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Developmental changes in the allocation of semantic feedback during visual word recognition

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The present study used a mediated priming paradigm to examine whether developmental differences exist in the integration of semantic information with orthographic and phonological information during visual word recognition. In Experiment 1, we found that the integration of semantics with phonology and orthography differed among third-grade, sixth-grade and college students: orthographically based mediated inhibition effects were found in third-grade children, whereas phonologically based mediated inhibition effects were found in sixth-grade children and college students. A second experiment was performed with adults to test the hypothesis that the orthographically based mediated inhibition effect observed with young children was due to deficits in orthographic processing. When stimulus quality was manipulated within the mediated priming paradigm, orthographically based mediated inhibition effects were found when targets were dim, whereas phonologically based mediated inhibition effects were found when targets were bright. Taken together, these results suggest that the allocation of activation during reading may depend on the processing demands of the word recognition system.

Regardless of whether information within the word recognition system is represented as distributed patterns of activity over a set of processing units (e.g. Plaut, 1995; Plaut, McClelland, Seidenberg & Patterson, 1996; Seidenberg & McClelland, 1989) or is represented more locally (e.g. Besner & Smith, 1992; Coltheart, Curtis, Atkins & Haller, 1993; Coltheart, Rastle, Perry, Langdon & Ziegler, 2001; Jacobs, Rey, Ziegler & Grainger, 1998), most models of visual word recognition contain at least three distinct groups or levels of representations: orthographic (spelling), phonological (sound) and semantic (meaning). Given that the word recognition system is composed of distinct levels of representations, a critical component of skilled reading is the integration of information stored at each level. The integration of information during reading is typically accomplished in word recognition models by including connections that allow representations at one level to interact with representations stored at another level. For example, connections between orthographic and phonological representations enable the reader to integrate information so that printed text may be transformed into verbal output. The primary purpose of the present research was to examine how the integration of distinct information within the word recognition system changes as children grow older and reading skill improves.

Because the integration of distinct information is an essential component of skilled reading, many prominent models of visual word recognition (e.g. Coltheart et al., 2001; Grossberg & Stone, 1986; Jacobs & Grainger, 1992; Jacobs et al., 1998; Van Orden & Goldinger, 1994) incorporate an interactive-activation framework (e.g. McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982; see also Morton, 1969). In such models, word recognition is a highly interactive process whereby the bidirectional flow of activation helps ensure the selection of the most appropriate representation at each level. Thus, in models that adopt an interactive-activation framework (see Figure 1), activation not only spreads from 'lower' to 'higher' levels, but is fed backwards from 'higher' to 'lower' levels as well. For example, activation is not only allowed to spread from orthographic and phonological levels to the semantic level, but can spread from the semantic level back to the phonological and orthographic levels as well. The presence of feedback activation within models of word recognition has played an important role in accounting for adult visual word recognition performance (see e.g. Besner & Smith, 1992; Borowsky & Besner, 1993; Brown & Besner, 2002; Hino & Lupker, 1996; Hino, Lupker & Pexman, 2002; Pecher, 2001; Pexman & Lupker, 1999; Pexman, Lupker & Hino, 2002; Smith & Besner, 2001; Stolz & Neely, 1995; Stone, Vanhoy & Van Orden, 1997; Ziegler, Montant & Jacobs, 1997).

Two studies (Farrar, Van Orden & Hamouz, 2001; Reimer, Brown & Lorsbach, 2001) recently examined feedback activation from semantic to phonological and orthographic representations (i.e. semantic feedback) in adult readers through the use of a mediated priming paradigm. Rather than possessing a direct relationship (e.g. *brush–comb*), primes and targets in the mediated priming paradigm are related via a third, mediating, word. Take, for example, the mediated prime-target word pair *brush*–[comb]–*tomb*. In this case, the prime *brush* is indirectly related to the target *tomb* because *brush* is associatively related to the word *comb* (the mediating word) which, in turn, is orthographically related to the target word *tomb*. Because primes and targets within the mediated priming paradigm are not directly related (e.g. *brush–tomb*), this paradigm is useful in testing for semantic feedback during word recognition. Specifically, the only way that prime processing will affect target processing in the mediated priming paradigm is if activation spreads from the mediating word's semantic representation back to its corresponding phonological and/or orthographic representation. Thus, the presence of semantically mediated inhibition effects within the mediated priming paradigm provides evidence of semantic feedback during word recognition.

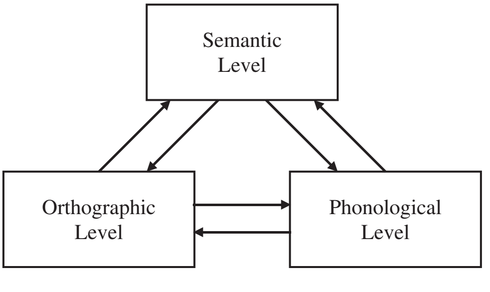

Figure 1. A partial model of visual word recognition based on the general interactive-activation framework.

Using the mediated priming paradigm, both Reimer et al. (2001) and Farrar et al. (2001) found semantically mediated inhibition effects in a 'phonologically incompatible' condition where mediating and target words shared spelling bodies but not pronunciation rimes (e.g. *brush*–[comb]–*tomb*). Specifically, in these studies, target words (e.g. *tomb*) were named more slowly and less accurately when preceded by mediated primes (e.g. *brush*) than when preceded by unrelated primes (e.g. *high*). In the Farrar et al. study, this effect was found with both low- and high-frequency target words. Using an interactive-activation framework (Farrar & Van Orden, 2001), Farrar et al. proposed that the mediated inhibition effect was the result of feedback activation from semantic to phonological representations during prime processing. According to this account, related semantic nodes (e.g. *comb*) became activated during prime (e.g. *brush*) processing which, in turn, via feedback activation, biased the word recognition system towards pronunciations of those semantic nodes (e.g. *comb*'s pronunciation). Thus, during target processing (e.g. *tomb*) competing pronunciations were activated: *tomb*'s incorrect pronunciation (i.e. one that rhymes with *comb*), activated during prime processing and *tomb*'s correct pronunciation, activated during target processing. Competition between the two activated pronunciations resulted in slower and less accurate target naming.

