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Temporal- and Stimulus-Based Constraints to Interactive Activation During Visual Word Recognition in Adult Readers

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In models of visual word recognition that incorporate an interactive activation framework, activation spreads from orthographic and phonological units to semantic units and from semantic units back to phonological and orthographic units. The present research examined whether semantic feedback changes over the time course of lexical processing and as a function of stimulus quality. Using a mediated priming paradigm, prime–target word pairs were associatively related (*frog–toad*), homophonically mediated (*frog–towed*), or orthographically mediated (*frog–told*). Evidence of semantic feedback to both orthography and phonology was found when the prime duration was 146 ms (Experiment 1) and only to phonology when the prime duration was 253 ms (Experiment 2a). However, when the prime duration was 253 ms and target words were degraded (Experiment 2b), feedback spread only to orthography. The results suggest that the dynamics of semantic feedback change as the function of processing demands in the visual word recognition system.

Both localist and parallel distributed processing models of visual word recognition typically contain distinct groups or levels of representations (e.g., orthographic, phonological, semantic). As a result, multiple models of visual word recognition (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Harm & Seidenberg, 2004; Plaut, McClelland, Seidenberg, & Patterson, 1996) incorporate an interactive activation (IA) framework. In models that incorporate the IA framework, word recognition is viewed as a highly interactive process involving a bidirectional flow of activation between levels of representations. Such interactivity during word processing aids in the selection of the appropriate representation at each level. Furthermore, the presence of IA has enabled models of reading to account for a number of interactions that have been found among various factors that affect word recognition.

However, Besner and colleagues (Besner, Wartak, & Robidoux, 2008; O'Malley & Besner, 2008) re-

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cently noted that incorporating an IA framework (along with cascaded processing) into models of visual word recognition makes it difficult to account for additive effects. Indeed, multiple reports of additive effects between factors that influence word recognition have been reported (e.g., O'Malley & Besner, 2008; Yap & Balota, 2007; see also Besner et al., 2008). These studies led Besner et al. to conclude that IA may be more limited in nature and less of a fundamental property of word processing than some have posited.

Results of studies that have examined the modulation of feedback activation from semantic representations to orthographic and phonological representations may be problematic for models using the IA framework (Besner et al., 2008). For example, according to Stolz and Neely (1995; see also Ferguson, Robidoux, & Besner, 2009), semantic feedback to orthography is contextually controlled such that feedback is engaged when relatedness proportion (RP)[1] is high but is blocked when RP is low in order to conserve activation. This claim is based on the finding that stimulus quality and context interact when RP is high but are additive when RP is low, in both word naming (Ferguson et al., 2009) and lexical decision (Stolz & Neely, 1995) tasks. Such modulation of semantic feedback is important because it (along with other additive effects) appears to present a theoretical challenge for IA-based models that assume interactivity is unconstrained.

The modulation of semantic feedback has also been the focus of multiple studies that have used the mediated priming paradigm to examine IA during word processing (e.g., Farrar, Van Orden, & Hamouz, 2001; O'Seaghdha & Marin, 1997; Reimer, 2006; Reimer, Brown, & Lorsbach, 2001; Reimer, Lorsbach, & Bleakney, 2008). In these studies, participants are presented with prime–target word pairs that are indirectly related via a mediating word. For example, consider the mediated prime–target word pair (e.g., *doctor*–[*nurse*]–*purse*).[2] In this case, the target, *purse,* is orthographically and phonologically related to the mediating word, *nurse,* which in turn is associatively related to the prime, *doctor*. Because primes and targets in the mediated priming paradigm (e.g., *doctor–purse*) are not directly related, this paradigm is useful for testing semantic feedback during word recognition. Specifically, the only way prime processing may affect target processing in the mediated priming paradigm is if activation spreads from the mediating word's semantic representation to its corresponding phonological or orthographic representation. Thus, the presence of semantically mediated priming effects (either facilitatory or inhibitory in nature) provides evidence of semantic feedback.

Using the mediated priming paradigm, Reimer et al. (2008) examined whether semantic activation automatically spreads to orthographic or phonological representations during the initial stage of lexical processing. Participants were presented with three types of prime–target word pairs: associatively related (e.g., *frog–toad*), homophonically mediated (e.g., *frog*–[*toad*]–*towed*), and orthographically mediated (e.g., *frog*–[*toad*]–*told*). Homophonically mediated word pairs contained mediating (e.g., *toad*) and target (e.g., *towed*) words that possessed greater phonological than orthographic similarity, whereas orthographically mediated word pairs possessed mediating (e.g., *toad*) and target (e.g., *told*) words that had a greater degree of orthographic than phonological similarity. Using a 53-ms prime duration, Reimer et al. (2008, Experiment 1) found significant facilitatory mediated priming effects with both associatively related and orthographically mediated prime–target word pairs but not with homophonically mediated word pairs. This pattern of results indicates that IA is constrained during the early stages of lexical processing, such that semantic feedback spreads to orthography but not phonology. The purpose of the present study was to examine potential changes in semantic feedback to orthography and phonology at later stages of lexical processing and determine whether such changes are in response to the ongoing processing demands of the visual word recognition system.

