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The influence of relatedness proportion on the joint relationship among word frequency, stimulus quality, and semantic priming in the lexical decision task

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Abstract

In the lexical decision task, the additive effects of stimulus quality and word frequency have been used to infer the presence of independent processing stages in visual word recognition. Importantly, this pattern can be moderated by semantic priming, suggesting the presence of a retrospective prime retrieval mechanism that is selectively engaged based on task context (i.e., utility of the primes). We examine the sensitivity of this mechanism in two lexical decision experiments that manipulate stimulus quality, word frequency, and semantic priming. Critically, we studied these joint effects when the proportion of related primes was set at .50 or .25. Results indicated that with a .50 relatedness proportion, a three-way interaction was obtained such that additivity between frequency and stimulus quality was found following related semantic primes, but an overadditive pattern was exhibited following unrelated primes. When the relatedness proportion was reduced to .25, this interaction was eliminated. Furthermore, relatedness proportion affected the magnitude of the stimulus quality by priming interaction but not the frequency by priming interaction. These results are interpreted within the context of a flexible lexical processer that adaptively engages processes in response to task context.

Keywords

Semantic priming; word frequency; stimulus quality; lexical decision

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Response times (RTs) have historically played a key role in inferring the structure, order, and duration of fundamental cognitive processes (Luce, 1986). In a seminal series of experiments, Sternberg (1969) pioneered the use of additive factors logic to probe the sequence of mental operations involved in short-term memory scanning. According to additive factors, two variables that produce significant main effects on RT but do not interact (i.e., are additive) influence separate processing stages, whereas an interaction would indicate an influence on a shared stage. For example, Sternberg administered a short-term memory scanning task in which participants studied short lists of numbers followed by a probe item. They were to determine whether or not the probe was contained in the array that was just studied. Two factors were manipulated: the size of the memory set to be studied and the quality of the probe (either presented in the clear or perceptually degraded). Critically, both increasing set size and stimulus degradation slowed RT, but the two factors did not interact. Based on this pattern of results, Sternberg inferred the presence of two independent stages: an initial "clean-up" process in which the degraded stimulus is first normalised followed by a scan of short-term memory.

Interestingly, in contrast to sequential stages, the currently most successful models of visual word recognition include some degree of cascaded processing (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Grainger & Jacobs, 1996; Perry, Ziegler, & Zorzi, 2007) because they are based at their core on the interactive activation (IA) framework (McClelland, 1987; McClelland & Rumelhart,

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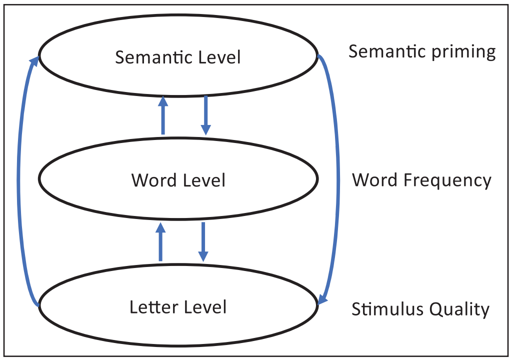

Figure 1. Illustration of an interactive activation model with three levels. Variables that affect each level are listed.

1981). According to IA, language processing consists of multiple processing levels, with excitatory activity flowing in both directions across the different levels. For ease of discussion, we will consider an IA model that includes three levels (see Figure 1), the letter level, the word level, and the semantic level (Stolz & Besner, 1998; Yap, Balota, & Tan, 2013), although other levels (such as morphological) are certainly possible and indeed likely. This hypothesised model can be evaluated by examining the joint influence of different factors that are thought to influence a specific level of processing. Two of the most well-studied variables in visual word recognition are *word frequency* (responses are faster for words that occur frequently in the language), which affects the word level, and *semantic priming* (responses are faster for targets that are preceded by a related word), which influences the semantic level. It has been repeatedly shown that word frequency and priming interact overadditively (such that there is more priming for low-frequency targets; Becker, 1979; Plaut & Booth, 2000). Such a pattern can be accommodated within the IA framework by the feedback from the semantic system to the lexical system, which disproportionally facilitates the more difficult, low-frequency words.