The mediated priming paradigm has also been used to examine feedback activation from semantic to orthographic representations through the use of an 'orthographically incompatible' condition in which mediating and target words share pronunciation rimes but not spelling bodies (e.g. *table*–[chair]–*rare*). In this condition, mediating (e.g. *chair*) and target (e.g. *rare*) words contain pronunciation rimes that map onto more than one spelling body. Within the word recognition literature, words of this type are referred to as being feedback inconsistent (Stone et al., 1997). Multiple studies (Stone et al., 1997; Ziegler & Ferrand, 1998; Ziegler et al., 1997; see also Perry, 2003) have demonstrated that feedback inconsistent words are recognised more slowly and less accurately than feedback consistent words (i.e. words whose rimes can be spelled only one way). This feedback consistency effect can be accounted for in models of word recognition that adopt an interactive-activation framework (e.g. see Stone et al., 1997; Ziegler et al., 1997). Assuming that 'any inconsistencies in mappings take time to resolve' (Stone et al., 1997, p. 340), feedback inconsistent words (e.g. *chair*) are more difficult to recognise than feedback consistent words (e.g. *probe*) in such models because interactive activation between orthographic and phonological representations results in the activation of competing spelling bodies. For example, the activation of *chair*'s pronunciation rime (/_Er/) at the phonological level will result in the activation of two inconsistent spelling bodies (_AIR and _ARE) at the orthographic level via feedback activation.

Because mediating and target words within the orthographically incompatible condition are feedback inconsistent, feedback activation from semantic to orthographic representations should cause target words (e.g. *rare*) to be named more slowly and/or less accurately when preceded by a mediated prime (e.g. *table*–*rare*) than when preceded by an unrelated prime (e.g. *sheep*–*rare*). Consider first the mediated prime-target word pair *table*–*rare*. If feedback activation spreads from semantic to orthographic representations, after being activated at the semantic level during prime (*table*) processing, the mediating word's (*chair*) semantic representation will activate its corresponding orthographic representation. Because the mediating word (*chair*) is feedback inconsistent, upon receiving activation from the semantic level, interactive activation will result in the activation of inconsistent spelling bodies (_AIR and _ARE).

This inconsistency at the orthographic level will be increased when the target word (*rare*) is presented because it possesses a pronunciation rime (/_Er/) that maps onto the same spelling bodies (_AIR and _ARE) that were activated during prime processing. The increased amount of time required to resolve the conflict at the orthographic level will result in slower and/or less accurate target processing. In contrast, with unrelated prime-target word pairs (e.g. *sheep–rare*), conflict among alternate spelling bodies during target processing will not be as great because mediating (e.g. *wool*) and target (*rare*) words do not possess pronunciation rimes that map onto the same spelling bodies. Thus, compared with mediated prime-target word pairs, target processing in unrelated word pairs should be relatively faster and/or more accurate. Although the orthographically incompatible condition can be used to test feedback activation from semantic to orthographic representations, Reimer et al. (2001) failed to find a semantically mediated inhibition effect in this condition with adult readers. The absence of this effect in Reimer et al.'s study indicates that semantic feedback does not typically spread to orthographic representations during word recognition in adults.

Experiment 1

Although adult visual word recognition appears to involve only feedback activation from semantic to phonological representations (Farrar et al., 2001; Reimer et al., 2001), it is currently not known whether feedback activation similarly occurs during word recognition in children. Therefore, the purpose of Experiment 1 was to examine whether semantic feedback occurs in children, and, if so, whether the pattern of semantic feedback differs between children and adults. The existence of possible developmental differences in semantic feedback was examined in the present experiment using third- and sixth-grade children and young adults. Third- and sixth-grade children were chosen as participants because previous research has shown that word recognition skills undergo rapid changes during this period (Booth, Perfetti & MacWhinney, 1999; Plaut & Booth, 2000; Simpson & Lorsbach, 1983, 1987; Simpson, Lorsbach & Whitehouse, 1983). For example, Booth et al. (1999) (see also Plaut & Booth, 2000) recently observed that the influence of orthographic, phonological and semantic information on word recognition appears to change as children grow older and reading skill improves. Specifically, Booth et al. noted that the influence of orthographic and phonological information on word recognition increases as reading skill develops, whereas the influence of semantic information on word recognition decreases.

Evidence supporting the observation that the use of orthographic and phonological information increases as reading skill develops has been provided by multiple developmental studies. For example, Juel (1983) demonstrated that although children may possess knowledge of orthographic structure by the second grade (Leslie & Thimke, 1986), such knowledge does not facilitate word reading until sometime between the third and fifth grades (Ehri, 1991). Similarly, Hansen and Bowey (1992) found that although fourth-grade children can use orthographic rimes to facilitate reading, unlike adults (see Bowey, 1990, 1993), their use of such information is not yet automatised. Finally, using the brief-exposure paradigm with second- through sixth-grade children, Booth et al. (1999) found that children with high reading skill produced greater orthographic and phonological priming than children with low reading skill. According to Booth et al., this finding indicates that younger and poorer readers may possess weaker activation of orthographic and phonological information during word recognition.

