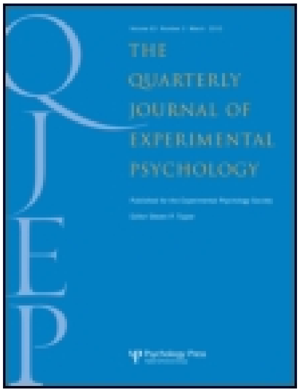

The Quarterly Journal of Experimental Psychology
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/pqje20

Exploring the additive effects of stimulus quality and word frequency: The influence of local and list-wide prime relatedness

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Accepted author version posted online: 31 May 2012.Version of record first published: 21 Aug 2012.

THE QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY, 2013
Vol. 66, No. 1, 91–107, http://dx.doi.org/10.1080/17470218.2012.698628

Exploring the additive effects of stimulus quality and word frequency: The influence of local and list-wide prime relatedness

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Stimulus quality and word frequency produce additive effects in lexical decision performance, whereas the semantic priming effect interacts with both stimulus quality and word frequency effects. This pattern places important constraints on models of visual word recognition. In Experiment 1, all three variables were investigated within a single speeded pronunciation study. The results indicated that the joint effects of stimulus quality and word frequency were dependent upon prime relatedness. In particular, an additive effect of stimulus quality and word frequency was found after related primes, and an interactive effect was found after unrelated primes. It was hypothesized that this pattern reflects an adaptive reliance on related prime information within the experimental context. In Experiment 2, related primes were eliminated from the list, and the interactive effects of stimulus quality and word frequency found following unrelated primes in Experiment 1 reverted to additive effects for the same unrelated prime conditions. The results are supportive of a flexible lexical processor that adapts to both local prime information and global list-wide context.

Keywords: Semantic priming; Word frequency; Stimulus quality.

There has been considerable research focusing on the processes involved in simple visual word recognition, since the days of Cattell (1890). One conundrum that has surfaced in this area is the combined effects of three important variables in factorial studies of lexical decision performance: semantic priming, word frequency, and stimulus quality (hereafter referred to as SQ). The conundrum is as follows: Word frequency and SQ both produce an overadditive interaction with semantic priming (e.g., Balota, Yap, Cortese, & Watson, 2008; Becker, 1979; Becker & Killion, 1977; Besner & Smith, 1992; Borowsky & Besner, 1993; Meyer, Schvaneveldt, & Ruddy, 1975). That is, the detrimental effects of visual degradation and low frequency are amplified when the target appears after a semantically unrelated prime. From a complementary perspective, a semantically related prime speeds up processing more for difficult (lower frequency or visually degraded) word targets than for easy (higher frequency or clearly visible) word targets. In contrast, word frequency and SQ produce clear additive effects (e.g., Balota & Abrams, 1995; Plourde &

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This work was supported by a graduate grant to Michele Scaltritti from the Department of Developmental and Social Psychology, University of Padova and by a PRIN 2008 grant to Francesca Peressotti from the Ministry of Education, University and Research of Italy. We are grateful to Derek Besner and Jim Neely for very helpful comments on an earlier version of this article.

Besner, 1997; Stanners, Jastrzembski, & Westbrook, 1975). According to Sternberg's additive-factors logic (Sternberg, 1969), two variables that exert additive effects are affecting two separate stages of processing (but see McClelland, 1979, regarding alternative accounts).[1] In contrast, two variables that interact presumably affect at least one common stage of processing. Within the additive-factors perspective, the combined effects of word frequency, SQ, and semantic priming can best be interpreted as suggesting that SQ and word frequency are affecting two separate, discrete, and serially organized stages, while semantic context is affecting both of these stages (e.g., Borowsky & Besner, 1993; Peressotti, Job, Rumiati, & Nicoletti, 1995; but see Masson & Kliegl, in press).

The notion of serially organized stages is particularly challenging for the currently most successful models of word recognition. These models rely heavily on interactive activation mechanisms (McClelland & Rumelhart, 1981). In fact, models such as the dual-route cascaded (DRC) model (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) and the connectionist dual process (CDP+) model (Perry, Ziegler, & Zorzi, 2007) implement cascaded activation within an interactive activation framework, and strong additive effects of SQ and word frequency do not easily fall from such a perspective. Indeed, the issue has led to lively debates in the field (e.g., Besner, 2006; Besner & O'Malley, 2009; Reynolds & Besner, 2004; Ziegler, Perry, & Zorzi, 2009). Notably, Plaut and Booth (2006; see also Borowsky & Besner, 2006; Plaut & Booth, 2000) reported simulations of the full pattern (interactive effects of semantic priming with both SQ and frequency, with concomitant additive effects of SQ and frequency) within a PDP (parallel distributed processing) computational model. Although there were aspects of the data that could be accommodated by the PDP model, there were also some problems (Besner, Wartak, & Robidoux, 2008). For example, whereas humans show the pattern of additive effects of SQ and frequency across a wide variety of stimulus qualities, the model displays underadditive, additive, or overadditive effects of SQ and frequency depending on the size of the SQ effect.

Are the additive effects of SQ and word frequency task independent?

Yap and Balota (2007; see also O'Malley, Reynolds, & Besner, 2007) systematically investigated the joint effects of SQ and word frequency across different experimental tasks and found that the additive pattern holds only for the lexical decision, while interactive effects are found both in pronunciation and in semantic categorization. The authors argued that the different pattern found for lexical decisions might be related to task-specific operations that engage an early clean-up process that is particularly important for making word/nonword decisions (see also Yap, Balota, Tse, & Besner, 2008). This argument is important because if these additive effects only occur for lexical decisions, then they may not produce difficulties for recent models of visual word recognition, because task-specific lexical decision operations may fall outside their scope.