EXPERIMENT 1

Reimer et al. (2008, Experiment 1) examined semantic feedback at a very early stage of lexical processing when visual features are being mapped onto prelexical orthographic representations. In Experiment 1, a longer (146 ms) prime duration was used in the mediated priming paradigm. The use of a longer prime duration is significant because it will reveal the nature of semantic feedback closer to an important point during the time course of lexical processing when activated prelexical orthographic representations are beginning to be mapped onto phonology (Barber & Kutas, 2007; Holcomb & Grainger, 2007). Given the activational demands associated with such mapping, it is possible that when a 146-ms prime duration is used, semantic feedback will spread to phonology as well as orthography. Such a change in semantic feedback between 53 and 146 ms would be consistent with the activation allocation hypothesis (see Reimer, 2006), which states that the allocation of semantic feedback to orthography and phonology changes in response to the ongoing processing demands of the visual word recognition system in order to increase the overall efficiency of lexical processing.

The present experiment used the three types of prime–target word pairs that were used by Reimer et al. (2008): associatively related (*frog–toad*), homophonically mediated (*frog–*[*toad*]*–towed*), and orthographically mediated (*frog–*[*toad*]*–told*). In addition, as with multiple other studies that used the mediated priming paradigm (Farrar et al., 2001; O'Seaghdha & Marin, 1997; Reimer, 2006; Reimer et al., 2001, 2008), a naming task was used. A naming task is well suited for examining semantic feedback in the mediated priming paradigm for two reasons. First, because word naming explicitly requires the activation of phonological information (Frost, Ahissar, Gotesman, & Tayeb, 2003; Pexman, Lupker, & Reggin, 2002), the naming task is more sensitive to the effects of potential semantic feedback to phonology than alternative tasks (e.g., the lexical decision task). Second, requiring participants to name stimuli aloud enables one to determine whether word stimuli have been processed correctly. Thus, potential processing errors caused by semantic feedback can be measured.

The pattern of mediated priming effects with homophonically and orthographically mediated word pairs provides information about the spread of feedback activation. Because homophones possess a high degree of feedback inconsistency (i.e., the pronunciations of homophones map onto more than one spelling; see Pexman et al., 2002; Stone, Vanhoy, & Van Orden, 1997), use of the homophone-mediated condition made it possible to test semantic feedback under conditions in which the amount of phonological similarity between mediating (e.g., *toad*) and target (e.g., *towed*) words was maximized while minimizing the amount of orthographic overlap. If semantic feedback spreads to phonological representations during lexical processing, target naming in the homophone (e.g., *frog–towed*) condition should be faster or more accurate than in a control condition (e.g., *kite–towed*). Such facilitation would be expected because of the shared phonology of mediating and target words (see Farrar et al., 2001). In contrast, mediating (e.g., *toad*) and target (e.g., *told*) words in the orthographic condition possessed a high degree of orthographic similarity but were only moderately phonologically similar. If semantic feedback spreads to orthography, a mediated priming effect should appear with orthographically mediated word pairs.

However, it should be noted that feedback to orthography would be manifested by an *inhibitory* mediated priming effect, as opposed to the facilitatory effect observed by Reimer et al. (2008, Experiment 1). Although the brief prime duration (53 ms) used in Experiment 1 of Reimer et al.'s study rendered primes largely unidentifiable, the prime duration (146 ms) used in the present study is long enough for primes to be identified by the participants. In previous mediated priming studies (Reimer, 2006; Reimer et al., 2001) in which prime durations (e.g., 150 and 300 ms) were long enough for participants to identify the primes, semantic feedback to orthography has resulted in inhibitory priming effects (however, see Reimer et al., 2008, Experiment 3). Although the nature of such mediated inhibition effects is discussed in more detail later, at this point it is important to note that finding any mediated priming effect with orthographically mediated prime–target word pairs would not be possible without the presence of semantic feedback to orthography.

METHOD

Participants

Participants were 51 college students enrolled at California State University, San Bernardino, who received partial course credit for their participation. All participants were native English speakers and possessed normal or corrected-to-normal vision.

Design

A 3 (prime–target relationship: associatively related vs. homophonically mediated vs. orthographically mediated) × 2 (condition: experimental vs. control) within-participants design was used. The levels of each variable were presented randomly throughout each test list. Response time (RT) and accuracy served as dependent variables and were measured on each trial.