Booth et al.'s (1999) observation that the influence of semantic information on word recognition decreases as children develop has also been well established. For example, multiple studies have demonstrated that the magnitude of semantic priming effects decreases as children grow older (Plaut & Booth, 2000; Schwantes, 1981; Simpson & Foster, 1986; Simpson & Lorsbach, 1983; Stanovich, West & Feeman, 1981; West & Stanovich, 1978). This finding suggests that the use of semantic information to support orthographic and phonological processes decreases as reading skill improves (Booth et al., 1999; Plaut & Booth, 2000).

In order to examine semantic feedback in both children and adults, three mediated priming conditions were used in the current experiment: (a) an orthographically incompatible condition in which mediating and target words shared pronunciation rimes but not spelling bodies (e.g. *table*–[chair]–*rare*); (b) a phonologically incompatible condition in which mediating and target words shared spelling bodies but not pronunciation rimes (e.g. *brush*–[comb]–*tomb*) and (c) an orthographically–phonologically compatible condition in which mediating and target words shared both spelling bodies and pronunciation rimes (e.g. *cat*–[dog]–*log*). If activation spreads from the semantic level to the phonological level during visual word recognition, a mediated inhibition effect should be found in the phonologically incompatible condition due to conflict at the phonological level. However, if activation spreads from the semantic level to the orthographic level, a mediated inhibition effect should be found in the orthographically incompatible condition due to conflict at the orthographic level. Because mediating and target words in the orthographically–phonologically mediated condition do not possess incompatible spelling bodies or rimes, semantic feedback to either the orthographic or the phonological level should not produce a mediated inhibition effect in this condition.

Based on the results of recent mediated priming studies (Farrar et al., 2001; Reimer et al., 2001), adult participants in Experiment 1 were expected to produce a semantically mediated inhibition effect in the phonologically incompatible condition, but not in the orthographically incompatible or the orthographically–phonologically compatible conditions. Assuming that feedback activation is a fundamental property of the visual word recognition system, semantic feedback also should be present during word recognition in children. However, given that the influence of lower-level (orthographic and phonological) and higher-level (semantic) information on word recognition appears to change with age (Booth et al., 1999; Plaut & Booth, 2000), it is possible that developmental differences exist in the nature of semantic feedback. Specifically, given that orthographic and phonological processes are less developed than semantic processes in young children, semantic feedback may spread to both the orthographic and phonological levels during word recognition in third-grade children. If this is the case, a semantically mediated inhibition effect should be found in both the phonologically incompatible and orthographically incompatible conditions in third-grade children. However, given the apparent age-related increase in orthographic and phonological processing, as well as the finding that contextual (i.e. semantic) influences on word recognition appear to decrease with age, as in adults, semantic feedback may be restricted to only the phonological level in sixth-grade children. If this is the case, a semantically mediated inhibition effect should be found only in the phonologically incompatible condition with sixth graders.

Method

Participants. Participants were 50 third-grade children (*M* age = 9.3 years; *SD* = 0.38; 28 female), 50 sixth-grade children (*M* age = 12.2 years; *SD* = 0.38; 28 female) and 50 college students (*M* age = 22.3 years; *SD* = 3.95; 32 female). The child participants were recruited from two parochial elementary schools in the Omaha, NE metropolitan area by sending a letter of invitation and a parent consent form to all parents of children in the third and sixth grades. Children who were receiving special education services or were enrolled in gifted programmes were excluded from participation. College students were enrolled at the University of Nebraska at Omaha and received partial course credit for their participation. All participants were native English speakers and possessed normal or corrected-to-normal vision.

Apparatus. The presentation of stimuli and the recording of both accuracy and response time (RT) were accomplished using a Compaq Presario 1090ES computer controlled by SuperLab Pro 2.0 software (Abboud, 1997). The RTs of each participant were obtained by interfacing a microphone with the computer. 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. A computer keyboard was used to record the accuracy of each response. Stimuli were presented in the centre of a 15-in CRT colour monitor, using white lower-case letters in Arial font on a black background.

Design. A 3 (Age group: third grade vs sixth grade vs college students) × 4 (Condition: associatively related vs orthographically incompatible vs phonologically incompatible vs orthographically–phonologically compatible) × 2 (Relatedness: related vs unrelated) mixed-design was used. Age was varied between participants, while condition and relatedness were varied within participants. Both RT and accuracy were measured on each trial.

Materials and stimuli. A large portion of the stimuli that were used in Reimer et al. (2001) was also used in the present experiment. Critical stimuli were constructed from 24 word triplets in each of three conditions: the orthographically incompatible condition (e.g. *table–chair–rare*), the phonologically incompatible condition (e.g. *brush–comb–tomb*) and the orthographically–phonologically compatible condition (e.g. *cat–dog–log*). The 72 word triplets were constructed by first selecting word pairs that were associatively related (e.g. *table–chair*; *brush–comb*; *cat–dog*) based on established word association norms (Nelson, McEvoy & Schreiber, 1998). In most cases (79%), the second word of each pair was the most probable word generated in response to its respective context word. The mean strength of association for these word pairs was 0.44 (*SD* = 0.23). Word triplets were completed through the addition of a third word to each of the 72 associatively related word pairs. Although completely unrelated to the first word in each triplet, the second and third words of each triplet shared spelling bodies but not pronunciation rimes in the phonologically incompatible condition (e.g. *comb–tomb*), shared pronunciation rimes but not spelling bodies in the orthographically incompatible condition (e.g. *chair–rare*) or shared spelling bodies and pronunciation rimes in the orthographically–phonologically compatible condition (e.g. *dog–log*). In terms of overall orthographic similarity, the average number of letters contained in the mediating and target words that matched and were in the same order was 73% (*SD* = 7%) for the orthographically–phonologically compatible condition, 74% (*SD* = 6%) for the phonologically incompatible condition and 35% ($SD = 12\%$) for the orthographically incompatible condition. The mean frequency of target words in the associatively related, orthographically–phonologically compatible, orthographically incompatible and phonologically incompatible conditions were 212 ($SD = 337$), 53 ($SD = 123$), 167 ($SD = 396$) and 184 ($SD = 407$) words per million, respectively (Kucera & Francis, 1967). The Appendix provides a complete listing of the 72 word triplets.

