58$, $p < .01$, $\eta_p^2 = .13$, and a main effect of duration in the items analysis but not in the participants analysis, $F_1(5, 25) = 1.58$, $p > .2$, $\eta_p^2 = .23$, and $F_2(5, 245) = 3.39$, $p < .01$, $\eta_p^2 = .07$. Just as with the RT analysis, the interaction between the two factors was reliable, $F_1(5, 25) = 3.29$, $p = .02$, $\eta_p^2 = .39$, and $F_2(5, 245) = 1.97$, $p = .08$, $\eta_p^2 = .04$. The nature of this interaction is clear in Figure 9: Error rates increase as a function of prime duration in the incongruent condition but not in the congruent condition.

Table 2
Paired Samples t Test for Mean Response Latencies in Experiment 5 by Prime Duration (20–60 Milliseconds), Prime Type (Congruent Vs. Incongruent), and Response Modality (Verbal Vs. Manual)

Response	Comparison (prime duration)	$t(5)$	p (two-tailed)
Verbal			
Pair 1	Baseline-congruent (20 ms)	2.66	.04
Pair 2	Baseline-incongruent (20 ms)	0.23	.83
Pair 3	Baseline-congruent (30 ms)	5.80	.00
Pair 4	Baseline-incongruent (30 ms)	0.08	.94
Pair 5	Baseline-congruent (40 ms)	1.27	.26
Pair 6	Baseline-incongruent (40 ms)	−2.49	.05
Pair 7	Baseline-congruent (50 ms)	6.11	.00
Pair 8	Baseline-incongruent (50 ms)	−2.56	.05
Pair 9	Baseline-congruent (60 ms)	3.98	.01
Pair 10	Baseline-incongruent (60 ms)	−3.92	.01
Manual			
Pair 1	Baseline-congruent (20 ms)	−0.86	.43
Pair 2	Baseline-incongruent (20 ms)	−0.94	.39
Pair 3	Baseline-congruent (30 ms)	0.24	.82
Pair 4	Baseline-incongruent (30 ms)	−3.09	.03
Pair 5	Baseline-congruent (40 ms)	1.62	.17
Pair 6	Baseline-incongruent (40 ms)	−2.74	.04
Pair 7	Baseline-congruent (50 ms)	6.90	.00
Pair 8	Baseline-incongruent (50 ms)	−2.74	.04
Pair 9	Baseline-congruent (60 ms)	1.17	.30
Pair 10	Baseline-incongruent (60 ms)	−3.13	.03

Manual Responses

Just as with the verbal responses, and as is clear in Figure 10, effects of both prime type and prime duration were obtained with manual responses. The repeated measures ANOVA revealed a main effect of prime type, $F_1(1, 5) = 16.35$, $p < .01$, $\eta_p^2 = .77$, and $F_2(1, 49) = 64.23$, $p < .01$, $\eta_p^2 = .57$, and prime duration, $F_1(5, 25) = 2.35$, $p = .07$, $\eta_p^2 = .32$, and $F_2(5, 245) = 6.64$, $p < .01$, $\eta_p^2 = .12$. There was a robust interaction between the two factors, $F_1(5, 25) = 9.47$, $p < .01$, $\eta_p^2 = .65$, and $F_2(5, 245) = 14.24$, $p < .01$, $\eta_p^2 = .23$. The nature of this interaction is the same as it was with verbal responses: Incongruent primes produced interference, and congruent primes produced facilitation.

To determine whether detectability modulated the processing of masked incongruent primes in the manual response modality (as it did in the verbal response modality), the item means from the incongruent condition were entered into a repeated measures ANOVA with the factors detectability and prime duration. This analysis revealed a main effect of detectability, $F(1, 49) = 48.73$, $p < .01$, $\eta_p^2 = .50$, and prime duration, $F(2, 98) = 16.49$, $p < .01$, $\eta_p^2 = .25$. Interestingly, no interaction between these two factors was observed, $F(2, 98) = 1.63$, $p > .2$. In other words, prime duration similarly modulated the magnitude of the interference effect produced by detected and undetected primes. The same analysis with mean response latencies from the congruent condition revealed a main effect of detectability, $F(1, 49) = 7.3$, $p < .01$, $\eta_p^2 = .13$, but no effect of prime duration ($F < 1$) and no interaction between the two factors, $F(2, 98) = 2.2$, $p = .12$. A series of post hoc t tests confirmed the general pattern of effects established in the previous experiments for manual responses: interference in the incongruent condition and little to no facilitation in the congruent condition. This general pattern was found to hold for both detected and undetected primes.

In the analysis of the errors produced in the manual response modality, the main effect of prime type did not reach significance in the participants analysis but did in the items analysis, $F_1(1, 5) = 3.64$, $p = .12$, $\eta_p^2 = .42$, and $F_2(1, 49) = 17.15$, $p < .01$, $\eta_p^2 = .26$. The main effect of prime duration was reliable in the items analysis, $F_2(5, 245) = 2.61$, $p = .02$, $\eta_p^2 = .05$, but not in the participants analysis. Again, just as with the RT analysis, the interaction between the two factors was reliable, $F_1(5, 25) = 3.37$, $p = .02$, $\eta_p^2 = .40$, and $F_2(5, 245) = 4.64$, $p < .01$, $\eta_p^2 = .08$. Essentially, error rates in the incongruent condition increase with prime duration, but error rates in the congruent condition do not (see Figure 10).