O'Malley and Besner (2008) hypothesized that the difference across tasks observed in the Yap and Balota (2007) study might be due to the presence or absence of nonwords. Indeed, they demonstrated that SQ and word frequency also produce additive effects in pronunciation when words and nonwords are randomly

[1] Although cascaded interactive models can produce additive effects, it is important to evaluate how easily they can do so. Roberts and Sternberg (1993) directly compared a class of serial-stage models and a class of cascaded models in accounting for a pattern of additive effects at the level of the mean and higher order moments of the reaction time distributions. They noted that some cascaded models could predict additive effects at the level of the mean, but these models actually resembled serially staged models, and, more important, cascaded models had difficulty accommodating additivity in the higher order moments, such as variance and skewness. Thus, although additive effects do not demand serial stages, Sternberg's (1969) additive-factors logic still provides a powerful tool for understanding the combined effects of various variables.

intermixed, as in the lexical decision task. O'Malley and Besner argued that when nonwords are present, the level of letter processing is thresholded. Specifically, stimulus information is forwarded to the orthographic lexicon only after activation has reached a certain criterion at the letter level. When nonwords are embedded in the list, this should be useful even in speeded pronunciation because it would prevent the activation of lexical entries that might interfere with the recognition process (possibly producing lexicalization errors) when the nonword stimuli are degraded. The crucial point is that additive effects of word frequency and SQ in isolated word recognition (without primes) can be obtained in both lexical decision and speeded pronunciation, as long as the pronunciation task includes nonwords. Hence, the theoretical importance of the additive effects for current models is strengthened by this task independence.

Does priming influence the additive effects of SQ and word frequency?

Although many studies have manipulated two of the three variables (word frequency, semantic priming, and SQ), to our knowledge there is only one published study that has jointly manipulated all three variables within the same experiment. Borowsky and Besner (1993, Experiment 3) manipulated SQ (clear vs. degraded), word frequency (measured as a continuous variable), and context (semantically related primes vs. nonword primes vs. semantically unrelated primes) in lexical decision. Importantly, within this same study, the authors found, consistent with the literature, additive effects of SQ and word frequency, overadditive effects of SQ and semantic priming, and overadditive effects of word frequency and semantic priming. Borowsky and Besner emphasized the importance of the additive effects of SQ and word frequency on targets preceded by nonword primes and specifically noted that the nonword-prime condition in the experiment was selected "for the purpose of assessing the joint effect of Stimulus Quality and Word Frequency uncontaminated by Context" (Borowsky & Besner, 1993, pp. 826–827).

Borowsky and Besner's (1993) results suggest that when the three targeted variables are jointly manipulated, one obtains the same pattern as when only two variables are manipulated, further solidifying the empirical conundrum for interactive activation models noted above. However, if one looks more closely at their results, an interesting pattern emerges. Specifically, on related priming trials, frequency and SQ produce clear additive effects, similar to the nonword prime condition, as noted above. Importantly, however, when targets were primed by unrelated words, SQ and word frequency appear to produce an overadditive interaction, with larger frequency effects for degraded targets. It is not immediately clear why the Borowsky and Besner framework would predict interactive effects on unrelated trials. Moreover, one might question the emphasis on nonword prime trials producing additive effects of SQ and word frequency, because nonwords may increase the likelihood of dampening input from the lexical system on a trial-by-trial basis, thereby producing the more additive pattern found in the lexical decision task.

Because of the potential idiosyncratic nature of the nonword primes, in the present study we focus on the joint effects of SQ and word frequency following related or unrelated primes, which in the Borowsky and Besner (1993) study produced either additive (following related primes) or overadditive (following unrelated primes) effects. This intriguing pattern may reflect a list-wide reliance on lexical/semantic information, which we refer to as the *prime reliance account*. Specifically, the presence of related primes and degraded targets may influence how the lexical processing system adaptively adjusts to the demands of the task. This proposal is consistent with a large body of recent literature that investigates the influence of top-down factors, such as task set, task requirements, or list composition, on word processing from very early stages in processing (e.g., Balota & Yap, 2006; Kiefer & Martens, 2010).

According to the prime reliance account, because of the difficulty of recognizing degraded targets and the benefit of related primes on half of these degraded trials, participants may increase their reliance on prime information (see Balota et al., 2008, for evidence of such a mechanism). This notion is quite similar to the interactive compensatory perspective originally advocated by Stanovich and West (1983; see also Stanovich, 1980; Stanovich & West, 1979, 1981) and recent arguments by Thomas, Neely, and O'Connor (2012) further discussed below. How might an increased reliance on prime information accommodate the Borowsky and Besner's (1993) results of additive effects following related primes and overadditive effects following unrelated primes? First consider targets following related trials. Here, one might expect that the utility of a related prime will be greatest for the most difficult targets—that is, the low-frequency degraded targets. Hence, response latency for these items will produce the greatest facilitation from related primes, thereby decreasing the likelihood of obtaining an overadditive interaction between SQ and word frequency.[2] In contrast, when targets follow unrelated primes, prime information will not be helpful. Consequently, the degraded low-frequency words will be most disrupted by failing to access useful information from the prime. This increases the likelihood of obtaining an overadditive interaction between word frequency and SQ.

In light of the prime reliance account of the intriguing Borowsky and Besner's (1993) results, the present study had four goals. First, it further explores the combined effects of the three targeted variables (SQ, word frequency, and semantic priming) within the same experiment. As noted above, to our knowledge the Borowsky and Besner study is the only study to jointly manipulate all three variables. Moreover, the interesting additive effects of word frequency and SQ following related primes and the overadditive interactive effects of word frequency and SQ are particularly important to replicate. Second, the present study extends the lexical decision study of Borowsky and Besner to speeded word pronunciation. As noted above, it is important to demonstrate task independence of the three-way interaction obtained by Borowsky and Besner. Third, the present experiment examines the reaction time distributions to determine whether any evidence of the three-way interaction is localized for the most difficult items —that is, in the slow tail of the reaction time distributions, as the prime reliance framework predicts. Finally, to explore further the influence of related primes as a list-wide effect, a second experiment is reported in which no related primes are included in the experimental list. If the first experiment replicates Borowsky and Besner's overadditive frequency by degradation interaction following unrelated primes, and this interaction is due to a reliance on prime information that is invoked by the presence of related primes in the experimental list, then, when related primes are removed from the list this interaction should be eliminated for those very same unrelated prime–target pairs.