Stimuli

Stimuli used in the present study were identical to those used in Reimer et al. (2008). Thus, the following description of the stimuli follows directly from that article. Test stimuli were generated from 36 word quadruplets (see the Appendix). Each quadruplet was constructed by first selecting an English homophone word pair (e.g., *toad–towed*). Using established word association norms (Nelson, McEvoy, & Schreiber, 1998), a third word was selected (e.g., *frog*) that possessed a strong associative relationship with the first word in each homophone pair (e.g., *toad*). In most cases (83%), the first word in each homophone word pair (e.g., *toad*) was the most probable word generated in response to its respective context word (e.g., *frog*). The mean strength of association for these two words (e.g., *frog–toad*) was .43 (SD = .19). In addition to an associatively related word (e.g., *frog*), a word (e.g., *told*) that possessed a strong orthographic relationship with the first word (e.g., *toad*) of each homophone pair was also selected. The average percentage of letters in these two words (e.g., *toad–told*) that matched and were in the same serial position was 75% (SD = 4%). From the resulting 36 word quadruplets (e.g., *frog–toad–towed–told*), each of the three types of prime–target word pairs (associatively related, homophonically mediated, and orthographically mediated) was generated. For the associatively related word pairs, the first and second words of each quadruplet were used, with the first word (e.g., *frog*) serving as the prime and the second word (e.g., *toad*) serving as the target. For the homophonically mediated word pairs, the first and third words of each quadruplet were used, with the first word (e.g., *frog*) serving as the prime and the third word (e.g., *towed*) serving as the target. Finally, for the orthographically mediated word pairs, the first and fourth words of each quadruplet were used with the first word (e.g., *frog*) serving as the prime and the fourth word (e.g., *told*) serving as the target. The median frequency of target words in the associatively related, homophonically mediated, and orthographically mediated word pairs was 66 (SD = 153), 14 (SD = 201), and 29 (SD = 178) words per million, respectively (Kučera & Francis, 1967). Orthographic and phonological neighborhood characteristics were also calculated for targets in each type of prime–target word pair (Table 1) using the Hoosier Mental Lexicon (Nusbaum, Pisoni, & Davis, 1984). As can be seen, homophonically and orthographically mediated targets are quite comparable with each of the four neighborhood characteristics. The one exception resides with phonological neighborhood density, where homophonically mediated targets (M = 5.8) have fewer phonological neighbors than orthographically mediated targets (M = 13.3). However, based on the available literature, it is unclear whether this characteristic alone exerts a systematic influence on visual word recognition performance (see Grainger, Muneaux, Farioli, & Ziegler, 2005; Yates, 2005).

Finally, for each experimental prime–target word pair (e.g., *frog–toad, frog–towed, frog–told*), a control prime–target word pair was generated (e.g.,

TABLE 1. Mean Orthographic and Phonological Neighborhood Characteristics for Target Words in Each Type of Prime–Target Word Pair

Neighborhood characteristic	Type of target word: Associatively related	Homophonically mediated	Orthographically mediated
ON density	8.2	6.5	7.9
Average ON frequency	111	110	118
PN density	12.2	5.8	13.3
Average PN frequency	167	87	83

Note. *ON = orthographic neighborhood; PN = phonological neighborhood.*

kite–toad, kite–towed, kite–told). Control prime–target word pairs (e.g., *kite–toad*) were constructed by assigning each target in the experimental word pairs (e.g., *frog–toad*) to a new, unrelated prime (e.g., *kite*). In each case, the control prime word (e.g., *kite*) possessed the same word length and frequency as the experimental prime (e.g., *frog*). Thus, the stimuli used in the present study consisted of 36 associatively related (e.g., *frog–toad*), 36 homophonically mediated (e.g., *frog–towed*), and 36 orthographically mediated (e.g., *frog–told*) experimental prime–target word pairs, as well as 36 corresponding associatively related (e.g., *kite–toad*), 36 homophonically mediated (e.g., *kite–towed*), and 36 orthographically mediated (e.g., *kite–told*) control prime–target word pairs.

From the complete list of 216 experimental and control prime–target word pairs, six test lists were constructed. Six test lists were needed in order to avoid presenting the same word twice, either as a prime or a target, in a given test list, and to ensure that each target word appeared equally often in the experimental and control conditions within a given type of prime–target word pair. The six test lists were used about equally often across participants. Each of the six test lists consisted of 36 critical prime–target word pairs: six experimental word pairs from each of the three types of prime–target word pairs (associatively related, homophonically mediated, and orthographically mediated) and six control prime–target word pairs from each of the three types of prime–target word pairs. In addition, each of the six test lists contained 30 filler prime–target word pairs (6 associatively related and 24 unrelated), resulting in a total of 66 prime–target word pairs. Ten unrelated practice prime–target word pairs were also constructed. None of the words contained in the practice prime–target word pairs appeared in the test lists. In addition, practice and filler word pairs were excluded from all statistical analyses.

Apparatus

The presentation of stimuli and the recording of both RT and accuracy data were accomplished using a Dell OptiPlex GX115 computer controlled by E-Prime 1.1 software (Schneider, Eschman, & Zuccolotto, 2002). The RTs of each participant were obtained by interfacing a microphone with the computer via a response box (model 200A, Psychological Software Tools, Inc.). RTs were computed by measuring the amount of time that elapsed between the presentation of the target word and the onset of the participant's vocal response. The serial response box was used by the experimenter to record the accuracy of each response. Stimuli were displayed on a 15-in. CRT color monitor (Dell M570; refresh rate = 75 Hz) using white letters (red, green, blue = 255, 255, 255) in Courier New font on a black background.

Procedure

Participants were tested individually in a quiet room. Each participant was seated approximately 50 cm from the computer monitor and instructed to hold a microphone about 2 cm from his or her mouth. At this distance, stimuli, on average, subtended a visual angle of approximately 1.5°. Instructions were verbally presented at the beginning of each experimental session and were followed by the presentation of 10 practice trials and 66 test trials. Each trial began with the presentation of a forward mask (i.e., ########). After 710 ms, the mask disappeared and was immediately replaced by the prime word. Each prime was presented in lowercase letters for 146 ms and was immediately followed by the target that appeared in the same location as the prime. Targets were presented in uppercase letters and remained visible on the computer monitor for either 500 ms or until the participant made his or her verbal response, depending on which came first. After the participant responded, the experimenter coded the response for accuracy using the response box. Participants were instructed to read the prime silently and name aloud the target as quickly but as accurately as possible. Once the participants completed the 66 test trials, they were debriefed and excused. Each experimental session lasted approximately 20 min.