Discussion

In this experiment, we made use of pictorial stimuli as opposed to orthographic stimuli. In the previous experiments, all of the stimuli were orthographic, and it is reasonable to think that orthographic stimuli may be preferentially encoded into a phonological (verbal) response as opposed to a manual response. This important difference in the nature of the stimulus–response mapping might have been responsible for the difference in the processing of masked primes in the two response modalities. The present experiment addressed this possibility by using pictures. Interestingly, changing from orthographic stimuli to pictorial stimuli had no appreciable effect on the pattern of performance. Just as in the previous experiments, undetected incongruent primes produced interference in the manual response modality but not in the verbal response modality. Hence, once again, the processing of masked (undetected) primes appears to extend down to the response level in the manual response modality but not in the verbal response

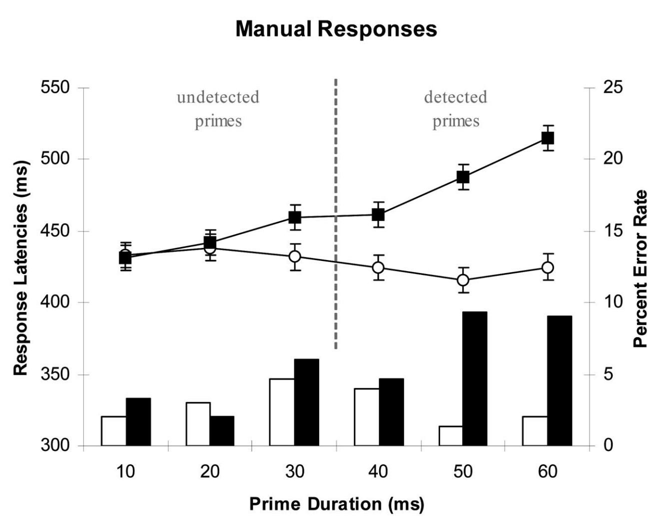

Figure 10. Manual responses in Experiment 5. Response latencies (lines) are plotted against the left *y* axis and error rates (bars) are plotted against the right *y* axis. Incongruent trials are depicted with filled squares and bars; congruent trials are depicted with open circles and bars. The error bars represent 95% confidence intervals calculated on the basis of pooled error terms as described in Masson and Loftus (2003) for two-factor, within-subject designs.

modality. And this modulation by response modality is not limited to orthographic stimuli.

An important difference between this experiment and the previous experiments was the use of multiple prime durations. One reason for manipulating the prime duration was to test the hypothesis put forward by Finkbeiner and Caramazza (2006) that undetected prime stimuli do not engender an articulatory response and, hence, do not produce interference in the verbal response modality. We tested this claim directly by varying the prime duration from 10 ms to 60 ms in 10-ms increments. We then had participants perform two different prime detection tasks and one prime identification task. The prime detection tasks were performed in the third and fourth experimental sessions in which participants first responded to the target (just as they had done in Sessions 1 and 2) followed by a response in which they indicated whether the target had been preceded by a prime stimulus or not. This prime detection task was done twice, once when responses to the target stimulus were made manually and once when they were made verbally. We found that participants were able to reliably detect the presence of the prime stimulus when the prime was presented for 40 ms or longer and that this was true when participants responded to the target both manually and verbally. Interestingly, in the fifth session it was found that participants could identify the prime stimulus as a face or a tool just as quickly (40 ms) as they could detect the stimulus's presence. Participants were not able to detect the presence of primes that were presented for 30 ms or less. For our purposes, it is important to note that detected incongruent primes produced interference in the verbal response modality, but undetected primes did not. Just as with the previous experiments, this pattern of effects was not due to participants being unable to process the undetected primes because (a) undetected incongruent primes (30 ms) produced interference in the manual response modality and (b) undetected congruent primes (20 ms and 30 ms) produced facilitation in the verbal response modality. These findings establish that the processing of prime stimuli is strongly modulated by detectability in the verbal response modality. The processing of undetected primes does not extend down to the response level, but the processing of detected primes does. The results of this experiment also demonstrate that the processing of prime stimuli in the manual response modality is not modulated by participants' ability to detect the primes. When participants respond manually, the processing of the prime extends down to the response level regardless of whether participants detect the prime or not. This latter finding is consistent with the findings reported by Vorberg et al. (2003), who also observed a robust masked congruence effect but no effect of prime detectability in a manual response modality.

A second reason for manipulating prime duration was to establish an appropriate baseline condition by using the same primes in the baseline condition as were used in the experimental conditions. In the previous experiments, separate stimuli were used in the neutral condition, and these may have interacted with the verbal and manual response modalities differently. If this is the case, then it may be that the neutral primes in the previous experiments did not constitute an appropriate baseline. To address this possibility in the present experiment, we used the shortest prime duration (10 ms) as our "neutral" prime. Because prime stimuli presented for only 10 ms did not produce an effect (either numerically or statistically) on target responses, we were able to use the mean response latencies in this display condition as our baseline. By establishing the baseline condition in this way, we were able to plot the effects of congruent and incongruent prime types as a function of increasing participants' opportunity to process the prime stimulus. Notably, changing the way in which we determined the baseline did not change the pattern of effects that we observed.

At this point, we have established that the extent of processing of masked primes, as indexed by the presence or absence of an interference effect in the incongruent condition, is modulated by the response modality, and by replicating this contrasting pattern of effects several times under a variety of different conditions, we have been able to rule out a wide range of possible explanations. However, although the findings confirm nicely the claim put forth by Finkbeiner and Caramazza (2006), it is still not clear why masked primes should not engage the articulators—especially as they so clearly engage the hands. Up to this point, we have worked under the assumption that once a response is selected at a premotor (i.e., semantic) level of representation, it is then encoded into a motor response (either manual or articulatory) and that the translation from premotor response to motor response is essentially equivalent in kind across the two response modalities. With this assumption in mind, we have conducted several experiments designed to probe how quantitative differences across the two response modalities (e.g., number of response channels, response "difficulty") may influence this translation process. Perhaps, however, it is wrong to assume that the decision that BLOOD is red or that JULY is a month is encoded into a motor program in qualitatively equivalent ways across the two modalities. Below we consider the possibility that encoding a premotor representation into a manual motor response is different in kind from the way in which that same representation is encoded into a verbal motor response.

In the experiments that we have reported above, participants categorized stimuli (e.g., BLOOD) into one of two predefined categories (e.g., red or green). In the case of the stimulus BLOOD, the premotor (semantic) representation RED must be selected before the motor system may be engaged appropriately. In the case of manual (button-press) responses, the mapping between the semantic representation RED and a button press is established during the course of the experiment. And, presumably, this experiment-induced mapping is direct and able to be run off straightaway. Although it seems reasonable to think that participants would establish similarly direct mappings in the verbal response modality, especially when there are only two possible responses, they may be prevented from doing so by virtue of there already being a well-established lexical system that mediates premotor- and motor-level representations. In normal speech production contexts, it is well accepted that premotor (i.e., semantic) representations do not map directly onto motor (i.e., articulatory) responses but rather onto lexical–phonological representations that, in turn, specify the information necessary for the articulatory gesture (Caramazza, 1997; Dell, 1986; Goldrick & Rapp, 2007; Levelt, Roelofs, & Meyer, 1999). Hence, in the measure for which there already exists a well-established lexical–phonological system whose sole purpose is to mediate premotor- and motor-level (articulatory) representations, it may be that participants are unable to bypass this system when producing speech responses—even when only two responses are required for the entire experiment.