EXPERIMENT 1

Method

Participants

Thirty-two undergraduate students from Washington University in St. Louis participated in the experiment for course credit. All were native English speakers and reported normal or corrected-to-normal vision.

Design

The experiment was a 2 (related vs. unrelated primes) × 2 (clear vs. degraded targets) × 2 (high

[2] An examination of the SQ by semantic priming two-way interaction across the reaction time distribution has consistently shown that the disproportionately greater priming effects for degraded targets are found at the slower tail of the reaction time distribution (Balota et al., 2008; Thomas et al., 2012). This result has been interpreted as evidence of a greater reliance on prime information for the most difficult targets (the ones requiring more processing time) when they are visually degraded. It is worth noting that such a distributional analysis of the semantic priming by SQ interaction can be interpreted as functionally examining the three-way interaction between SQ, semantic priming, and frequency, because the fastest RTs in the distribution are probably coming from high-frequency words and the slowest from low-frequency words. If that is the case, greater priming effects at the tail of the distributions would imply greater priming effects for low-frequency words—that is, the hypothesis outlined in the present work.

vs. low-frequency targets) factorial design, with all factors manipulated within participants.

Stimuli

One hundred and sixty prime–target pairs were selected from the Nelson, McEvoy, and Schreiber (1998) norms. Eighty of these pairs included high-frequency words as targets, while the other 80 included low-frequency words as targets. Backward and forward association strength was controlled across high- and low-frequency prime–target pairs, based on the Nelson et al. norms. Frequency values, as well as other variables controlled in the study, were taken from the English Lexicon Project database (Balota et al., 2007).

As shown in Table 1, onset phoneme, orthographic and phonological neighbourhood density, length, and summed and mean bigram frequencies were controlled across high- and low-frequency targets. Primes for high- and low-frequency targets were also balanced for frequency, length, and orthographic and phonological neighbourhood size. Unrelated pairs were created by randomly reassigning primes to targets. This re-pairing was done separately for high- and low-frequency words. One hundred and sixty pronounceable nonwords were selected from the English Lexicon Project database. Words and nonwords did not significantly differ in length. However, following O'Malley and Besner (2008), we selected very word-like nonwords that had significantly more orthographic neighbours than words did, as well as higher summed and mean bigram frequencies ($ps < .001$). One hundred and sixty words were selected as primes for nonwords and were not different from the primes used for words on frequency, length, and orthographic and phonological neighbourhood size. Prime relatedness and SQ were

Table 1. *Properties of the items used in Experiment 1 and 2*

Variable	*LF*	*HF*	t_{freq}	*NW*	t_{lex}
Primes					
Length	5.34	5.78	−1.52	5.49	−0.32
Freq.	47,327	29,396	0.80	28,075	−0.83
Log freq.	8.27	8.73	−1.39	8.52	0.07
Orth. N	4.33	3.84	0.59	4.17	0.15
Phon. N	9.36	7.53	1.13	8.45	0.01
Targets					
Length	5.18	4.93	1.03	5.23	1.03
Freq.	4,785	80,518	−5.77*	—	
Log freq.	8.21	10.86	−20.34*	—	
Orth. N	4.59	7.13	−1.03	7.23	3.98*
Phon. N	10.73	15.73	−0.38	—	
Sum bigram	6,737	7,227	−0.64	13,610	10.90*
Mean bigram	1,518	1,714	−1.60	3,182	15.74*
FAS	.54	.58	−1.11	—	
BAS	.34	.28	−1.33	—	

Note: LF = low frequency. HF = high frequency. NW = nonwords. Orth. N = orthographic neighbourhood. Phon. N = phonological neighbourhood. Sum bigram = summed bigram frequencies. Mean bigram = mean bigram frequency. FAS = forward association strength. BAS = backward association strength. Both FAS and BAS are taken from Nelson et al. (1998). All other variables' values have been retrieved from the English Lexicon Project database (Balota et al., 2007), where frequency values refer to the Hyperspace Analogue to Language (HAL) frequency norms (Lund & Burgess, 1996). $t_{freq} = t$ values generated from an independent-samples t test between items belonging to the LF group and items belonging to the HF group. $t_{lex} = t$ values generated from an independent-samples t test between items belonging to the nonword group and items belonging to the word group (collapsed across frequency). The t values that correspond to a $p < .05$ are marked (*). Otherwise, the difference was not significant (all $ps > .1$).

counterbalanced across subjects, such that each target appeared equally often in all conditions across participants, and no word or nonword was repeated within a participant.

Apparatus and procedure

Participants were tested individually in a dimly lit room, seated at a distance of approximately 50 cm from the computer's monitor. Vocal responses triggered, via an ATR 20 microphone (Audio-Technica), a serial response box (Psychology Software Tools). Data were collected on a Pentium 4 computer using E-Prime 1.1 (Schneider, Eschman, & Zuccolotto, 2001). Participants were asked to silently read the primes and to name the targets aloud as fast and as accurately as possible. A set of 32 practice trials (16 words and 16 nonwords) preceded the experimental session. For practice word-trials, SQ and prime relatedness (but not word frequency) were manipulated (4 trials per condition). Practice nonword-trials consisted of 8 word-primed clear nonwords and 8 word-primed degraded nonwords. Primes and targets (words and nonwords) used in the practice session were never presented in the experimental phase. The session lasted about 45 min. After every 80 trials, participants were prompted to take a short break. Responses were coded as correct, incorrect, or voice-key errors online by the experimenter.