RESULTS

Trials in which the voice key was triggered by noise before the participant responded or trials in which the voice key failed to register the participant's response were excluded from the analyses (2.0%). In addition, correct RTs more than two standard deviations above and below each participant's mean were excluded (5.4%). Following previous studies that have used the mediated priming paradigm (e.g., Farrar et al., 2001; Reimer, 2006; Reimer et al., 2001), planned comparisons were used to test for direct and mediated priming effects in each type of prime–target word pair. Because items used in the present study were not randomly selected, tests using items as the random variable were not conducted (Wike & Church, 1976; see also Pexman et al., 2002). Mean RTs and error rates were computed for each participant and submitted to a 3 (prime–target relationship: associatively related vs. homophonically mediated vs. orthographically mediated) × 2 (condition: experimental vs. control) within-participant analysis of variance (ANOVA; see Table 2 for means). An alpha level of .05 was used for all statistical tests reported in the present study.

RTs

Only correct responses were included in the analysis of RT data. The effect of prime–target relationship, $F(2, 100) = 6.53$, $MSE = 1{,}765$, was significant, with associatively related ($M = 542$ ms) and orthographically mediated ($M = 547$ ms) targets being named faster than homophonically mediated ($M = 562$ ms) targets. This effect was probably the result of the differences in the median word frequency of the three targets types (see also Reimer et al., 2008). The effect of condition was significant, $F(1, 50) = 5.89$, $MSE = 700$, with targets in the experimental condition ($M = 547$ ms) yielding significantly shorter RTs than targets in the control condition ($M = 554$ ms). These main effects were qualified by a significant two-way interaction between prime–target relationship and condition, $F(2, 100) = 3.47$, $MSE = 1{,}104$. Planned comparisons revealed that RTs in the experimental condition were significantly shorter than those in the control condition with both associatively related, $t(50) = -2.46$, and homophonically mediated, $t(50) = -2.06$, prime–target word pairs, but not with orthographically mediated word pairs. No other significant effects were found in the RT data.

Error Rates

With the error rate data, the effect of prime–target relationship was significant, $F(2,100) = 5.47$, $MSE = 60$, with associatively related targets ($M = 1.7\%$) yielding fewer naming errors than orthographically mediated ($M = 5.2\%$) and homophonically mediated ($M = 4.3\%$) targets. The prime–target relationship × condition interaction was also significant, F(2,

TABLE 2. Mean Correct Response Times (RT, in ms), Error Rates (%E), and Context Effects by Prime–Target Relationship and Condition, Experiments 1, 2a, and 2b

	Prime–target relationship					
	Associative		Homophonic		Orthographic	
Condition	RT	%E	RT	%E	RT	%E
	Experiment 1					
Control	549 (70.4)	2.4	570 (78.3)	5.0	544 (70.0)	2.9
Experimental	535 (69.2)	1.0	555 (86.8)	3.7	551 (77.3)	7.4
Context effect	+14*	+1.4	+15*	+1.3	−7	−4.5*
	Experiment 2a					
Control	572 (108.3)	1.0	591 (113.2)	4.2	564 (106.2)	1.8
Experimental	549 (93.4)	0.6	574 (110.0)	1.7	572 (98.1)	3.7
Context effect	+23*	+0.4	+17*	+2.5	−8	−1.9
	Experiment 2b					
Control	742 (127.1)	4.9	764 (124.3)	6.2	737 (119.9)	4.7
Experimental	716 (102.8)	3.5	758 (134.6)	5.9	759 (122.6)	8.9
Context effect	+26*	+1.4	+6	+0.3	−22*	−4.2

Note. *associative = associatively related; homophonic = homophonically mediated; orthographic = orthographically mediated. Context effect = control – experimental. Standard deviations are in parentheses.*
*p < 05.

100) = 4.47, *MSE* = 4. Planned comparisons revealed that significantly more errors were produced in the experimental condition than the control condition, $t(50) = -2.40$, with orthographically mediated prime–target word pairs. No other significant effects were found in the error rate data.

DISCUSSION

In Experiment 1, significant facilitatory priming effects were found in the RT data with associatively related (e.g., *frog–toad*) and homophonically mediated prime–target (e.g., *frog–towed*) word pairs. In addition, a significant inhibitory priming effect was found in the error rate data with orthographically mediated word pairs (e.g., *frog–told*). Together, these results indicate that semantic feedback spread to both orthographic and phonological representations during lexical processing. This claim is based on the fact that primes and targets in mediated word pairs (e.g., *frog–towed, frog–told*) were not directly related. As a result, it was possible for prime processing to affect target processing only if feedback activation spread from the mediating words' (e.g., *toad*) semantic representations to their corresponding orthographic and phonological representations. The facilitatory priming effect found with associatively related word pairs (e.g., *frog–toad*) provides evidence that activation spread to the semantic representations of mediating words during prime processing. Furthermore, the facilitatory mediated priming effect found with target words (e.g., *towed*) sharing phonology (but not semantics) with the mediated words (e.g., *toad*) provides evidence that feedback activation spread from the semantic representations of mediating words to their corresponding phonological representations. Similarly, the inhibitory mediated priming effect found with target words (e.g., *told*) sharing orthography (but not semantics) with the mediating words (e.g., *toad*) provides evidence that feedback activation spread from the semantic representations of mediating words to their corresponding orthographic representations.