If we assume that speech responses are necessarily mediated by a lexical route, how does this help to explain the modulation by response modality of the extent of processing of masked primes? Put simply, masked primes may not produce enough activation to drive lexically mediated responses. If this is the case, and if interference arises as a function of the conflict that arises between two incompatible motor responses, then masked primes should not produce interference in the verbal response modality but could in the manual response modality (by virtue of the direct experiment-induced mapping between premotor- and motor-level representations in the manual response modality). In contrast, if we assume that masked primes are able to produce some activation along the lexical route, it is reasonable to think that the facilitation effect that we have observed in the verbal response modality could be due to the preactivation of lexical–phonological representations.

If this account of the findings reported up to this point is correct, then masked incongruent primes should produce interference in the verbal response modality when verbal responses are not lexically mediated. In the following experiment, we use the go–no-go paradigm in an attempt to bypass the lexical route. Our reasoning was as follows: In the go–no-go paradigm, participants are able to precompile their articulatory response. This is because their task is simply to release (or not) a single response (e.g., "red"). Importantly, when participants can precompile their articulatory response, there is no need for lexical access. Thus, we reasoned that participants should be able to proceed directly from the premotor decision level to the motor response (e.g., /rɛd/), and hence, we should be able to detect the influence of the prime stimulus on the motor response in the same way that we do in the manual response modality. We explore this possibility in the following experiment.

Experiment 6: Bypassing Lexical Access With Go–No-Go

The purpose of this experiment was to test the possibility that allowing participants to precompile their verbal response would allow them to bypass lexical access and, thus, to proceed directly from the decision stage to the articulatory response. If this reasoning is correct, then in this task the extent of processing of masked primes in the verbal and manual response modalities should be equated.

Experiment 6 consisted of four separate experiments. In Experiments 6a and 6b, half of the participants were asked to respond when the target stimulus referred to a "red thing" and the other half were asked to respond when it referred to a "green thing." In Experiments 6c and 6d, half of the participants responded when the target referred to a color, and half responded when it referred to a month. In Experiments 6a and 6c, participants responded manually; in Experiments 6b and 6d, participants responded verbally.

Participants

Sixty-four individuals (16 each in Experiments 6a, 6b, 6c, and 6d) at Harvard University participated for course credit or pay. All participants were native speakers of English and had normal or corrected-to-normal vision.

Materials

The materials were identical to those used in Experiment 1. The neutral primes were *boy* and *mouth* in Experiments 6a and 6b and *basic* and *limit* in Experiments 6c and 6d.

Procedure

The procedure was very similar to that of Experiment 1 except that in the present set of experiments two lists were created for each experiment to counterbalance across the go trial type. In Experiments 6a and 6b, the target words referred to either red objects or green objects, and in each experiment the "go" items were the red targets on List 1 and the green targets on List 2. In Experiments 6c and 6d, the target words referred to either a color or a month, and in each experiment the "go" items were the color words on List 1 and the month words on List 2. In Experiments 6a and 6c, participants responded on go trials by pressing a single button with their dominant hand. In Experiments 6b and 6d, participants responded on go trials by saying only "red" (6b, List 1) or "green" (6b, List 2) or by saying "color" (6d, List 1) or "month" (6d, List 2). The total number of trials per list were the same as in the previous experiments ($N = 120$), but because participants only responded to half of the items in the present experiment, there were only 60 critical trials per list. All other aspects of the design and procedure were identical to that of Experiments 1 and 3.

Results

Experiments 6a and 6c: Button-Press Responses

In Experiment 6a, the mean response latencies were 425 ms, 421 ms, and 428 ms in the congruent, neutral, and incongruent conditions, respectively. In Experiment 6c, the mean response latencies were 423 ms, 421 ms, and 439 ms in the congruent, neutral, and incongruent conditions, respectively. A repeated measures ANOVA with experiment and list as between-subjects factors and prime type as a within-subjects factor revealed a main effect of prime type, $F_1(2, 56) = 5.12$, $p < .01$, $\eta_p^2 = .15$. There was no effect of experiment or list (all Fs < 1), nor was there an interaction between the factors experiment and prime type, $F = 1.5$, $p > .2$. Because of this, the data were collapsed across the experiment factor (see Figure 11), and post hoc t tests were run over the collapsed data set. These analyses revealed an effect of interference (incongruent was slower than neutral), $t(31) = 2.79$, $p < .01$, and a marginal effect of congruence, $t(31) = 1.97$, $p = .06$, but not of facilitation.

The error rates on the go trials were negligible ($M < 0.1\%$), and so we report here only the error rates on the no-go trials. In Experiment 6a, the mean error rates were 1.56%, 2.18%, and 2.81% in the congruent, neutral, and incongruent conditions, respectively. In Experiment 6c, the mean error rates were 3.5%, 2.5%, and 5.9% in the congruent, neutral, and incongruent conditions, respectively. A marginal effect of prime type was revealed in the repeated measures ANOVA, $F_1(2, 56) = 2.45$, $p = .09$. No effect of experiment was revealed, nor was there an interaction between the two factors. Post hoc t tests over the data collapsed across the experiment and list factors revealed nonsignificant effects of interference (more errors in the incongruent condition than in the neutral condition), $t(31) = 1.71$, $p = .09$, and congruence (fewer errors in the congruent condition than in the incongruent condition), $t(31) = -1.75$, $p = .09$; there was no difference in the error rates between the congruent and neutral conditions.