Four types of related prime-target word pairs were constructed from the 72 word triplets. With three of the types, primes and targets contained a mediated relationship, and with one type, the prime and target had a direct associative relationship. The creation of mediated prime-target word pairs was accomplished by using the first and third word of each triplet, with the first word serving as the prime and the third word serving as the target (e.g. *brush–tomb*; *table–rare*; *cat–log*). Associatively related prime-target word pairs were created by using the first and second word of each triplet. Unrelated word pairs were created by reassigning each prime in the mediated and associatively related conditions to a different target. In all cases, the primes and targets that were used in the unrelated condition did not possess a mediated or associative relationship (e.g. *high–tomb*; *sheep–rare*; *doctor–log*).

From the complete list of 288 prime-target word pairs that were created, four test-lists were constructed. Four test-lists were required in order to (a) avoid presenting the same word twice, either as a prime or as a target and (b) assure that each target word appeared equally often in both the experimental and control conditions within a given type of relation. Each of the four test-lists consisted of 72 critical word pairs: 36 related prime-target word pairs and 36 unrelated prime-target word pairs. For the related items, each list contained 18 associatively related prime-target word pairs, 6 orthographically incompatible word pairs, 6 phonologically incompatible word pairs and 6 orthographically–phonologically compatible word pairs. For the unrelated items, each of the four lists consisted of 18 word pairs that served as controls for mediated word pairs and 18 word pairs that served as controls for the associatively related word pairs.

Finally, nine associatively related filler items were included in each test-list, resulting in a total of 81 prime-target word pairs. Ten practice items were also constructed. Of the 10 practice items, 5 were associatively related and 5 were unrelated. None of the words contained in the practice items appeared in the test-lists. The practice and filler items were excluded from all statistical analyses.

Procedure. Participants were seated approximately 50 cm from the computer monitor and instructed to hold a microphone approximately 2 cm from their mouth. At a distance of 50 cm, target words, on average, subtended a visual angle of 1.5°. At the beginning of each experimental session, participants were read instructions and presented with one example trial. The instructions were followed by the presentation of 10 practice trials and 81 test trials. Each trial began with the presentation of the words 'Get Ready' for 1500 ms, followed by the presentation of a centrally located fixation cross for 1500 ms. Immediately following the fixation cross, the prime word (e.g. *brush*) was presented for 600 ms. A 200 ms inter-stimulus interval (ISI) followed the presentation of the prime word during which a blank screen was presented. Following the ISI, the target word (e.g. *tomb*) was presented and remained on the screen until the participant responded. For each trial, participants were instructed to fixate on the cross, read the prime word (e.g. *brush*) silently and name aloud the target word (e.g. *tomb*) as quickly but as accurately as possible into the microphone. After the participant made their response, the experimenter coded the response for accuracy. A 1000 ms delay was used between trials. The entire set of 81 test trials required approximately 20 min to complete.

Results and discussion

Trials in which the voice-key was triggered by noise before the participant responded and trials in which there was a failure of the voice-key to register the participant's response were excluded from the analyses (4.2%). In addition, correct RTs that were outside the range of 2.5 standard deviations above and below the overall mean of each age group were excluded (1.8%). As in previous research (e.g. Farrar et al., 2001; Reimer et al., 2001), planned comparisons were used to test for direct and mediated context effects separately within each condition and age group. Tests using items as the random variable were not performed because items were not randomly selected (Wike & Church, 1976; see also Pexman et al., 2002). An alpha level of 0.05 was used for all statistical tests.

Mean RTs and error rates were computed for each participant and submitted to a 3 (Age group: third grade vs sixth grade vs college students) $\times$ 4 (Condition: associatively related vs orthographically incompatible vs phonologically incompatible vs orthographically–phonologically compatible) $\times$ 2 (Relatedness: related vs unrelated) mixed-design analysis of variance (ANOVA; see Table 1 for means).

Response times. Only correct responses were included in the analysis of the RT data. The three-way interaction involving age, condition and relatedness was marginally significant, $F(6, 441) = 2.037$, $MSE = 2232.333$, $p < .07$. However, the Condition $\times$ Relatedness interaction was significant, $F(3, 441) = 22.966$, $MSE = 2232.333$, $p < .05$. A significant main effect of age was found, $F(2, 147) = 53.320$, $MSE = 43{,}106.613$, $p < .05$, with college students ($M = 543$ ms) producing reliably faster RTs than sixth graders ($M = 576$ ms) who, in turn, produced faster RTs than third graders ($M = 688$ ms). The

Table 1. Mean correct response times (RT; in ms), error rates (%E) and context effects by age group, condition and relatedness in Experiment 1.