Each trial started with a fixation point (+) presented at the centre of the screen. After 1,000 ms, the prime (presented in lower case) appeared on the screen for 100 ms, followed by a blank screen for the same duration. The target (in upper case) was then displayed until the voice-key detected a response. If no response was detected, the target disappeared from the screen after 5,000 ms. A blank screen was presented for 1,800 ms after the response (or after the 5,000-ms interval elapsed), producing a clear separation between adjacent trials, which may be necessary for strategic priming effects to occur (Neely, O'Connor, & Calabrese, 2010). The letter strings were displayed in 18-point Courier New font on a black background: red, green, blue (RGB) 0, 0, 0. In the bright condition, targets were presented in RGB (65, 65, 65); in the dim condition, they appeared in RGB (5, 5, 5). Primes and the fixation point were always presented in the bright RGB (65, 65, 65).

Results

Response latencies and accuracies were analysed across both participants and items, thus yielding, respectively, F_1 and F_2 statistics. Context (related vs. unrelated primes), frequency, and SQ were within-subject factors in the analyses across participants. For the item analysis, context and SQ were within-item factors, and frequency was a between-item factor.

Trials with incorrect responses (4.10%) or voice-key errors (3.98%) were first removed. The remaining reaction times (RTs) were submitted to a recursive trimming procedure, in which the criterion for outlier removal was determined by the sample size of each experimental cell (see Van Selst & Jolicœur, 1994). This procedure resulted in the removal of a further 1.68% of the data. In order to minimize the contribution of overall response latency within a participant unduly influencing the results (see Faust, Balota, Spieler, & Ferraro, 1999; Hutchison, Balota, Cortese, & Watson, 2008), the RTs were transformed into within-participant z scores (hereafter referred to as z-RTs) for the analyses of variance (ANOVAs).

Response latencies

Mean response latencies and mean proportion of errors as a function of condition are displayed in Table 2. The ANOVA yielded large main effects of SQ [$F_1(1, 31) = 320.91$, $MSE = .156$, $p < .001$; $F_2(1, 158) = 2{,}499.88$, $MSE = .05$, $p < .001$], semantic context [$F_1(1, 31) = 66.60$, $MSE = .036$, $p < .001$; $F_2(1, 158) = 103.20$, $MSE = .058$, $p < .001$], and word frequency [$F_1(1, 31) = 31.70$, $MSE = .016$, $p < .001$; $F_2(1, 158) = 11.20$, $MSE = .12$, $p < .01$]. The SQ by context interaction was significant [$F_1(1, 31) = 7.50$, $MSE = 0.36$, $p < .05$; $F_2(1, 158) = 15.12$, $MSE = .047$, $p < .001$], but the context by frequency interaction did not reach significance [$F_1(1, 31) = 1.99$, $MSE = .016$, $p > .1$; $F_2(1, 158) = 1.44$, $MSE = .058$, $p > .2$]. Although this latter result may be surprising, it is fully consistent

Table 2. *Mean reaction times and mean proportion of errors as a function of context, target frequency, and stimulus quality in Experiment 1*

	Clear			*Degraded*		
DV	*LF*	*HF*	*FE*	*LF*	*HF*	*FE*
RT						
Unrelated	619	607	12 [0, 24]	802	771	31 [18, 44]
Related	599	584	15 [6, 24]	750	739	11 [−1, 23]
PE	20 [10, 30]	23 [13, 33]		52 [34, 70]	32 [14, 50]	
ERR						
Unrelated	.01	.01	.00 [−.01, .01]	.03	.02	.01 [−.01, .03]
Related	.00	.00	.00 [−.01, .01]	.03	.02	.01 [−.01, .03]
PE	.01 [.00, .02]	.01 [.00, .02]		.00 [−.02, .02]	.00 [−.02, .02]	

Note: DV = dependent variable; RT = mean reaction time (in ms); ERR = mean proportion of errors. LF = low frequency; HF = high frequency; FE = frequency effect; PE = priming effect. The 95% confidence intervals for the frequency and priming effects are reported within brackets.

with previous investigations conducted on the same pool of participants (Yap, Tse, & Balota, 2009).[3] Separate analyses revealed that the overadditive interaction between frequency and context was significant for degraded targets [$F_1(1, 31) = 5.06$, $MSE = .023$, $p < .05$; $F_2(1, 158) = 4.39$, $MSE = .061$, $p < .05$], but not for the clear targets (Fs < 1). Most important, the three-way interaction among SQ, word frequency, and prime relatedness was significant: $F_1(1, 31) = 4.61$, $MSE = .02$, $p < .05$; $F_2(1, 158) = 4.26$, $MSE = .047$, $p < .05$. Planned comparisons indicated that the frequency by SQ interaction was significant for the unrelated priming condition [$F_1(1, 31) = 5.52$, $MSE = .022$, $p < .05$; $F_2(1, 158) = 5.57$, $MSE = .054$, $p < .05$], but not for the related priming condition (Fs < 1).

Accuracy

There were significant main effects of SQ [$F_1(1, 31) = 10.92$, $MSE = .002$, $p < .001$; $F_2(1, 158) = 28.60$, $MSE = .002$, $p < .001$] and word frequency in the subjects analysis only [$F_1(1, 31) = 4.22$, $MSE = .001$, $p < .05$; $F_2(1, 158) = 2.61$, $MSE = .002$, $p > .1$]. None of the remaining effects or interactions were significant.

Distributional analyses

Our hypothesis is that the additive and overadditive effects of word frequency and SQ obtained in this experiment are due to the fact that participants are relying relatively more on prime information in order to capitalize on all the sources of information useful to recognize difficult items (i.e., low-frequency degraded words). The reaction time distributions as a function of condition can be used to assess this hypothesis. Specifically, for the degraded targets in the unrelated condition, one would expect a larger frequency effect at the tail of the RT distribution. For clear targets, on the other hand, the presence of an unrelated prime should not be as detrimental, since these targets are processed relatively fluently. Finally,

[3] It is noteworthy that our data did not replicate the two-way interaction between the effects of semantic priming and frequency (the interaction was significant for degraded targets, but not for clear ones). However, it has been demonstrated that such an interaction does not always occur. Yap et al. (2009) examined the joint effects of frequency and semantic priming as a function of vocabulary knowledge (intended as a proxy for lexical proficiency) across different populations (undergraduate students from different universities). The results showed that the overadditive frequency by semantic priming interaction is statistically significant only for participants that scored relatively low on vocabulary knowledge. For participants who had a high score in vocabulary knowledge, frequency and semantic priming had additive effects. These results suggest that participants differentially rely on contextual information provided by the prime, depending on how fluent they are in processing the target. Consistent with the present results, participants from the same population as the one of the present study (Washington University undergraduates) showed robust additive effects of priming and frequency.

for targets following related primes, we hypothesize that there should not be an increase in the frequency effect for the slowest bins in the degraded condition, because the related prime compensates for the increase in target difficulty.