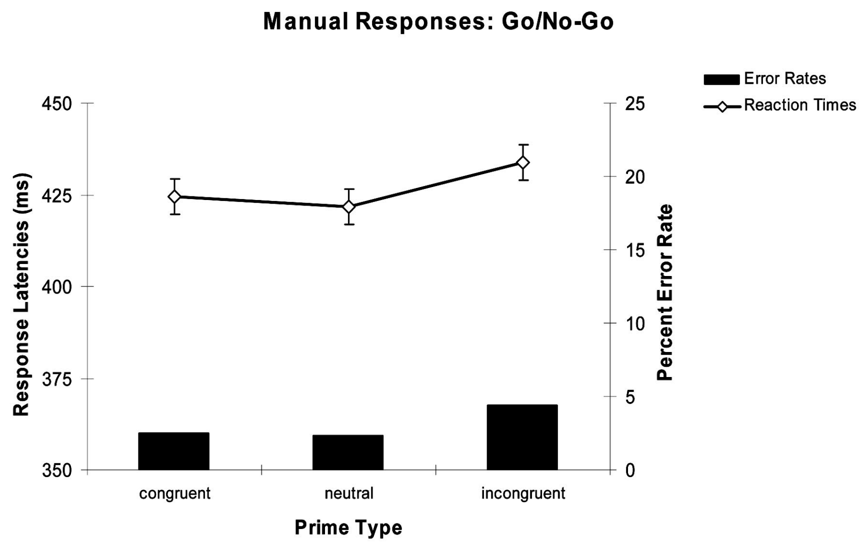

Figure 11. Manual responses in Experiment 6 (go–no-go) as a function of prime type. Response latencies (lines) are plotted against the left *y* axis and error rates (bars) are plotted against the right *y* axis.

Experiments 6b and 6d: Verbal Responses

In Experiment 6b, the mean response latencies were 522 ms, 528 ms, and 535 ms in the congruent, neutral, and incongruent conditions, respectively. In Experiment 6d, the mean response latencies were 497 ms, 505 ms, and 521 ms in the congruent, neutral, and incongruent conditions, respectively. A repeated measures ANOVA with experiment and list as between-subjects factors and prime type as a within-subjects factor revealed a main effect of prime type, $F_1(2, 56) = 12.85$, $p < .01$, $\eta_p^2 = .32$. There was no effect of experiment or list (all *F*s < 1), nor was there an interaction between the factors experiment and prime type, $F = 1.1$, $p > .3$. Hence, just as with the manual responses, the data were collapsed across the experiment factor (see Figure 12) and post hoc *t* tests were run over the collapsed data set. These analyses revealed an effect of interference (incongruent was slower than neutral), $t(31) = 2.55$, $p = .03$; an effect of congruence, $t(31) = 4.51$, $p < .01$; and an effect of facilitation, $t(31) = 2.56$, $p = .05$. This finding represents the first demonstration of both facilitation and interference by undetected primes in the verbal modality.

In Experiment 6b, the error rates on the go trials were 1.9%, 1.9%, and 4.4% in the congruent, neutral, and incongruent conditions, respectively. In Experiment 6d, the error rates on the go trials were 4.7%, 5.3%, and 4.7% in the congruent, neutral, and incongruent conditions, respectively. The repeated measures ANOVA with experiment and list as between-subjects factors and prime type as a within-subjects factor failed to reveal a main effect of prime type, experiment, or list or any interaction between the factors. Looking at the no-go trials, the mean error rates in Exper-

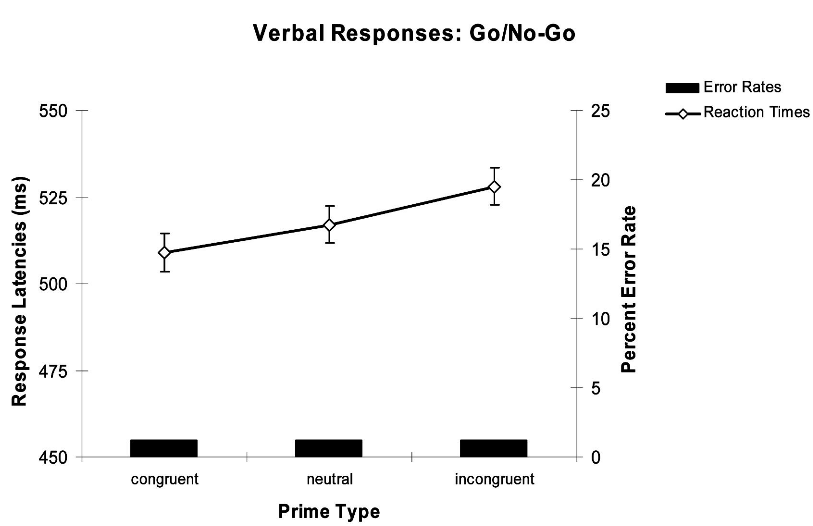

Figure 12. Verbal responses in Experiment 6 (go–no-go) as a function of prime type. Response latencies (lines) are plotted against the left *y* axis and error rates (bars) are plotted against the right *y* axis.

iment 6b were 1.56%, 0.63%, and 0.94% in the congruent, neutral, and incongruent conditions, respectively. In Experiment 6d, the mean error rates were 0.94%, 1.88%, and 1.56% in the congruent, neutral, and incongruent conditions, respectively. Just as with the error rates on the go trials, the repeated measures ANOVA revealed no effect of prime type, experiment, or list or any interaction between the factors.

Analysis of Prime Detectability

The prime detection task was identical to that of Experiment 1. The mean d' value was -0.19 in the verbal response modality and 0.16 in the manual response modality. In neither case was d' found to differ from the null mean.

Discussion

The motivation for this experiment was to establish the extent of processing of masked primes in the go–no-go paradigm for both manual and verbal response modalities. Specifically, we were interested in the possibility that in the go–no-go paradigm, the extent of processing of masked primes in the verbal response modality would approximate that of the manual response modality. Our reasoning was that in the go–no-go paradigm, participants are able to precompile their verbal response and, hence, bypass lexical access that is otherwise required to guide the formulation of an articulatory response. If the critical difference between the two response modalities in the two-choice experiments is lexical access in the verbal but not the manual response modality, and if lexical access is effectively bypassed in the go–no-go paradigm, then the extent of processing of masked primes in the manual and verbal response modalities should be equivalent in the go–no-go paradigm. The findings provided support for this line of reasoning. In contrast to the two-choice experiments reported above, the findings from the go–no-go paradigm indicate that masked primes are able to be processed down to the response execution stage in the verbal response modality. That is, for the first time in this series of experiments, interference was obtained for incongruent primes in the verbal response modality. With respect to the manual response modality, there was no apparent difference between the findings obtained in the previous two-choice experiments and the present go–no-go experiments.