Relatedness	Condition							
	Associative		Ortho/Phono		Phono		Ortho	
	RT	%E	RT	%E	RT	%E	RT	%E
				Grade 3				
Unrelated	677 (15.7)	6.0	693 (20.0)	15.3	699 (15.0)	23.2	672 (14.6)	12.3
Related	625 (15.2)	2.4	706 (21.5)	16.0	726 (17.5)	28.7	703 (18.6)	9.6
Context effect	+52	+3.6	− 13	− 0.7	− 27	− 5.5	− 31	+2.7
				Grade 6				
Unrelated	567 (7.2)	2.6	577 (9.0)	8.8	584 (8.4)	15.7	578 (7.8)	6.3
Related	531 (6.3)	0.6	587 (9.6)	9.4	608 (8.8)	25.4	577 (8.2)	6.4
Context effect	+36	+2.0	− 10	− 0.6	− 24	− 9.7	+1	− 0.1
				College				
Unrelated	537 (7.3)	1.8	548 (8.4)	5.9	550 (9.5)	10	540 (8.7)	4.0
Related	512 (7.3)	0.5	553 (9.1)	7.5	563 (9.4)	14.3	540 (8.9)	6.6
Context effect	+25	+1.3	− 5	− 1.6	− 13	− 4.3	0.0	− 2.6

Notes: Ortho/Phono, orthographically–phonologically compatible; Phono, phonologically incompatible; Ortho, orthographically incompatible; context effect = unrelated − related. Standard deviations are in parentheses.

main effect of condition was also significant, $F(3, 441) = 45.996$, $MSE = 2616.452$, $p < .05$. This main effect was not at all unexpected given that different words were used with each of the four conditions.

Planned comparisons revealed that RTs for related word pairs were significantly faster than those for unrelated word pairs in the associatively related condition with third graders ($t[49] = -9.051$, $p < .05$), sixth graders ($t[49] = -10.405$, $p < .05$) and college students ($t[49] = -8.408$, $p < .05$). However, with third graders, related word pairs yielded significantly slower RTs than unrelated word pairs in the orthographically incompatible condition, $t(49) = 2.509$, $p < .05$. RTs were also slower for related word pairs than for unrelated word pairs in the phonologically incompatible condition with third graders; however, this effect was significant only at the trend level, $t(49) = 1.794$, $p < .08$. For both sixth-grade children, $t(49) = 2.974$, $p < .05$, and college students, $t(49) = 3.189$, $p < .05$, significantly slower RTs were produced with related word pairs than with unrelated word pairs in the phonologically incompatible condition as well. No other significant effects were found in the RT data.

Error rates. With the error rate data, the three-way interaction involving age, condition and relatedness was not significant ($F < 1$). However, the Condition × Relatedness interaction was significant, $F(3, 441) = 6.119$, $MSE = 0.017$, $p < .05$, as was the Condition × Age interaction, $F(6, 441) = 4.700$, $MSE = 0.013$, $p < .05$. As with the RT data, a significant main effect was found for age, $F(2, 147) = 21.689$, $MSE = 0.029$, $p < .05$, with third-grade children ($M = 14\%$) producing more naming errors than sixth-grade children ($M = 9\%$) who, in turn, produced more errors than the college students ($M = 6\%$).

Planned comparisons revealed that for third graders ($t[49] = 3.281$, $p < .05$), sixth graders ($t[49] = 2.974$, $p < .05$) and college students ($t[49] = 3.112$, $p < .05$), error rates were significantly greater with unrelated than with related word pairs in the associatively related condition. However, for sixth graders, error rates were significantly greater with related word pairs than with unrelated word pairs in the phonologically incompatible condition, $t(49) = -2.290$, $p < .05$.

Consistent with the results of previous research (e.g. Plaut & Booth, 2000; Simpson & Lorsbach, 1983), the size of associatively related priming effects decreased as age increased. More importantly, both sixth-grade children and college students produced reliable mediated inhibition effects in the phonologically incompatible condition, an effect that has been demonstrated in previous research (Farrar et al., 2001; Reimer et al., 2001). In contrast, third-grade children produced a reliable mediated inhibition effect in the orthographically incompatible condition as well as a trend-level-mediated inhibition effect in the phonologically incompatible condition. Taken together, these results are important for at least two reasons. First, the present findings demonstrate that semantic feedback is evident in both adult and young readers. This result has implications for models of reading acquisition by indicating that semantic feedback may be a fundamental property of the word recognition system, allowing the integration of higher-level (semantic) information and lower-level (phonological and orthographic) information during the early stages of reading acquisition.

Second, and perhaps more importantly, the results indicate very clearly that the allocation of semantic feedback to the orthographic and phonological levels changes as children grow older and reading skill improves. Based on the fact that younger children possess slower, less efficient orthographic and phonological processing skills than older children and adults (e.g. Booth et al., 1999; Hansen & Bowey, 1992; Juel, 1983; Leslie & Thimke, 1986; Maisto & Sipe, 1980; Simpson et al., 1983), the spread of activation from the semantic level to the orthographic and phonological levels that was observed with younger children in the current experiment presumably reflected an attempt to compensate for less efficient processing. Furthermore, given that the mediated inhibition effect found in the phonologically incompatible condition with third graders was significant only at a trend level, a greater amount of semantic feedback may have been directed to the orthographic level than to the phonological level. Increased allocation of semantic feedback to the orthographic level is consistent with the notion that deficits in young children's phonological processing are related to deficits at the orthographic level. Specifically, because their orthographic representations are incomplete, young children possess imprecise mappings between orthographic and phonological representations (Perfetti, 1992; see also Booth et al., 1999). Thus, by increasing the amount of semantic feedback that is allocated to the orthographic level, inefficient orthographic and phonological processes can be facilitated. However, assuming that there is a limited amount of activation available to the word recognition system at any given time (Anderson, 1976, 1983; McNamara, 1992a, 1992b), increased semantic feedback to the orthographic level will lead to a decrease in the amount of semantic feedback to the phonological level. As a result, in the phonologically incompatible condition, competition among conflicting phonological codes will be decreased, resulting in a less reliable mediated inhibition effect.

In contrast to young children, because orthographic and phonological processes are more developed in the older children and adults, semantic feedback to the orthographic level was not necessary. Therefore, in the sixth-grade children and adults, semantic feedback could be fully allocated to the phonological level in order to facilitate the phonological processing required in a word naming task. As a result, mediated inhibition effects were only found in the phonologically incompatible condition.