In the same manner, the IA model would also predict an interaction between priming and a variable that affects the letter level, for example, *stimulus quality* (SQ: responses to perceptually clear targets are faster than responses to targets that are degraded). Indeed, it has repeatedly been shown that priming is stronger for visually degraded targets (Becker & Killion, 1977; Meyer, Schvaneveldt, & Ruddy, 1975). This effect can again be accommodated by the notion that feedback from the semantic layer disproportionately facilitates the perceptually degraded items at the letter level. An interesting conundrum arises, however, when one considers the joint effects of word frequency and SQ. The IA framework would again predict an interaction wherein feedback from the word level would facilitate recognition of degraded words at the letter level; however, this pattern has not been found. Indeed, word frequency and SQ have been shown to be robustly additive, at least in the lexical decision task (LDT; Becker & Killion, 1977; Plourde & Besner, 1997; Yap & Balota, 2007). According to additive factors logic, this additivity implies processing at the letter level is kept separate from processing at the word level, yet activity at the semantic level is clearly interactive with both.

How can this pattern be reconciled with the IA framework? One option is to assume that word recognition is not a modular process but instead changes and adapts according to ongoing task demands. That is, the degree to which communication among processing levels is interactive or discrete may be influenced by the structure of the task and/or individual differences. Indeed, several converging lines of evidence suggest this to be the case. For example, the "problematic" additive relationship between word frequency and SQ is task-specific, appearing only in the LDT but not in speeded word naming, in which participants read words aloud (Yap & Balota, 2007). However, O'Malley and Besner (2008) further showed that additivity is also obtained in the word naming task when nonword stimuli are included in the list, a finding which they interpreted as evidence of cascaded processing between orthographic and lexical representations when the stimulus list includes only words (thus producing a statistical interaction), but thresholded processing when nonwords are also presented (resulting in additivity). Importantly, this indicates that spread of activity across processing levels can be modulated by the list context.

Stolz and Neely (1995) demonstrated that the interactive relationship between semantic priming and SQ, typically thought to arise as a consequence of feedback from the semantic system facilitating the processing of degraded stimuli, becomes additive when the proportion of related primes is reduced from the typical .50 to .25. Again, one interpretation of this finding is that interactive feedback from the semantic layer to the letter layer can be selectively engaged (or disengaged) based on the overall utility of the primes. Thus, when the majority of primes are unrelated and therefore are not useful, semantic feedback to letter-level representations is constrained or throttled, yielding the additive relationship.

As mentioned, most of the prior work in this domain has involved factorial studies that manipulate two of the three critical variables. Given the evidence that processing dynamics can vary depending on task context, it is possible the additive effects of SQ and word frequency will become interactive once semantic priming is also manipulated in the same task (Borowsky & Besner, 1993; Masson & Kliegl, 2013; Scaltritti, Balota, & Peressotti, 2013). In other words, activity between the letter and word levels may become interactive when related context (in the form of semantic primes) is provided. To address this question, Borowsky and Besner (1993) used three types of semantic primes (related, unrelated, and nonwords) together with a manipulation of word frequency and SQ. Importantly, their results showed that when the relationship between frequency and SQ was assessed following a nonword prime, additivity between these two factors was obtained. This finding suggests the additive effects of frequency and SQ are not modulated by the presence of primes.

However, it is important to keep in mind that Borowsky and Besner (1993), going with Neely's (1991) recommendation, assessed the additive relationship only following nonword primes. Based on visual inspection, there actually appears to be an interaction between frequency and SQ following *unrelated* word primes, such that there was a larger effect of frequency for degraded stimuli. Scaltritti et al. (2013) followed up on this observation and extended the pattern to the speeded word naming task. These authors provided statistical evidence for a three-way interaction such that the standard additive relationship between word frequency and SQ was found following related semantic primes, but the same variables significantly interacted following unrelated primes, which is consistent with Borowsky and Besner (1993). Scaltritti et al. (2013) inferred the presence of a retrospective prime retrieval[1] mechanism which becomes increasingly dependent on the prime context as targets become more difficult to resolve.