The finding of interference for masked incongruent primes in the verbal response modality is important for at least two reasons. Minimally, this finding reveals that there is nothing inherent about the verbal response modality that precludes masked incongruent primes from producing interference. Second, and perhaps more important, this finding serves to constrain the type of account that one can put forth to explain how the extent of information processing may be modulated by the response modality. In particular, these findings suggest that the modulation by response modality arises in those cases in which individuals are unable to precompile their articulatory response.

We have suggested that the difference between the two response modalities in the two-choice experiments may be that participants cannot avoid going through the lexical system when producing speech but can avoid doing this when pressing buttons. Presumably, because the decision-to-manual-response mapping is established in the context of the experiment, individuals create direct mappings between the premotor (semantic) representations RED and GREEN and the appropriate button presses on the basis of the task instructions. In contrast, individuals may find it difficult (or unnecessary) to establish similarly direct mappings when responding verbally because there already exists a well-established lexical–phonological system whose sole purpose is to mediate premotor representations and their corresponding articulatory gestures. Why should the extent of processing of masked primes be modulated as a function of whether the response is lexically mediated or not? One possibility is that more activation is needed to engage lexically mediated responses than is needed for directly mapped responses. This account of the data follows closely the account that Finkbeiner and Caramazza (2006) put forth to explain their observation that the polarity of the semantic effect in the picture–word naming paradigm shifts as a function of masking. Nevertheless, although this account provides a reasonably good fit of the data, it falls short of explaining the full pattern of the findings that we have reported here. In the General Discussion that follows, we address these additional aspects of the findings.

General Discussion

A fundamental assumption in information-processing theory is that the processing of information proceeds through stages, beginning with the input stimulus and ending with the selection of an appropriate response. Although there is a lively debate over how information is transformed within and transmitted between stages (Fodor, 1983; Massaro & Cohen, 1991; Rumelhart & McClelland, 1986), it is widely taken for granted that information processing, culminating in the selection of a response, is unaffected by the particular effector that is ultimately recruited to execute that response. A second widely held assumption is that priming effects arise as a function of the overlap in the processing of the prime and target stimuli (Dehaene et al., 1998; Tulving & Schacter, 1990; Vorberg et al., 2003). Taking these two assumptions together, a clear prediction follows: Whatever priming effects are found to arise in one response modality should similarly be found to arise in a separate response modality (if not in degree, at least in kind). In contrast to this prediction, we found in the present study that the priming effects obtained in the manual and verbal response modalities differed in kind. This is clear in Figure 13, which provides a comparison of the effect sizes (interference and facilitation) across each of the experiments reported above as a function of the response modality and the task (two-choice or go–no-go).

In this study, participants were asked to categorize target stimuli into one of two groups. For example, in Experiment 5, participants were presented with target pictures and asked to indicate whether the target was a picture of a face or a tool. Participants made their responses either manually (by pressing one of two buttons) or verbally (by saying "face" or "tool"). The target stimuli were preceded by masked prime stimuli that were either congruent or incongruent with the targets. The goal of this work was to establish the effect of the masked prime on the overt response to the target and to test the hypothesis put forth by Finkbeiner and Caramazza (2006) that undetected primes do not engender an articulatory response and, hence, should not produce interference in the verbal response modality.

We have reported two main findings in this study. First, we found that masked primes had a robust effect on the overt response

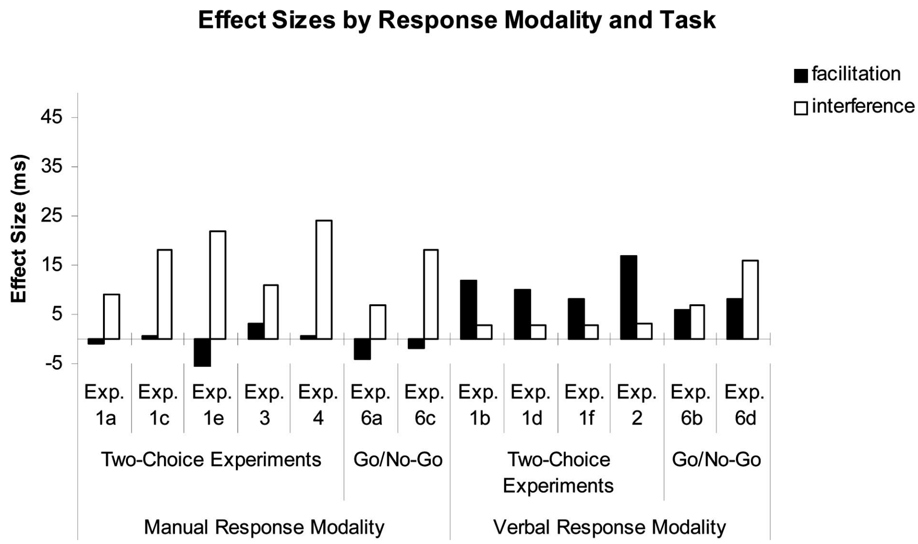

Figure 13. Effect sizes in milliseconds for all experiments reported in this study. Open bars depict the size of the interference effect (incongruent – neutral) and filled bars depict the facilitation effect (neutral – congruent). The graph is organized according to response modality (manual and verbal) and experiment type (two-choice and go–no-go).

in both the manual and the verbal response modalities. Second, we found that the direction of the masked congruence effect was modulated by the response modality such that masked incongruent primes produced interference in the manual response modality but not in the verbal response modality. Our findings suggest that this modulation of the priming effect by response modality may be due to verbal (but not manual) responses being mediated by the lexical–phonological production system.

In Experiment 1, participants were presented with target stimuli that referred to "red things" or "green things" (e.g., BLOOD or CUCUMBER) in one set of experiments and colors or months (e.g., JULY or YELLOW) in another set of experiments. Depending on the particular experiment, participants categorized these targets as either *red* or *green* or as either *color* or *month*. The target stimuli were preceded by the primes *red* or *green* in the "red–green" experiments and *april* or *green* in the "color–month" experiments. It is important to note that the prime stimuli were presented very briefly (30 ms) and were heavily masked such that they were not able to be identified by the participants. The results of this experiment were clear: Masked incongruent primes produced interference in the manual modality but not in the verbal modality, and masked congruent primes produced facilitation in the verbal modality but not in the manual modality.