Experiment 2

The developmental differences that were found in the nature of semantic feedback in Experiment 1 suggest that the allocation of semantic feedback to the orthographic and phonological levels may change as children grow older and reading skill improves. According to this *activation–allocation* hypothesis, the limited resources associated with semantic feedback are allocated in a flexible manner to the orthographic or phonological levels, depending upon the reader's level of word recognition skill. Because of mature orthographic processing, older children and adults are able to allocate semantic feedback only to the phonological level during a word naming task. In contrast, because of their inefficient orthographic processing, younger readers must allocate semantic feedback to the orthographic level as well. If this interpretation is correct, any disturbance in orthographic processing should result in an increase in semantic feedback to the orthographic level.

Using adult readers, the activation–allocation hypothesis was tested directly in Experiment 2 by manipulating the visual quality of target words within the mediated priming paradigm. Multiple studies have demonstrated that visually degraded stimuli are recognised more slowly and less accurately than intact stimuli in both lexical decision and naming tasks (Besner & Smith, 1992; Borowsky & Besner, 1993; Meyer, Schvaneveldt & Ruddy, 1975; Stolz & Neely, 1995). In adult models of visual word recognition (e.g. Besner & Smith, 1992; Borowsky & Besner, 1993; see also Plaut, 1995), alterations in the visual quality of word stimuli affect the rate at which orthographic representations are activated. Specifically, by slowing pre-lexical processes (i.e. feature and letter processes), visually degraded stimuli provide weaker input to the orthographic level than intact stimuli, resulting in slower activation of orthographic representations (Brown & Besner, 2002). Given that stimulus degradation results in less efficient orthographic processing in adults, visually degraded targets should increase processing demands at the orthographic level relative to intact targets. Thus, according to the activation–allocation hypothesis, when targets are visually degraded in the mediated priming paradigm, increased semantic feedback should spread to the orthographic level in order to support inefficient orthographic processing. As a result, a semantically mediated inhibition effect should be found in the orthographically incompatible condition, but may be reduced or absent in the phonologically incompatible condition. However, when targets are intact, semantic feedback should spread only to the phonological level, resulting in semantically mediated inhibition effects in the phonologically, but not orthographically, incompatible condition.

Finally, it should be noted that in Experiment 2, a stimulus onset asynchrony (SOA) of 200 ms was used. A short SOA was used in order to determine whether the modulation of semantic feedback can occur under conditions in which conscious expectancy is not operational (see Neely, 1977, 1991; Stolz & Neely, 1995).

Method

Participants. Participants were 48 college students (*M* age = 27.8 years; *SD* = 8.35; 38 female) enrolled at the 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.

Apparatus. The presentation of stimuli and the recording of both accuracy and response time (RT) were accomplished using a Dell OptiPlex GX115 computer controlled by E-Prime 1.0 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., Pittsburgh, PA, USA). 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 to record the accuracy of each response. Stimuli were displayed on a 15-in CRT colour monitor.

Design. A 2 (Stimulus quality: bright vs dim) × 4 (Condition: associatively related vs orthographically incompatible vs phonologically incompatible vs orthographically–phonologically compatible) × 2 (Relatedness: related vs unrelated) within-participants design was used. The levels of each variable were presented randomly throughout each test-list. Both RT and accuracy were measured on each trial.

Materials and stimuli. The materials and stimuli were identical to those used in Experiment 1 with two exceptions: (a) eight test-lists were constructed and (b) eight, as opposed to nine, filler items were included in each test-list. These changes were required in order to ensure that each target word appeared equally often as both bright and dim targets for both the related and unrelated word pairs within a given condition. Variation in stimulus quality was accomplished by altering the luminance of the target word. Target words in the bright condition were composed of white letters presented on a black background, whereas targets in the dim condition were composed of dark-grey letters on a black background (see also Stolz & Neely, 1995).

Procedure. The procedure was the same as the one used in Experiment 1 with the exception that each prime was presented for 150 ms and was followed by a 50 ms ISI.

Results and discussion

Mean RTs and error rates were computed for each participant and submitted to a 2 (Stimulus quality: bright vs dim) × 4 (Condition: associatively related vs orthographically incompatible vs phonologically incompatible vs orthographically–phonologically compatible) × 2 (Relatedness: related vs unrelated) within-participants ANOVA (see Table 2 for means). Trials in which the voice-key was triggered by noise before the participant responded and trials in which there was a failure of the voice-key to register the participant's response were excluded (2.7%). In addition, correct RTs that were outside the range of 2.5 standard deviations above and below the overall mean were excluded (1.2%). As with Experiment 1, planned comparisons were performed to measure both direct and mediated context effects.

Response times. Only correct responses were included in the analysis of the RT data. The three-way interaction involving stimulus quality, condition and relatedness was not significant ($F < 1$). However, the Condition × Relatedness interaction was significant, $F(3, 141) = 3.510$, $MSE = 2310.875$, $p < .05$, as was the main effect of condition, $F(3, 141) = 30.108$, $MSE = 2015.737$, $p < .05$. The main effect of stimulus quality was also statistically significant, $F(1, 47) = 46.513$, $MSE = 10{,}130.038$, $p < .05$, indicating that responses to dim targets ($M = 621$ ms) were reliably slower than responses to bright targets ($M = 571$ ms).

For bright targets, planned comparisons revealed that RTs associated with related word pairs were significantly slower than RTs associated with unrelated word pairs in the phonologically incompatible condition, $t(47) = -2.210$, $p < .05$. For dim targets, RTs

Table 2. Mean correct response times (RT; in ms), error rates (%E) and context effects by stimulus quality, condition and relatedness in Experiment 2.