Although the inhibitory priming effect found with orthographically mediated prime–target word pairs replicates the findings of previous studies (Reimer, 2006; Reimer et al., 2001), as indicated earlier, Reimer et al. (2008, Experiment 1) found a facilitatory mediated priming effect when primes were briefly presented (53 ms) and masked. In fact, Reimer et al. found that target (e.g., *told*) naming was facilitated equally regardless of whether it was preceded by an orthographically related prime (e.g., *toad*) or a semantic associate of the orthographically related prime (e.g., *frog*). Thus, the results of Reimer et al. indicate that when primes are unidentifiable, target naming is facilitated when semantic feedback spreads to orthography. Similar to some instances of masked orthographic priming (e.g., Evett & Humphreys, 1981; Forster & Davis, 1984; Humphreys, Besner, & Quinlan, 1988), such facilitation results from the orthographic overlap of mediating (e.g., *toad*) and target (e.g., *told*) words.

Given the fact that facilitatory orthographically mediated priming effects were previously found when primes were briefly presented and masked, an important question is why longer prime durations (e.g., 146 ms or more) typically yield inhibition effects. One possible explanation is that because participants were able to identify the prime (e.g., *frog*) at longer prime durations, they became aware that target words (e.g., *told*) were orthographically similar to a semantic associate of the prime (e.g., *toad*). The awareness of such orthographic similarity probably increased naming errors or increased RTs associated with the processing of experimental, relative to control, targets, producing an inhibitory priming effect. In contrast, because primes are unidentifiable when a brief prime duration is used, participants are unaware that orthographically mediated targets are visually similar to mediating words. As a result, semantic feedback to orthography facilitates target naming in a manner comparable to form priming. Similar qualitative differences in orthographic priming have been found as a function of prime identifiability in multiple previous studies (e.g., Colombo, 1986; Humphreys, Evett, Quinlan, & Besner, 1987; Segui & Grainger, 1990).

This account introduces the possibility that when a longer prime duration was used, strategic processing, perhaps in the form a postlexical spelling check, played a role in target naming. Specifically, when the orthographic representation of a mediating word became activated, at longer prime durations participants became aware that the target (e.g., *told*) was orthographically similar to the mediating word (e.g., *toad*). At this point, participants must engage in a postlexical spelling check in order to ensure that a correct response is provided. Failing to engage in a spelling check would have increased the likelihood of committing a naming error (e.g., incorrectly pronouncing the mediating word instead of the target word). This appeared to be the case in the present experiment, where error rates were significantly greater in the experimental than the control condition. Nonetheless, it should be pointed out that a spelling check on target words (e.g., *told*) would not have been needed in the first place if the mediating words' (e.g., *toad*) orthographic representation had not been activated via feedback from the semantic system.[3]

Therefore, when the results of Experiment 1 are considered along with those of Reimer et al. (2008, Experiment 1), there appears to be a shift in semantic feedback during the first 146 ms of lexical processing. Using a 53-ms prime duration, Reimer et al. found that activation spreads only to orthography at a very early stage of lexical processing. The results of Experiment 1 indicate that when the prime duration is increased to 146 ms, however, semantic feedback spreads to phonology as well. Such a shift in semantic feedback over the course of lexical processing is consistent with the activation allocation hypothesis. According to this hypothesis, semantic feedback is allocated in a flexible manner in order to support the activational demands of ongoing lexical processing. Thus, it is possible that semantic feedback spreads only to orthography in order to provide support for early processing when visual features are being mapped onto prelexical orthographic representations. However, in order to provide support for the subsequent mapping of activated prelexical orthographic representations onto phonological representations, semantic feedback shifts and begins to spread to both orthography and phonology.

EXPERIMENT 2

We tested the activation allocation hypothesis in Experiment 2 by increasing the prime duration from 146 ms to 253 ms (Experiment 2a) and reducing the visual quality of target words (Experiment 2b). If the activation allocation hypothesis is correct, feedback activation from semantics shifts dynamically between orthography and phonology in order to support ongoing lexical processing. Therefore, it is plausible that when a 253-ms prime duration is used, semantic feedback shifts from the activation of orthography and phonology to only the activation of phonology. This predicted shift in semantic feedback is based on two findings in the literature. First, using a prime duration of 250 ms, Farrar et al. (2001) found an inhibitory mediated priming effect with targets that were body-rime inconsistent with mediating words (e.g., *sofa*–[*couch*]–*touch*) but not with targets that were body-rime consistent with mediating words (e.g., *sofa*–[*couch*]–*pouch*). These results suggest that semantic feedback spreads to phonology, but not orthography, at this prime duration. Second, according to studies that have examined the time course of visual word recognition using event-related potentials (Barber & Kutas, 2007; Holcomb & Grainger, 2007), phonological processing peaks around 250 ms posttarget onset. Assuming that this time course is accurate, when a 253-ms prime duration is used, semantic feedback may be decreased to orthography and increased to phonology in order to support ongoing phonological processing. Therefore, facilitatory effects in Experiment 2a should be found with associatively related and homophonically mediated prime–target word pairs but not with orthographically mediated word pairs.