The presence of an interference effect is important in the masked congruence priming paradigm. It has been established empirically with functional MRI, event-related potentials, and kinematic analyses that the processing of masked incongruent primes extends down to include the formulation of a motor response (see the introduction), and hence interference in the incongruent prime condition is assumed to occur, at least in part, as a function of the conflict that arises between two incompatible motor programs. As such, the presence of interference in the masked congruence priming paradigm is taken as an index of the extent of processing of the masked prime. With this in mind, the obvious question is why the processing of masked primes extended to the response level in the manual modality but not in the verbal modality. The experiments that followed Experiment 1 were designed to address this question.

The first possible account that we tested hinged on the hypothesis that orthographic primes are encoded directly into covert articulatory responses, regardless of the strength of the masking procedure, and that this produces interference in both the incongruent and the neutral prime conditions in the verbal modality. On this account, the apparent effect of facilitation in the congruent condition was actually due to a lack of interference in that condition. We addressed this possibility by testing individuals who were Chinese–English bilingual and by replacing the English primes with their phonologically unrelated Chinese translation-equivalent characters. If participants directly encode the prime stimulus into an articulatory gesture and if interference arises whenever the prime and target map onto incompatible articulatory gestures, then using phonologically unrelated Chinese characters as primes should result in interference in all three conditions (congruent, incongruent, and neutral). In contrast, we observed the same pattern of results in Experiment 2 that we observed in the verbal response modality in Experiment 1—no interference for incongruent primes but facilitation for congruent primes. In the measure for which the prime–target pairs in the three conditions did not differ in terms of their orthographic or phonological overlap, it seems reasonable to attribute the facilitation effect by congruent primes in the verbal modality to the overlap in lexical–semantic processing.

In Experiment 3, we considered the possibility that the difference in the number of response channels between the manual response modality (two response channels) and the verbal response modality (one response channel) may be responsible for the difference in the pattern of priming effects obtained in each modality. To test this possibility, we reduced the number of response channels in the manual response modality to one by having participants respond with just their index finger. The pattern of priming effects obtained in this experiment with one finger was the same as those obtained with two fingers. Hence, the difference in the number of response channels between the two response modalities does not appear to be responsible for the shift in the polarity of the masked priming effect as a function of response modality.

In Experiment 4, we investigated the possibility that the reason masked incongruent primes did not produce interference in the verbal response modality was because of the relative difficulty of producing a verbal response. To test this possibility, we increased the difficulty of producing a manual response by increasing the number of response categories from two to four. This had the effect of slowing response latencies down to where they were even longer than those obtained in the verbal response modality. Nevertheless, the same pattern of priming effects were obtained in this experiment as had been obtained in the manual response modality in previous experiments: namely, interference in the incongruent condition.

In Experiment 5, we addressed two important issues. One had to do with the possibility that the use of orthographic target stimuli in the previous experiments may have interfered with the execution of a verbal response and, hence, contributed to the modulation of the priming effect by the response modalities; the second issue had to do with the possibility that our baseline in the previous experiments was not appropriate. To address the first issue, we replaced the orthographic stimuli with pictures. To address the second issue, we eliminated the neutral prime and used as our baseline the response latencies obtained with a very short prime duration (10 ms). In this display condition, no effect of the prime was found (targets preceded by congruent primes and targets preceded by incongruent primes were responded to equally as fast), which allowed us to use the response latencies in this condition as our baseline. To determine the direction of the priming effect produced by congruent and incongruent primes, we compared response latencies to targets with increasingly longer prime durations (20–60 ms) against the baseline measure. As expected, we found that as participants' opportunity to process the primes increased, so did the effect size of the priming manipulation. Notably, the direction of the priming effect was identical to what had been observed in the previous experiments. Essentially, for undetected primes ($<$40 ms), incongruent primes produced interference in the manual but not in the verbal response modality and congruent primes produced facilitation in the verbal but not in the manual response modality. Thus, it does not appear that the modulation of the priming effect by the response modality is restricted to orthographic stimuli or to a particular way of determining the neutral baseline. Interestingly, with detected primes (40–60 ms), both facilitation and interference were observed in both response modalities, indicating that the modulation of the priming effect by response modality is restricted to undetected primes.

In Experiment 6 we considered the possibility that the processing of masked primes failed to extend down to the articulatory level in the verbal response modality because verbal responses are lexically mediated. To address this possibility, we used the go–no-go paradigm that allows participants to precompile their target response (e.g., "red" or "green"). Lexical access can be bypassed when participants have already precompiled their response because the phonological information that is otherwise necessary to retrieve has already been compiled into an articulatory gesture. Thus, if the critical difference between the two response modalities is lexical access, then the pattern of effects obtained between the two response modalities in the go–no-go paradigm should be roughly the same. This is what we found. In this experiment, and for the first time in this study, we found that masked incongruent primes produced interference in both response modalities. Hence, it appears that only when participants have the opportunity to precompile their articulatory response, and thereby bypass lexical access, is the extent of processing of masked primes equivalent in the two response modalities.

Direct Versus Lexically Mediated Mappings

We have suggested that the modulation by response modality (in the two-choice experiments) is due to the lexical–phonological system that mediates semantic- and motor-level representations in the verbal (but not the manual) response modality. Once an individual has decided that the target stimulus BLOOD refers to a red thing, it is necessary to encode the semantic-level representation RED into a motor representation, and it is well established that there are several levels of representation and processing that mediate the semantic system and the articulators. At the very least, there is a lexical–phonological level that specifies abstract phonological information (Caramazza, 1997; Dell, 1986; Levelt et al., 1999); a "postlexical" phonological level, which specifies the featural information needed to assemble the articulatory gesture (cf. Goldrick & Rapp, 2007); and finally a buffering process by which the components of the utterance are assembled just before the execution of the motor program (Caramazza, Miceli, & Villa, 1986). In contrast, there is no need to access lexical–phonological or postlexical–phonological information when responding manually because this information is superfluous to pushing a button (although, as in the verbal response modality, there may be a need to buffer the individual components of the manual motor program before executing it). If this line of reasoning is correct, then it follows that the manual response effectors would become engaged more easily than the articulators because fewer levels of representation and processing mediate the semantic- and motor-level representations in the manual response modality than in the verbal response modality.