Relatedness	Condition							
	Associative		Ortho/Phono		Phono		Ortho	
	RT	%E	RT	%E	RT	%E	RT	%E
				Dim				
Unrelated	607 (12.5)	1.5	613 (12.0)	13.2	641 (15.7)	10.7	626 (13.9)	2.1
Related	585 (12.7)	0.9	617 (13.9)	7.6	655 (15.2)	14.1	623 (14.2)	6.9
Context effect	+22	+0.6	−4	+5.6	−14	−3.4	+3	−4.8
				Bright				
Unrelated	555 (10.7)	1.1	576 (13.3)	3.4	576 (12.4)	9.7	566 (12.5)	2.8
Related	551 (10.8)	0.5	575 (12.1)	3.1	599 (13.5)	13.2	575 (12.6)	4.8
Context effect	+4	+0.6	+1	+0.3	−23	−3.5	−9	−2.0

Notes: Ortho/Phono, orthographically–phonologically compatible, Phono, phonologically incompatible; Ortho, orthographically incompatible; context effect = unrelated – related. Standard deviations are in parentheses.

associated with related word pairs were significantly faster than RTs associated with unrelated word pairs in the associatively related condition, $t(47) = 4.082$, $p < .05$. No other significant effects were found in the RT data.

Error rates. In the error rate data, a significant three-way interaction among stimulus quality, condition and relatedness was not found ($F < 1$). However, a significant Condition × Relatedness interaction was found, $F(3, 141) = 3.159$, $MSE = 0.015$, $p < .05$, as was a significant main effect of condition, $F(3, 141) = 18.631$, $MSE = 0.019$, $p < .05$. As with the RT data, a significant main effect of stimulus quality was found, $F(1, 47) = 5.440$, $MSE = 0.019$, $p < .05$, indicating that participants committed significantly more naming errors when targets were dim ($M = 7.1\%$) than when they were bright ($M = 4.8\%$). The only significant planned comparison found in the error rate data was for dim targets in the orthographically incompatible condition, $t(47) = 2.193$, $p < .05$, where significantly more errors were produced with related ($M = 6.9\%$) than with unrelated ($M = 2.1\%$) word pairs.

As predicted by the activation–allocation hypothesis, a semantically mediated inhibition effect was found only in the phonologically incompatible condition when target words were bright, and only in the orthographically incompatible condition when targets were dim. The presence of mediated priming in the phonologically incompatible condition when targets were bright replicates the sixth-grade and college student data from Experiment 1, as well as the results of two previous studies (Farrar et al., 2001; Reimer et al., 2001). In contrast, the pattern of results found when targets were dim has not been demonstrated previously in adult readers. However, this pattern of results is quite similar to the one produced by third graders in Experiment 1. According to the activation–allocation hypothesis, this pattern of results indicates that when orthographic processing was slowed, semantic feedback was allocated to the orthographic level, resulting in a mediated inhibition effect in the orthographically incompatible condition. However, because semantic feedback spread to the orthographic level, less semantic feedback spread to the phonological level, resulting in the elimination of a mediated effect in the phonologically incompatible condition.

Finally, in Experiment 2 a reliable associatively related priming effect was absent with bright targets. Although associatively related priming effects were found in Experiment 1 when all targets were bright (see also Reimer et al., 2001), the absence of this effect in Experiment 2 is consistent with at least one other priming study in which stimulus quality was altered. Specifically, Besner and Smith (1992) also found a significant reduction in associatively related priming with bright targets compared to dim targets when stimulus quality was manipulated within blocks of trials. Nevertheless, the specific relationship between the typical Relatedness × Stimulus Quality interaction (see Becker & Killion, 1977; Borowsky & Besner, 1993; Stolz & Neely, 1995) and semantically mediated priming needs further examination.

General discussion

The present study used a mediated priming paradigm to examine semantic feedback during word recognition in children and adults. Developmental differences were found in the pattern of semantically mediated inhibition effects in Experiment 1: third-grade children produced a mediated inhibition effect in the orthographically incompatible condition (e.g. *table*–[chair]–*rare*) and a trend-level-mediated inhibition effect in the phonologically incompatible condition (e.g. *brush*–[comb]–*tomb*), whereas sixth-grade children and college students produced mediated inhibition effects only in the phonologically incompatible condition. In order to explain these developmental differences, an activation–allocation hypothesis was proposed. The activation–allocation hypothesis is based on the assumption that the amount of activation that is available to the word recognition system is limited, and that this limited amount of activation may be allocated in a flexible manner to lower levels of processing (e.g. the orthographic and phonological levels) in an attempt to enhance the efficiency of the word recognition system. Based on the activation–allocation hypothesis, the developmental differences that were found in semantic feedback in Experiment 1 were interpreted as a reflection of age-related changes in the demands of orthographic and phonological processing during word recognition. Given that younger children possess relatively weaker activation of orthographic and phonological information (e.g. Booth et al., 1999), the pattern of semantic feedback that was exhibited by third-grade children appears to reflect an increased demand for activation at these lower levels of processing. More precisely, the results of the present study suggest that third graders were required to allocate significant amounts of activation to the orthographic level, and to a somewhat lesser extent, the phonological level. Within the mediated priming paradigm, this resulted in mediated inhibition effects in the orthographically incompatible condition, and a trend-level effect in the phonologically incompatible condition. In contrast to younger readers, the word recognition skills of mature readers are considered to be based largely on phonology (e.g. Frost, 1998; Lukatela & Turvey, 1994a, 1994b; Perfetti & Bell, 1991; Van Orden, 1987; Van Orden, Johnston & Hale, 1988). Consequently, the pattern of feedback observed with older children and adults presumably reflected this increased demand for activation at the phonological level. Within the mediated priming paradigm, evidence of semantic feedback to the phonological level in sixth graders and adults was found in the form of mediated inhibition effects in the phonologically incompatible condition.