Frequency effects as a function of SQ, prime relatedness and quintile are plotted in Figure 1 (see Appendix A for mean reaction times for each quintile in each condition of Experiment 1 and 2). As predicted, in the unrelated condition (upper half of the plot), degraded targets show a larger frequency effect at the slowest quintile. On the other hand, for targets following related primes (lower half), frequency exerts a comparable influence on clear and degraded targets, even for the slowest responses.

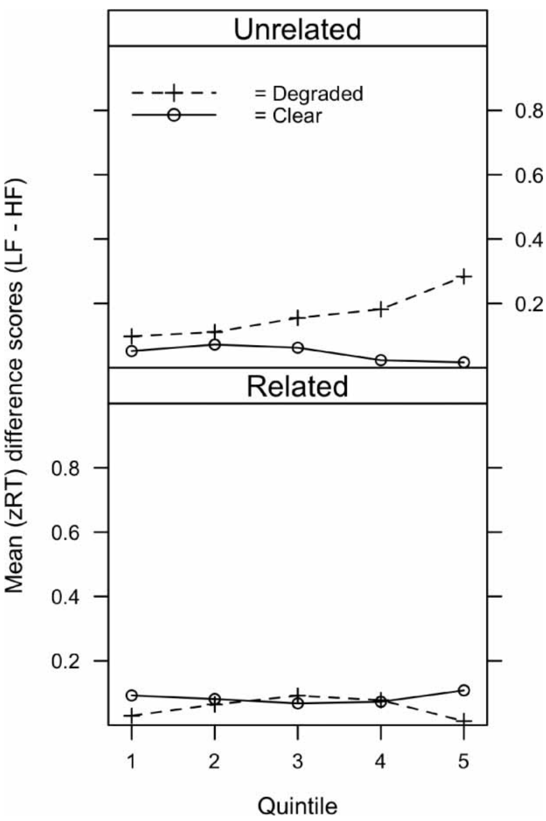

Figure 1. *Experiment 1: Difference in the quintile-means for low-frequency versus high-frequency words as a function of stimulus quality in words primed by unrelated primes (upper panel) and by related primes (lower panel). HF = high frequency. LF = low frequency. zRT = standardized reaction time.*

To test this directly, data in the slowest quintile were submitted to an ANOVA with prime relatedness, SQ, and word frequency as within-subject factors. The three-way interaction amongst these factors was significant, $F(1, 31) = 6.14$, $MSE = .085$, $p < .05$. Planned comparison revealed that the SQ by frequency interaction was reliable for unrelated trials, $F(1, 31) = 5.73$, $MSE = .099$, $p < .05$, but not for the related trials, $F(1, 31) = 1.19$, $MSE = .062$, $p > .2$.

Discussion

The results from Experiment 1 are clear: There was evidence of a three-way interaction among SQ, prime relatedness, and word frequency. Specifically, there were additive effects of SQ and word frequency following related primes, but clear interactive effects of the same variables following unrelated primes. Hence, we replicated the intriguing pattern observed by Borowsky and Besner (1993), and we extended their lexical decision results to speeded pronunciation, thus showing that this pattern is not task specific. Furthermore, the distributional results indicated that the three-way interaction was occurring for the slowest bins, precisely where the prime reliance account predicts. Thus, the present results are consistent with the notion that participants adaptively rely on prime information because (a) some trials involve relatively difficult-to-identify degraded low-frequency targets, and (b) the prime information can be especially helpful on such trials to facilitate processing of these difficult targets. The reliance on prime information produces both additive and interactive effects of word frequency and SQ within the same experiment, depending upon the utility of the prime information.

Experiment 2 was conducted to test directly a specific prediction derived from the prime reliance account. The main assumption of this account is that prime reliance is driven by list composition—that is, by the presence of useful related prime stimuli that might support the processing of difficult items. If the presence of related primes induced this strategy, the absence of related primes should eliminate it. Therefore, in Experiment 2, we replaced the related primes with unrelated primes such that participants only received unrelated prime–target pairs. Because there will be no utility of prime information when all primes are unrelated, if the prime reliance account is correct, then the overadditive effects of SQ and word frequency following unrelated primes observed in Experiment 1 should turn to additive effects in Experiment 2.

EXPERIMENT 2

Method

Participants

Thirty-two undergraduate students from the Washington University in St. Louis participated for course credit. All were native English speakers and reported normal or corrected-to-normal vision. None had participated in Experiment 1.

Design

The design was the same as that in Experiment 1, except that there was no manipulation of prime context. All targets were preceded by unrelated primes.

Stimuli, apparatus, and procedure

The stimuli consisted of the same targets (160 words and 160 nonwords) and unrelated primes as those used in Experiment 1, along with identical apparatus and procedure.

Results

Errors (3.63%) and voice-key failures (3.38%) were first removed from the analyses. The remaining data were submitted to the same recursive data trimming procedure as that used for Experiment 1, resulting in the removal of a further 1.8% of the data. Reaction times were again transformed to within-participant z scores for the ANOVAs.