Although it seems reasonable to argue that the semantic-to-motor-level mappings are more complex in the verbal response modality than they are in the manual response modality, this, admittedly, is not a full explanation. For this difference in mapping complexity to be relevant to the findings that we have reported here, we must assume that not only is information processed along two distinct channels depending on the response modality, but that participants were able to make use of the task instructions to "turn on" the appropriate channel. Furthermore, because participants were unable to detect the prime stimuli in these experiments, we must also assume that once a response channel is selected consciously, processing along that channel can run to completion in the absence of any further conscious-level decisions. This is a remarkable assumption to make, particularly in the case of manual responses. Here, because the semantic-to-motor-level mappings are newly established within the context of the experiment, the intuition is that the processing of unconsciously perceived prime stimuli would take place along the already-established speech production channel (and then be "translated" into a manual response). Yet this does not appear to be the case. Rather, participants are apparently able to establish within the context of an experiment a new semantic-to-response-level mapping and then process stimuli along that pathway even when those stimuli are not perceived consciously.

Although this possibility strikes us as remarkable, it is not without precedent. In a recent transcranial magnetic stimulation study, Nakamura et al. (2006) reported findings that lend themselves to a similar conclusion. In their study, participants had to either pronounce a target stimulus or indicate with a button press whether it was a real word or not (lexical decision). As in our study, the target stimuli were preceded by masked primes. The critical finding in Nakamura et al.'s study was that transcranial magnetic stimulation applied to the left inferior parietal lobe eliminated priming in the pronunciation task but not in the lexical decision task. In contrast, transcranial magnetic stimulation applied to the left superior temporal gyrus eliminated priming in the lexical decision task but not in the pronunciation task. These findings are compelling insofar as they demonstrate that the pronunciation task and the lexical decision task rely on distinct processing pathways and, important for our purposes, that the masked priming effects were mediated by different pathways depending on the task. The findings reported by Nakamura et al. converge with a growing body of findings that demonstrate that an individual's expectations within an experimental context can modulate the processing of subliminally presented stimuli (cf. Dehaene & Naccache, 2006; Kiefer & Brendel, 2006; Lachter, Forster, & Ruthruff, 2004). Thus, as we have argued here, it seems increasingly likely that within the context of a single experiment, participants can establish on the basis of the task instructions a task-appropriate chain of processing that they then apply to nonconsciously perceived stimuli. And for the reasons we outlined above, it is reasonable to think that the "task-appropriate chain of processing" applied to the subliminally presented prime stimulus would be more likely to run to completion in the manual response modality than in the verbal response modality.

What About Spoken Responses That Are Not Lexically Mediated?

The tentative account that we have put forth here to explain the modulation of the masked congruence priming effect by response modality hinges on the assumption that spoken responses in our tasks were lexically mediated. However, although spoken responses are typically lexically mediated, this is not necessarily the case in all experimental contexts. For example, in our Experiment 6 in which we used the go–no-go task, we argued that participants could precompile their articulatory response, thereby bypassing lexical–phonological output processing. We also suspect that lexical processing may be bypassed in experimental contexts in which the formulation of a verbal response does not involve a semantic analysis of the target stimulus. This presumably occurs when the prime stimuli appear as target stimuli, thereby allowing for direct stimulus–response mappings to be established.

There are several examples in the masked congruence priming literature of "nonsemantic" priming effects, although again these are primarily in the manual response modality. In one example, Eimer and Schlaghecken (1998) found that masked arrow primes affected response latencies in a "left–right" decision task when the targets were also arrows but not when the targets were replaced with the letters LL and RR. In other words, the effect elicited by masked arrow primes depended on participants having learned a specific response for those stimuli. Similarly, Damian (2001) reported that masked congruent primes produced robust priming effects in a size-judgment task, but only if those primes appeared as targets and were overtly categorized as "small things" or "big things." In one particularly compelling experiment, Damian interleaved a naming experiment with the size-judgment task and presented the primes in the size-judgment task as targets in the naming task. Strikingly, the masked congruence primes produced no effects, even though they had appeared as visible targets in the same experiment (albeit in the context of naming, not categorization).

On the basis of findings such as these in the literature, it seems reasonable to conclude that there are at least two distinct paths from stimulus to response: one that depends on semantic analysis of the prime stimulus and one that bypasses semantic processing by virtue of learned stimulus–response mappings. Although the majority of evidence for this possibility comes from the manual response modality, it seems reasonable to think that the same would also hold for the verbal response modality. That is, in experiments such as ours in which the prime stimuli never appear as visible targets, one can assume that the prime stimulus has been analyzed at the semantic level. In contrast, when the prime stimuli are responded to as targets in the experiment, one cannot be certain that the primes are analyzed semantically. In this latter case, priming effects may be obtained that are more similar to those that we have reported in our go–no-go task (Experiment 6) than those that we have reported in Experiments 1–5. There exists at least one example in the literature that provides some initial support for this possibility. Ansorge, Klotz, and Neumann (1998) used a metacontrast masking procedure in which individuals had to categorize two geometric shapes (squares and diamonds). As is standard in this type of masking procedure, the target stimulus was preceded by either a smaller version of itself (congruent prime condition) or by the other shape (incongruent prime condition). Thus, in their experiment there were two stimuli, and these appeared as both primes and targets. Similar to the findings that we observed in our go–no-go task in Experiment 6, Ansorge et al. found that the masked primes produced both facilitation and interference effects in the verbal response modality. These findings converge nicely with those of our Experiment 6 and further support the suggestion that the processing of masked primes may extend down to the verbal response level in the case of non–lexically mediated responses.

What About the Masked Onset Priming Effect?

An issue that we have deferred until now is the masked onset priming effect (MOPE), first reported by Forster and Davis (1991) and subsequently by Kinoshita (2000), Kinoshita and Woollams (2002), and Schiller (2004). In the masked onset priming task, participants are asked to name (read) words (e.g., SINK) aloud that are preceded by a masked prime that either shares an initial letter (e.g., *save*) or has no letters in common with the target (e.g., *farm*). The key finding with this paradigm is that naming latencies are faster when the prime and the target stimuli share an initial letter.