Suggesting that semantic feedback is allocated to lower levels in an attempt to increase overall processing efficiency is similar to other accounts of word recognition processes (e.g. Besner & Smith, 1992; Borowsky & Besner, 1993; Stolz & Neely, 1995). For example, within the context of a multistage activation model of word recognition, Stolz and Neely (1995) stated that the word recognition system may be '. . . sensitive to the amount of activation a pathway or sub-system demands. If the demand on activation is greater than the possible benefits from use of the subsystem-pathway, the spread of activation to that subsystem-pathway could be inhibited' (p. 608).

Experiment 2 tested the activation–allocation hypothesis with adult readers by manipulating the visual quality of target words within the mediated priming paradigm. Based upon the logic of the activation–allocation hypothesis, it was reasoned that semantic feedback in the mediated priming paradigm should be directed to the phonological level in adult readers as long as target words remained visually intact. On the other hand, if targets are visually degraded, the demand for activation at the orthographic level would be increased, resulting in semantic feedback being directed to the orthographic level. This prediction was supported in Experiment 2 where a mediated inhibition effect was found with young adults only in the phonologically incompatible condition with intact (bright) targets, and only in the orthographically incompatible condition with degraded (dim) targets.

In addition to providing support for the activation–allocation hypothesis, the results of Experiment 2 provide two additional observations about the nature of semantic feedback during word recognition. First, because a brief SOA in priming tasks is generally considered to measure automatic processes (Neely, 1977, 1991), the use of a 200 ms SOA in Experiment 2 rules out the possibility that a conscious-expectancy mechanism was operating during the mediated priming task. Thus, the results of Experiment 2 suggest that the modulation of semantic feedback depended on orthographic and phonological processing efficiency, rather than the conscious use of subject-generated strategies. Second, the results of Experiment 2 indicate that the modulation of semantic feedback occurred during target processing. Because stimulus quality was varied randomly within a block of test trials, participants could not predict a priori whether a target would be degraded or intact on a given trial. As a result, it would have been necessary for semantic feedback initially to be restricted only to the phonological level and be directed to the orthographic level only after it was determined that orthographic encoding was delayed. Unless this were the case, a mediated inhibition effect would not have been found in the phonologically incompatible condition with bright targets.

The results of the present study are most consistent with models of visual word recognition that implement fully interactive connections among processing levels (e.g. Coltheart et al.'s 2001, DRC model). The semantically mediated inhibition effects that were found in the present study were possible only if activation was allowed to spread from semantic to orthographic and/or phonological representations during word processing. It should be noted, however, that there is no a priori reason why other competing models (e.g. parallel distributed processing-based models) could not also account for the present results as long as they contain feedback connections from semantic to orthographic and phonological representations. Unfortunately, such connections are absent in many competing models (e.g. Plaut, 1995; Plaut & Booth, 2000).

Finally, some comment needs to be made regarding the stimulus materials that were used in the present mediated priming paradigm. Given that target words were used as their own controls within each condition of the present study (e.g. *brush–tomb*; *high–tomb*), the mediated effects found within conditions could not have been due to stimulus-related variables (e.g. word length, spelling regularity, etc.). However, one limitation of the present study was that the influence of such variables was not controlled for across priming conditions (with the exception of word frequency, which was reasonably comparable across the three mediated conditions). As a result, direct comparisons involving the magnitude of mediated inhibition effects across mediated conditions could not be made. Such comparisons may be important to make in future research to determine whether there are changes in the amount of semantic feedback as age and reading skill increase.

Conclusions

The central findings of the present study were that (a) semantic feedback is not only present in skilled, adult readers, but in young, less-skilled readers as well and (b) the integration of semantic information with orthographic and phonological information during word recognition can change in response to processing demands within the word recognition system. Although further research is required to replicate the findings of the present study, the results provide important constraints for models of visual word recognition and reading acquisition, particularly regarding the nature of interactivity among components of the visual word recognition system during word processing.

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Appendix. The 72 word triplets

Orthographically–phonologically compatible condition	Phonologically incompatible condition	Orthographically incompatible condition
Cat–dog–log	Mother–father–lather	Heavy–light–quite
Doctor–nurse–purse	High–low–now	Circle–square–fair
Night–day–hay	Lemon–sour–tour	Coffee–tea–bee
Pepper–salt–malt	Wish–want–pant	Table–chair–rare
Sleep–bed–led	Tulip–flower–blower	Knife–blade–raid
Hammer–nail–wail	Judge–jury–bury	Needle–thread–said
Slow–fast–cast	Music–sound–wound	Sheep–wool–pull
Shallow–deep–seep	House–home–some	Hint–clue–flew
Web–spider–cider	Month–year–wear	Foot–shoe–blue
Square–round–pound	Take–give–dive	Live–die–rye
Over–under–blunder	Uncle–aunt–punt	Book–read–seed
Sweep–broom–groom	Fridge–stove–prove	Early–late–eight
Water–drink–brink	Glove–hand–wand	Smooth–rough–cuff
Loud–soft–loft	Skin–bone–gone	Head–hair–bear
Long–short–port	Always–never–fever	Sell–buy–lie
Hill–mountain–fountain	Minute–hour–four	Thirsty–water–daughter
Girl–boy–joy	Brush–comb–tomb	Eating–food–rude
Arm–leg–peg	Below–above–cove	Black–white–fight
Lost–found–hound	Faster–slower–tower	Color–red–dead
Speak–talk–walk	Win–lose–nose	Robin–bird–heard
City–town–gown	Anger–mad–wad	Lamp–shade–laid
Truck–car–bar	Crack–break–freak	Hand–foot–put
Carpet–floor–poor	North–south–youth	Bitter–sweet–neat
Old–new–pew	In–out–rut	Open–close–toes

Note: Prime-target word pairs in the associatively related condition were constructed by using the first and second word of each word triplet.