The activation allocation hypothesis was further tested in Experiment 2b by using the same prime duration (253 ms) as Experiment 2a but reducing the visual quality of target words. Compared with intact stimuli, visually degraded stimuli produce more errors and slower responses in lexical decision and naming tasks (e.g., Borowsky & Besner, 1993; Stolz & Neely, 1995). Reductions in the visual quality of word stimuli slow prelexical orthographic processing, which in turn slows the rate at which orthographic representations are activated (Borowsky & Besner, 1993). Given that stimulus degradation reduces the efficiency of orthographic processing, visually degrading targets should increase the activational demands on such processing relative to intact targets. Therefore, when targets are visually degraded, semantic feedback to phonology may be decreased, whereas feedback to orthography may be increased in order to address the demands on orthographic processing. As a result, in contrast to the priming effects that were expected with associatively related and homophonically mediated word pairs in

Experiment 2a, mediated priming effects should be found with associatively related and orthographically mediated word pairs in Experiment 2b.

METHOD

Participants

Participants in Experiments 2a ($N = 55$) and 2b ($N = 55$) were college students enrolled at California State University, San Bernardino, who received partial course credit for their participation. All participants were native English speakers and possessed normal or corrected-to-normal vision. None of the participants participated in both Experiments 2a and 2b or in Experiment 1.

Design, Stimuli, and Apparatus

The design, stimuli, and apparatus were the same as those used in Experiment 1.

Procedure

The procedure was the same as that used in Experiment 1 except that a prime duration of 253 ms was used, and target words in Experiment 2b were visually degraded by presenting them in dark gray font (red, green, blue = 36, 36, 36) on a black background.

RESULTS

As with Experiment 1, voice key errors (7.3%) and correct RTs that were more than two standard deviations above and below each participant's mean (5.4%) were excluded from the analyses. Also, as with Experiment 1, planned comparisons were used to test for priming effects within each type of prime–target word pair. Mean RTs and error rates were computed for each participant and submitted to a 3 (prime–target relationship: associatively related vs. homophonically mediated vs. orthographically mediated) × 2 (condition: experimental vs. control) within-participant ANOVA (see Table 2 for means).

RTs

Only correct responses were included in the analysis of RT data. In Experiment 2a, a significant effect of prime–target relationship was found, $F(2, 108) = 8.90$, $MSE = 80$, with associatively related ($M = 560$ ms) and orthographically mediated ($M = 568$ ms) targets yielding shorter RTs than homophonically mediated ($M = 582$ ms) targets. The effect of condition was significant, $F(1, 54) = 6.82$, $MSE = 1{,}428$, with targets in the experimental condition ($M = 565$ ms) yielding shorter RTs than targets in the control condition ($M = 576$ ms). These main effects were qualified by a significant prime–target relationship × condition interaction, $F(2, 108) = 5.74$, $MSE = 1{,}293$. Planned comparisons revealed that RTs in the experimental condition were significantly shorter than those in the control condition with both associatively related, $t(54) = -3.04$, and homophonically mediated, $t(54) = -2.41$, prime–target word pairs but not with orthographically mediated word pairs.

In Experiment 2b, a significant effect of prime–target relationship was found $F(2, 108) = 9.12$, $MSE = 3{,}130$, with associatively related ($M = 729$ ms) and orthographically mediated ($M = 748$ ms) targets yielding shorter RTs than homophonically mediated ($M = 761$ ms) targets. The main effect of condition was not significant, $F < 1$; however, a significant prime–target relationship × condition interaction was found, $F(2, 108) = 5.59$, $MSE = 2{,}930$. Planned comparisons revealed that RTs in the experimental condition were significantly shorter than those in the control condition with associatively related word pairs, $t(54) = -2.44$, and RTs in the experimental condition were significantly longer than RTs in the control condition with orthographically mediated word pairs, $t(54) = 2.57$.

Error Rates

In Experiment 2a, the effect of prime–target relationship was significant, $F(2, 108) = 3.14$, $MSE = 49$, with associatively related targets ($M = 0.8\%$) yielding fewer errors than orthographically mediated ($M = 2.9\%$) and homophonically mediated ($M = 2.7\%$) targets. The prime–target relationship × condition interaction was again significant, $F(2, 108) = 3.29$, $MSE = 40$. Planned t tests revealed that error rates in the experimental and control conditions did not significantly differ for associatively related, homophonically mediated, or orthographically mediated prime–target word pairs. In Experiment 2b, none of the effects were reliable in the error rate data with the exception of a marginally significant effect of condition with orthographically mediated word pairs, $t(54) = -1.85$, $p < .08$, in which greater errors were found in the experimental condition ($M = 8.9\%$) than the control condition ($M = 4.7\%$).