Response latencies

Mean response latencies and proportion of errors as a function of condition are displayed in Table 3. There were main effects of SQ [$F_1(1, 31) = 280.12$, $MSE = .1$, $p < .001$; $F_2(1, 158) = 1{,}912.62$, $MSE = .036$, $p < .001$] and word frequency [$F_1(1, 31) = 19.32$, $MSE = .013$, $p < .001$; $F_2(1, 158) = 6.90$, $MSE = .09$, $p < .05$]. Critically, the interaction between the two variables did not approach significance (Fs < 1).

Accuracy

The main effect of SQ was significant, $F_1(1, 31) = 7.85$, $MSE = .002$, $p < .01$; $F_2(1, 158) = 34.11$, $MSE = .001$, $p < .001$. No other effects were significant.

Distributional analyses

Figure 2 displays the frequency effect for clear and degraded conditions across the quintiles. In contrast to Experiment 1, following the unrelated primes, there was no hint of an interaction between SQ and word frequency for the slowest quintile ($F < 1.00$) for the very same unrelated prime–target pairs.

Cross-experiment analysis

To further examine the different patterns of results following the same unrelated prime–target pairs in

Table 3. Mean reaction times and mean proportion of errors as a function of context, target frequency, and stimulus quality in Experiment 2

	Clear			*Degraded*		
DV	*LF*	*HF*	*FE*	*LF*	*HF*	*FE*
RT	606	590	16 [10, 22]	767	756	11 [−1, 23]
ERR	.01	.01	.00 [−.01, .01]	.03	.02	.01 [−.01, .03]

Note: DV = dependent variable; RT = mean reaction time (in ms); ERR = mean proportion of errors. LF = low frequency; HF = high frequency; FE = frequency effect; PE = priming effect. The 95% confidence intervals for the frequency and priming effects are reported within brackets.

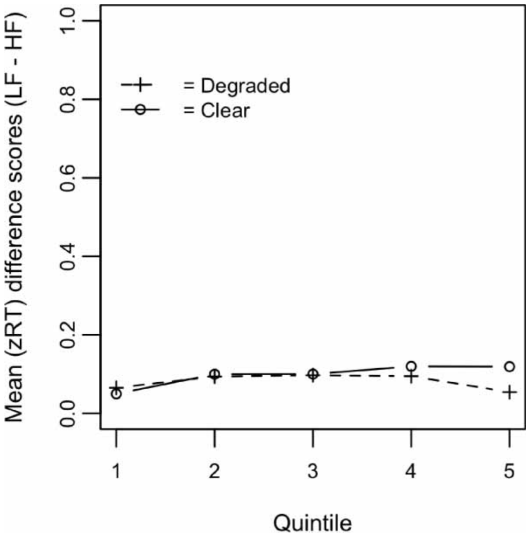

Figure 2. *Experiment 2: Difference in the quintile-means for low-frequency versus high-frequency targets as a function of stimulus quality. HF = high frequency. LF = low frequency. zRT = standardized reaction time.*

Experiments 1 and 2, we conducted an ANOVA with experiment, word frequency, and SQ as factors. As predicted, the three-way interaction was reliable [$F_1(1, 62) = 4.34$, $MSE = .018$, $p < .05$; $F_2(1, 158) = 6.08$, $MSE = .035$, $p < .05$], strengthening the argument that the presence of related primes within the list in Experiment 1 modulated the presence of overadditive or additive effects of SQ and word frequency.

GENERAL DISCUSSION

The present study yielded three important patterns regarding the theoretically important joint effects of SQ and word frequency. First, both overadditive and additive effects were found in Experiment 1, with additive effects being observed following related primes and overadditive effects following unrelated primes. Second, in contrast to Experiment 1, additive effects of SQ and word frequency were found in Experiment 2 for the same unrelated prime–target pairs when no related prime–target pairs appeared in the stimulus list. Third, the above two observations were primarily obtained in the slowest quintiles, wherein the most difficult targets were represented.

The present results suggest that participants adaptively rely on prime information when it is useful to identify degraded targets, thereby modulating the presence/absence of the additive effects of SQ and word frequency. First, consider the results from Experiment 1. We argue that the degree of influence of related primes is dependent on their utility in identifying the target. This utility is especially great for the most difficult targets—that is, the low-frequency degraded targets. Hence, mean response latency for the low-frequency degraded targets is particularly facilitated, thereby eliminating the overadditive interactive pattern between SQ and word frequency. In contrast, when the prime was not useful (i.e., the prime was unrelated to the target), the processing of difficult items—that is, the low-frequency degraded words—was disrupted by the failure to find a relationship following unrelated primes, thereby contributing to an overadditive interaction. This hypothesis was supported by the distributional features of the frequency effect as a function of SQ. Specifically, the overadditive pattern was particularly evident in the slowest quintiles—that is, for the slowest targets.

Importantly, the results of Experiment 2 nicely converge on the prime reliance account. Specifically, because related primes were no longer present in Experiment 2, there was no utility of the prime information to facilitate processing of low-frequency difficult targets, thereby eliminating prime reliance. Hence, the overadditive effects of frequency and SQ observed in Experiment 1 following unrelated trials reverted to additive effects for the very same prime–target pairs.

Although Borowsky and Besner (1993) did not focus on the interactive effects of word frequency and SQ in the context of unrelated primes, the present results provide a clear replication and extension of the pattern they obtained in lexical decision performance. That is, both overadditive and additive effects can be observed within the same experimental context. Critically, as noted earlier, the additive effects of SQ and word frequency are difficult to accommodate within standard interactive activation accounts of visual word recognition, and the present results pose a particular challenge to such models by showing that the Borowsky and Besner pattern is not task specific.