Although there is some debate over the locus of this effect (cf. Coltheart, Woollams, Kinoshita, & Perry, 1999; Grainger & Ferrand, 1996; Kinoshita & Woollams, 2002), it has generally been accepted that the onset effect is due to interference or response conflict in the all-letters-different condition (cf. Forster & Davis, 1991). If this is the case, then the MOPE would constitute a direct challenge to the claim made by Finkbeiner and Caramazza (2006) and would seem to stand in contrast to the findings that we have reported here. There are two points to be made here. First, the MOPE is generally found with long prime durations (approximately 50 ms and above), which is well within the range in which we observe interference in the verbal response modality in the masked congruence priming paradigm (see Experiment 5 above). Thus, it remains to be seen whether the MOPE can be obtained with prime durations that are brief enough to escape detection by participants (e.g., 30 ms). Furthermore, to our knowledge, there has been only one attempt to use a neutral prime in the masked onset priming paradigm. Schiller (2004) used all percent signs as a neutral prime (e.g., %%%%%–BANAAN), and he found no evidence for interference relative to this baseline. Thus, on the basis of this finding, it would appear that the MOPE is not due to interference or response conflict. One could argue, though, that percent signs are not an appropriate baseline. We are presently trying to resolve this issue by applying the procedure we used in Experiment 5 (of parametrically manipulating the prime duration) to the masked onset priming paradigm.

Further Issues to Be Investigated

In this article, we have focused on the interference effect produced by incongruent primes because the goal of this study was to investigate the extent of processing of masked primes in the manual and verbal response modalities. And while the presence of interference in this paradigm is informative in this respect, the presence of facilitation is not. Nevertheless, there is another aspect of our findings that deserves mention. Up to this point, we have taken the presence of facilitation in the verbal response modality simply as an indication of participants' ability to process masked primes when responding verbally. In other words, the lack of interference in the verbal response modality is not simply due to an inability to process masked primes when responding verbally. But why do masked congruent primes not produce facilitation in the manual response modality, too? The lack of facilitation in the manual response modality is perplexing, but it is not unique to the experiments reported here. Several researchers have reported interference without facilitation effects in the masked congruence priming paradigm (cf. Koechlin et al., 1999; Kunde et al., 2003, Experiment 1; Naccache & Dehaene, 2001). Strangely, though, this pattern of interference without facilitation is not found in other masked priming paradigms. For example, Vorberg et al. (2003) used a meta-contrast masking procedure to mask either a leftward- or a rightward-pointing arrow followed by a target arrow that pointed in either the same or the opposite direction. Similar to the procedure we used in Experiment 5, Vorberg et al. parametrically manipulated prime duration, and although they did not compare response latencies obtained with longer prime durations against those obtained with the shortest duration, their results suggest that masked congruent arrows facilitated manual left–right responses. Thus, the apparent lack of facilitation in the manual response modality in the present study and in the previous studies mentioned above and in the introduction (e.g., Koechlin et al., 1999; Kunde et al., 2003; Naccache & Dehaene, 2001) appears to stand in contrast to the findings that have been obtained with arrows (Vorberg et al., 2003; see also Ansorge et al., 1998). Needless to say, further research will be needed to determine the conditions under which masked congruent primes produce symmetrical versus asymmetrical effects of facilitation and interference in the manual response modality.

Finally, we have worked under the assumption that the decision processes were equivalent in both response modalities. That is, because participants had to decide whether, for example, BLOOD was a red thing or a green thing both when responding manually and when responding verbally, we have argued that the modulation by response modality must arise after the decision stage. One possibility that we did not consider is that individuals are able to bypass the semantically mediated decision process when responding manually but not when responding verbally. Regarding this possibility, verbal responses are necessarily semantically mediated, but manual responses may be generated on the basis of associations learned during the course of the experiment. This possibility is similar to our own proposal insofar as it posits an extra set of processes in the verbal modality. However, although the extra processes that we have proposed are specific to the verbal modality (i.e., the retrieval of lexical phonological information), this alternative possibility proposes that semantically mediated decision processes, which are common to both response modalities initially, quickly become truncated in the manual response modality. This is an interesting possibility that will require further investigation.

Conclusion

In this study, we tested the claim put forth by Finkbeiner and Caramazza (2006) that masked (undetected) prime stimuli do not engender an articulatory response and, hence, do not produce interference. To test this claim, we used the masked congruence priming paradigm (Dehaene et al., 1998), in which it has been clearly established that masked prime stimuli do produce interference when participants respond manually. In several experiments, we found that masked incongruent primes produce interference in the manual response modality, but consistent with the claim put forth by Finkbeiner and Caramazza, these same masked incongruent primes did not produce interference when participants responded verbally. The lack of interference in the verbal response modality was not due simply to participants being unable to process masked primes when responding verbally because when the same masked primes were re-paired to form the congruent condition, they produced facilitation. We conducted several follow-up experiments to determine whether the modulation of the priming effect by the response modality could be reduced to obvious differences between the response modalities. In these experiments, we found that the difference in the number of response channels, the difference in the relative difficulty of formulating a response, the procedure for determining the baseline, or the use of orthographic versus picture stimuli made no difference. In all cases, masked incongruent primes produced interference when participants responded manually but not when they responded verbally.

We have suggested that the critical difference between the manual and the verbal responses in the masked congruence priming paradigm is that verbal responses are mediated by the lexical–phonological production system and manual responses are not. This difference appears to be critical because in the measure to which interference occurs as a function of the conflict that arises between two incompatible motor programs, the presence of interference will depend on the ease with which the processing of the masked prime can be translated into a motor program. Essentially, the fewer stages of processing that mediate semantic- and motor-level representations, the easier it should be to translate the prime stimulus into a motor program. Support for this speculative account of our findings came from the go–no-go paradigm in which individuals were able to precompile their articulatory response and, hence, bypass the lexical system altogether. Using this paradigm, we found that masked incongruent primes produced interference in both response modalities.

Taken together, the findings that we have reported here suggest that the extent of processing of masked primes can be modulated by the response modality and that this modulation is due to whether the overt response is mediated by the lexical–phonological production system or not.

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