DISCUSSION

Although the prime duration (253 ms) was identical in Experiments 2a and 2b, the results of the two experiments were quite different. When target words were intact in Experiment 2a, facilitatory priming effects were found with both associatively related and homophonically mediated word pairs. However, when target words were degraded in Experiment 2b, a facilitatory priming effect was found with associatively related word pairs and an inhibitory mediated priming effect was found with orthographically mediated word pairs. Thus, as predicted by the activation allocation hypothesis, although a 253-ms prime duration typically reveals semantic feedback to phonology, feedback shifts back to orthography when prelexical orthographic processing is slowed through stimulus degradation. The combined results of these experiments suggest that there is a modulation of semantic feedback during lexical processing, such that feedback can be restricted to either orthography or phonology based on ongoing processing demands of the visual word recognition system. The present results are consistent with the results of other studies (Ferguson et al., 2009; Stolz & Neely, 1995) that have reported the modulation of semantic feedback to orthography.

As stated previously, a possible explanation for the orthographically mediated inhibition effects found in the present study is that when the orthographic representation of the mediating word (e.g., *toad*) was activated via semantic feedback, participants became aware that the target (e.g., *told*) was an orthographically similar word. As a result, the engagement of a postlexical spelling check was needed to ensure that a correct response would be provided. Although engaging in such a spelling check may reduce naming errors, it comes with the cost of longer RTs. Thus, the more often a spelling check is engaged, the greater the likelihood that a mediated inhibition effect will be found in the RT data. In contrast, a reduction in the use of a spelling check increases the likelihood that an inhibition effect will be found in the error rate data. A pattern of results consistent with this account emerges when one compares the orthographically mediated inhibition effects that were found in Experiments 1 and 2b. Specifically, in Experiment 1, an orthographically mediated inhibition effect was found in the error rate data but not in the RT data. In Experiment 2b, however, an orthographically mediated inhibition effect was found in the RT data but not in the error rate data. Thus, participants presumably engaged in a spelling check more frequently in Experiment 2b than in Experiment 1. A spelling check was probably used more frequently in Experiment 2b because the visual degradation of targets necessitated a more careful visual inspection of the target's specific orthographic structure. In contrast, because targets were not visually degraded in Experiment 1 and the orthographically mediated word pairs made up only a small portion of the total number of trials, a spelling check was not engaged as frequently, resulting in increased naming errors.

GENERAL DISCUSSION

Interactivity between groups of representations is typically unconstrained in IA-based models of visual word recognition (e.g., Coltheart et al., 2001; Harm & Seidenberg, 2004; Plaut et al., 1996). However, contrary to the assumption of unconstrained activation, there are multiple reports of constrained IA in the literature. For example, previous studies have found that semantic feedback to orthography is restricted when RP is low (Ferguson et al., 2009; Stolz & Neely, 1995), and that semantic feedback to phonology is restricted during the initial stages of word processing (Reimer et al., 2008, Experiment 1). When considered along with the results of Reimer et al., the results of the present study expand our understanding of IA by demonstrating that semantic feedback is modulated not only throughout the time course of lexical processing but also by the activational demands associated with orthographic and phonological processing.

Using a 53-ms prime duration, Reimer et al. (2008, Experiment 1) found a mediated priming effect only with orthographically mediated word pairs, suggesting that semantic feedback initially spreads only to orthography during lexical processing. When a longer prime duration (146 ms) was used in Experiment 1 of the present study, mediated priming effects were found with both orthographically and homophonically mediated word pairs. Thus, it appears that as processing progresses, semantic feedback spreads to both orthography and phonology. According to the activation allocation hypothesis, semantic feedback spreads only to orthography early in word processing in order to support the mapping of visual features onto prelexical orthographic representations. As processing progresses and prelexical orthographic units begin to be mapped onto phonological representations, semantic feedback spreads to phonology as well. The activation allocation hypothesis was tested by further extending the time course of lexical processing to 253 ms in Experiment 2a and increasing the activational demands associated with prelexical orthographic processing by visually degrading targets in Experiment 2b. In both cases, the results provided support for the activation allocation hypothesis. Specifically, in Experiment 2a when prime processing was extended to a point (253 ms) where phonological processing is at its peak (Barber & Kutas, 2007; Holcomb & Grainger, 2007), semantic feedback to orthography was reduced and spread only to phonology. However, even though the prime duration was the same as in Experiment 2a, when targets were visually degraded in Experiment 2b semantic feedback to phonology was decreased and spread only to orthography.

According to the activation allocation hypothesis, semantic feedback shifted from phonology to orthography in Experiment 2b in order to provide top-down, activational support for the impaired orthographic processing associated with degraded target words. What the activation allocation hypothesis does not specify, however, is the precise nature of this shift. One possibility is that the shift in semantic feedback from phonology to orthography was locally controlled and initiated by the presentation of each degraded target (see Besner, O'Malley, & Robidoux, 2010, for a similar proposal). Another possibility is that this shift in semantic feedback was the result of participants adopting a global strategy. In this account, rather than occurring each time a degraded target was presented, once participants realized that targets were difficult to read, semantic feedback shifted to orthography and remained in place for all subsequent trials. One way that the mediated priming paradigm could be used to test between these alternative explanations would be to present participants with mixed test lists containing both degraded and intact targets.[4] If semantic feedback is locally controlled, orthographically mediated inhibition effects should be found with degraded but not with intact targets. However, if the shift in semantic feedback is controlled by a more global strategy, orthographically mediated inhibition effects should be found with both degraded and intact targets. Regardless of whether the modulation of semantic feedback is under local or global control, the results of the present study are significant because they demonstrate that feedback activation during lexical processing can be modulated.