Recently, Robidoux, Stolz, and Besner (2010) have advanced a proposal that reconciles aspects of Borowsky and Besner's (1993) original results (additive effects of SQ and frequency following nonword primes and overadditive effects following unrelated trials) within an interactive activation framework. According to the authors, the pattern is due to the lexicality of the prime acting as a local (i.e., trial-by-trial) control factor on the activation dynamics. More precisely, the system will operate in a serial fashion (by placing a threshold at the letter-level processing stage) when the prime is a nonword, while it operates with cascaded and interactive activation when the prime is a real word. Although this account is consistent with the pattern obtained with nonwords (additive) and unrelated primes (interactive) in the original Borowsky and Besner results, at first glance it cannot accommodate the additive pattern obtained following related primes: Since related primes are "words", interactive effects should have also been found for these items. However, it is important to note that, in the presence of semantically related primes, the feedback from semantics to the orthographic lexicon (see Besner & Smith, 1992; Borowsky & Besner, 1993; Stolz & Neely, 1995) may exert a dampening effect on the SQ by frequency interaction, thus making less clear what pattern one might predict for this condition.[4] For the present experiments, the critical factor appears to have been the list-level presence of related primes. Specifically, the overadditive pattern following unrelated primes only occurred when related trials were also present in the list (Experiment 1) and became additive once related primes were removed from the list (Experiment 2). Thus, in addition to trial-by-trial control parameters, the present results suggest a list-wide control parameter.

It is noteworthy that list-wide variables have previously been shown to play an important role in shaping the joint effects of SQ and semantic priming. For example, Stolz and Neely (1995) found that the overadditive interaction of frequency and semantic priming obtained for lexical decisions occurs only when the relatedness proportion (the proportion of trials in which the prime–target pair is semantically related) is high. When the relatedness proportion is low, additive effects of SQ and priming are found (for replications in pronunciation see Ferguson, Robidoux, & Besner, 2009). Clearly, participants are sensitive to list-wide control parameters.

The prime reliance account is also consistent with recent arguments by Bodner and Masson (Bodner & Masson, 1997, 2001, 2003, 2004; Bodner, Masson, & Richards, 2006; Masson & Bodner, 2003; see also Whittlesea & Jacoby, 1990). These authors argue that in semantic priming experiments, the prime is encoded as an episodic representation that can be retrieved to facilitate target identification. Critically, such retrieval is a function of prime utility: It will occur only when the payoff is high (e.g., when the relatedness proportion is high). In the present first experiment, the presence of degraded low-frequency targets clearly produces difficulty in lexical processing, and so the utility of using the prime would be relatively high. When confronted with degraded stimuli, the system should recruit information from available sources (the primes), provided that these primes have been useful on previous trials—that is, a list-wide context effect. This would produce the strongest benefit for the most difficult targets following related primes, yielding the additive patterns of word frequency and SQ, and the overadditive effects of word frequency and SQ following unrelated primes. Of course, when the prime stimulus is no longer useful for target recognition, the system reverts back to additive effects of word frequency and SQ, as in Experiment 2.

Interestingly, a recent study by Thomas et al. (2012) has shown that a specific type of prime reliance may indeed be a major mechanism underlying the SQ by semantic priming interaction. These authors assessed the presence of this interaction as a function of the direction of the associative link between primes and targets. They compared prime–target pairs with strong backward association and no forward association (e.g., SMALL–SHRINK), pairs with strong forward association and no backward association (e.g., KEG–BEER),

[4] We thank Serje Robidoux for pointing this out.

and pairs with a symmetrical association strength (e.g., EAST–WEST) in both pronunciation and lexical decision tasks. The results from both experiments indicated that when there is only a forward association between prime and target, no hint of overadditivity is found. In contrast, when a backward association from the target to the prime is available, a robust overadditive interaction is found. Moreover, the magnitude of the overadditive interaction produced by symmetrically associated prime–target pairs is comparable to that produced by prime–target pairs where just a backward association occurs. Taken together, these findings strongly suggest that the SQ by semantic priming overadditive interaction is mediated by a retrospective mechanism, rather than by preactivation of the targets' representation by the primes. Our prime–target pairs were not selected to test for the role of backward association strength directly, since prime–target pairs contained both forward and backward association. On the other hand, in order to explain the present results we propose a mechanism similar to the one outlined by Thomas and colleagues (2012; see also Balota et al., 2008). That is, target degradation triggers the retrieval of local prime information. The system relies on this information depending upon the difficulty of target processing.

The Thomas et al. (2012) study nicely demonstrates a specific prime retrieval mechanism underlying the SQ by priming interaction. However, the present results could also be viewed as consistent with a more general compensatory activation account proposed by Stanovich and West (1983; see also Stanovich, 1980; Stanovich & West, 1979, 1981). According to this perspective, difficulty in lexical processing produced by degrading targets can trigger greater reliance on prime information. Although the general compensatory mechanism was developed primarily with sentence processing, the extension of this general mechanism of increased top down compensation for difficult-to-process targets is clearly within the spirit of the current account.

Finally, an interesting question arises when one considers the size of the frequency effect across experiments. The current hypothesis is that one finds additive effects of frequency and degradation following related primes in Experiment 1 due to the fact that the presence of related primes engages a top-down influence, which is particularly beneficial for low-frequency degraded targets that are related to the prime. However, if that is the case, then one might expect an overall smaller frequency effect in the related conditions of Experiment 1 than in the unrelated conditions of Experiment 2, with RTs to low-frequency degraded targets yielding a relatively greater speed-up following the related primes in Experiment 1 than following the unrelated primes of Experiment 2.[5] Although this pattern occurred across the related and unrelated conditions within Experiment 1, it did not occur when comparing the related conditions of Experiment 1 to the unrelated conditions of Experiment 2. So, although it is the case that the unrelated prime condition produces a relative slow-down in the degraded low frequency condition (comparing the unrelated vs. related prime conditions in Experiment 1), it does not appear that the related condition produces a relative facilitation in the degraded low-frequency condition (comparing the related prime conditions of Experiment 1 to the unrelated prime conditions of Experiment 2).

How might one reconcile this pattern? We would argue that the presence of related primes in Experiment 1 and their absence in Experiment 2 produced qualitatively different types of processing. Specifically, as Robidoux et al. (2010) have argued, the conditions of Experiment 1 are more likely to produce cascaded interactive processing, whereas as O'Malley and Besner (2008) have argued, the conditions of Experiment 2 are more likely to produce letter-thresholded processing. To further evaluate our hypothesis that related primes produce a larger benefit for the most difficult items, we examined the reaction distributional analyses. One would predict that the priming effect would be greater for the most difficult items—that is, those items at the slowest quintiles. Moreover, this increase across quintiles should be larger for low-frequency words than for high-frequency words. Figure 3 displays the priming effects for the degraded conditions as a

[5] We thank Jim Neely for pointing this out.