The results of the present study have at least two implications for models of visual word recognition. First, the results are consistent with the notion that orthography, phonology, and semantics are represented and processed at separate stages of the visual word recognition system. This notion has been supported by the results of multiple other studies (e.g., Becker & Killion, 1977; Besner & Smith, 1992; Borowsky & Besner, 1993; Coltheart et al., 2001; Grainger & Jacobs, 1996; McClelland & Rumelhart, 1981; Neely, 1991) and is central to accounts of how various experimental conditions lead to the presence of both additive and interactive effects among various factors (e.g., see Borowsky & Besner, 2006). Regarding the current study, it is not clear how semantics would interact only with orthography under some conditions (Experiment 2a) and only with phonology in others (Experiment 2b) in the absence of multiple stages of processing. Although attempts have been made to model the pattern of additive and interactive effects among lexical and semantic factors (i.e., context, stimulus quality, and word frequency) through the use of a single level of processing (Plaut, 1995; Plaut & Booth, 2000), the effectiveness of accounts based on these models remains under question (Borowsky & Besner, 2006). As a result, it is unclear whether models of visual word recognition that contain only a single level of processing would be able to account for the present results.

Second, the present results provide support for the presence of IA during word processing, whereby activation not only spreads in a forward manner but can be fed backward from higher to lower levels of representation within visual word recognition system. Indeed, multiple models of visual word recognition (e.g., the DRC model, Coltheart et al., 2001; and the CDP+ model, Perry, Ziegler, & Zorzi, 2007) incorporate IA by including both feedforward and feedback connections between levels of representation (or stages of processing). More importantly, however, the results of the present study suggest that IA during visual word recognition is not completely unconstrained but can be restricted under some conditions. Specifically, the present results demonstrate that semantic feedback can be restricted to only orthography or phonology depending on the ongoing processing demands of the visual word recognition system. The notion of constrained activation in models that incorporate an IA framework has been proposed in other studies as well. For example, in order to account for the three-way interaction between stimulus quality, context, and RP that has been found in word naming, Ferguson et al. (2009) proposed that feedback activation from semantics to orthography and from phonology to orthography is blocked when RP is low. Therefore, the modulation of semantic feedback has been shown across multiple studies to be caused by a variety of factors including changes in temporal- and stimulus-based variables (prime duration and stimulus quality), reading skill (Reimer, 2006), and RP (Ferguson et al., 2009; Stolz & Neely, 1995). These studies suggest that models of visual word recognition that incorporate an IA framework need to include a mechanism that allows the modulation of semantic feedback. Future research is needed to examine the precise nature of such a mechanism and how additional variables may affect interactivity between semantic, orthographic, and phonological representations.

NOTES

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1. In priming studies, *RP* refers to the proportion of prime–target word pairs that are associatively related in a test list.

2. In examples of mediated prime–target word pairs, mediating words are placed in brackets. Note that these words are not presented to participants.

3. Such a postlexical spelling check would need to be initiated only when there is considerable orthographic overlap between mediating and target words, as was the case with orthographically mediated word pairs. Given the lesser orthographic overlap between mediating and target words with homophonically mediated words pairs, a postlexical spelling check was probably unnecessary.

4. We thank Jim Neely for suggesting this to us.

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APPENDIX. 36 WORD QUADRUPLETS AND CORRESPONDING UNRELATED PRIMES

socks (tiger)–feet–feat–feed	bucket (turtle)–pail–pale–pair
airport (mustard)–plane–plain–plate	live (east)–die–dye–dim
shopping (reporter)–mall–maul–mill	female (driver)–male–mail–make
diamond (coconut)–ring–wring–rung	butcher (garbage)–meat–meet–melt
zero (jump)–none–nun–note	sky (leg)–blue–blew–blur
gun (eye)–shoot–chute–shook	fix (gum)–break–brake–bleak
book (fire)–read–reed–rear	shine (groom)–sun–son–sum
highway (display)–road–rode–roam	wag (zip)–tail–tale–tall
saddle (jersey)–horse–hoarse–house	coffee (secret)–tea–tee–ten
comb (sofa)–hair–hare–hail	fishing (courage)–pole–poll–poke
sour (clam)–sweet–suite–sweat	bargain (royalty)–sale–sail–salt
frog (kite)–toad–towed–told	ocean (smell)–sea–see–set
deer (cake)–doe–dough–dog	listen (stream)–hear–here–heap
dig (hip)–hole–whole–hope	umbrella (curtains)–rain–rein–rail
sand (dawn)–beach–beech–bench	print (angel)–write–right–wrote
buy (fit)–sell–cell–seal	vision (review)–sight–site–sighs
tulip (pizza)–flower–flour–flowed	step (army)–stair–stare–stain
strong (modern)–weak–week–wear	method (square)–way–weigh–wax

Note. *Each word quadruplet lists, in order, the related prime, the unrelated prime (in parentheses), the associatively related target, the homophonically mediated target, and the orthographically mediated target.*

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