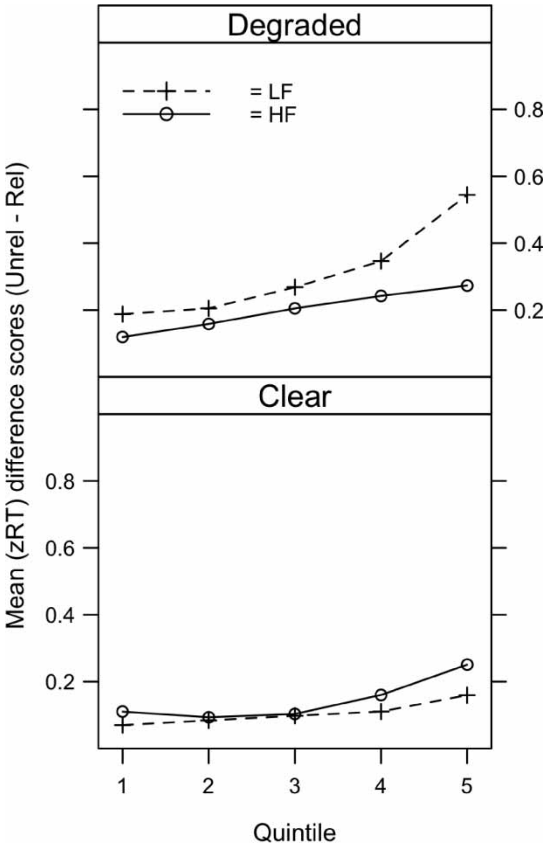

Figure 3. *Experiment 1: Difference in the quintile-means for unrelated versus related trials as a function of frequency in visually degraded (upper panel) and clear (lower panel) target words. HF = high frequency. LF = low frequency. zRT = standardized reaction time. Unrel = unrelated. Rel = related.*

function of word frequency across quintile. As shown, there is an increasing priming effect across quintiles that is indeed larger for the low-frequency words than for the high-frequency words. This is consistent with our suggestion that the related primes are particularly beneficial for the difficult, degraded, low-frequency targets, thereby contributing to the additivity following these items. Thus, we would argue that the present results are consistent with the accumulating evidence that individuals rely on prime information more under conditions in which the target is degraded (see Balota et al., 2008; Thomas et al., 2012). However, the present data clearly are not able to offer a definitive answer in that they do not rule out the possibility that the pattern is produced solely by unrelated primes interfering more with the processing of degraded low-frequency targets (rather than by both this mechanism *and* a greater facilitation for low-frequency degraded targets by related primes). One potential way to address this issue would be to rerun Experiment 1 adding a baseline condition to separate inhibitory unrelated priming effects from facilitatory related priming effects. Of course, this requires that one can create a truly neutral baseline condition to measure facilitation and inhibition, which is extremely difficult if not impossible to accomplish (see Jonides & Mack, 1984, for a discussion of this issue).

CONCLUSIONS

The present results underscore the adaptive flexibility of the lexical processing system to list-level contextual factors by showing that an increased reliance on primes is adopted primarily for difficult stimuli (i.e., degraded, low-frequency words), and only in certain conditions (i.e., when some primes in the experimental list are useful). The notion is that the system, while attempting to fulfil the goals of the task, modulates its control parameters to exploit all useful sources of information. Such a modulation could be accomplished via an attentional control system that would bias different modes of processing, according to task demands (e.g., Balota & Yap, 2006; Pohl, Kiesel, & Kunde, 2010; Vachon & Jolicœur, 2011). In this light, it is interesting to note that the stimulus onset asynchrony in the present study was only 200 ms, which has typically been viewed as reflecting more automatic influences of the prime (e.g., Neely, 1977). Apparently, these control parameters can be adjusted even at very short prime–target stimulus onset asynchronies.

The present results add an important finding to a growing literature that suggests that the reading system easily adapts to the goals of a task and that this has considerable influence on the theoretically important joint effects of SQ and word frequency. This literature has shown that the joint effects of these variables changes as a function of:

(a) experimental task (Yap & Balota, 2007); (b) type of nonwords included in a lexical decision task (Yap et al., 2008); (c) participants' lexical proficiency (Yap et al., 2008); and (d) presence versus absence of nonwords in a pronunciation task (O'Malley & Besner, 2008). The present results add (e) the relatedness of the primes within an experiment and the overall list structure to this list. These results are all quite consistent with the notion of an adaptive flexible lexical processor.

Original manuscript received 1 March 2012
Accepted revision received 23 May 2012
First published online 21 August 2012

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APPENDIX A

Mean reaction times for quintiles in Experiment 1 and Experiment 2 as a function of prime relatedness, stimulus quality, and frequency

Experiment	*Condition*	*Quintile 1*	*Quintile 2*	*Quintile 3*	*Quintile 4*	*Quintile 5*
Experiment 1	RCL	497	554	596	646	737
	RCH	479	538	581	622	696
	RDL	621	699	754	823	951
	RDH	601	673	720	784	908
	UCL	506	568	609	653	747
	UCH	493	552	592	636	721
	UDL	639	715	778	856	1006
	UDH	621	699	754	823	951
Experiment 2						
	UCL	508	566	599	641	716
	UCH	501	550	583	621	695
	UDL	625	697	753	816	945
	UDH	616	682	737	803	939

Note: Mean reaction times in ms. The three-letter labels describe conditions as follows. The first letter refers to prime relatedness: R = related and U = unrelated. The second letter codes for visual quality: C = clear and D = degraded. Finally, the third letter denotes frequency: L = low and H = high.