The prime retrieval mechanism works as follows. Consider the scenario when the prime context is *not* useful (i.e., prime and target are unrelated). Here, the attempt to retrieve the prime in the most difficult condition (i.e., low-frequency degraded targets) is disrupted by the failure to find a relationship between the prime and the target. This results in disproportionately slow responses to low-frequency degraded targets, yielding the overadditive SQ × Frequency interaction. In contrast, when the prime context *is* useful (i.e., prime and target are related), prime retrieval especially facilitates the recognition of low-frequency degraded targets, thereby abolishing the overadditive interaction described earlier.

More importantly, in a second experiment, Scaltritti et al. (2013) removed the related primes from the list and showed that following the same unrelated prime–target pairs as the initial experiment, there was now robust additivity between SQ and frequency. How can one explain this? Given that an interaction between these variables is the signature of the retrospective prime retrieval mechanism, this pattern suggests that participants become tuned to task context (i.e., the proportion of related primes) and selectively retrieve the prime word *only* when there is sufficient incentive for them to do so (see Thomas, Neely, & O'Connor, 2012, for additional direct evidence that this process is retrospective). The prime retrieval mechanism also accommodates the additive effects of SQ and priming (Stolz & Neely, 1995) in the .25 relatedness proportion (RP) condition, as participants could learn the prime is not useful on the majority of trials. In addition, retrospective prime retrieval can account for the additivity of SQ and frequency following nonword primes in Borowsky and Besner (1993) as a nonword cannot, by definition, provide a contextual benefit, and thus, participants do not retrieve the prime on these trials.

Finally, although not the primary focus of their study, Masson and Kliegl (2013) also provide data that support the prime reliance account. Specifically, they manipulated word frequency, SQ, and priming in a large lexical decision study, with a key difference being they used prime–target pairs that had a relatively low associative strength. Despite the study being well powered, they obtained no evidence of an interaction between SQ and frequency or of a three-way interaction among all three variables. Therefore, even though half of the trials were preceded by a related prime, the fact that those primes were only minimally related to the target potentially prompted participants not to retrieve the prime, which thus produced additivity between SQ and word frequency.

The important point from this growing literature is that list-wide and contextual factors (e.g., RP) support the notion of a flexible lexical processor that can adaptively engage specific processes to optimally meet task demands (Balota & Yap, 2006). In this article, we aim to further explore the flexibility of this processor and examine how the manipulation of a list-wide variable influences communication across three levels of processing (letter, lexical, semantic) within a single experiment. We do this by replicating and extending prior experiments that have manipulated SQ, word frequency, and semantic priming in two lexical decision experiments. The experiments were identical to one another, with the exception that the proportion of related primes varied (from .50 in Experiment 1 to .25 in Experiment 2). Our study has three primary goals. First, we extend the Scaltritti et al. (2013) results to the LDT. Such an extension is critical as the LDT is known to be subject to task-specific processes (e.g., Yap & Balota, 2007) and thus may mask or reveal novel mechanisms. Second, Scaltritti et al. completely removed all related primes in their second experiment to eliminate the three-way interaction, presumably due to the lack of engagement of the prime retrieval mechanism. We will address the sensitivity of this mechanism to contextual factors by reducing (rather than entirely eliminating) the proportion of related primes. It is possible that the prime retrieval mechanism will operate as long as there is *any* useful information to be gleaned from the environment. Our final goal was to further probe the intriguing moderation of the SQ by priming relationship as a function of RP. Specifically, we wanted to assess whether the feedback between semantic (priming) and lexical (word frequency) levels is modulated by RP in the same manner as semantic and letter (SQ) levels as shown by Stolz and Neely (1995). In this regard, we expect the interaction between priming and frequency to also be moderated by RP.

Experiment 1

Method

Participants. In total, 207 participants were recruited from the undergraduate research participant pool at the National University of Singapore. All had normal or corrected-to-normal vision and participated in exchange for course credit or payment. Fifteen participants were excluded because their mean RTs exceeded 1,000 ms and/or their mean accuracy rate was below 80%, leaving 192 participants available for analysis.

Stimuli and procedure. We used the Nelson, McEvoy, and Schreiber (2004) norms to select 240 symmetric prime–target pairs (e.g., CAT–DOG) that possessed strong and relatively similar forward (prime-to-target) and backward (target-to-prime) association strengths. There were 120 high-frequency targets and 120 low-frequency targets; these were closely matched on a variety of important characteristics (see Table 1). Items were degraded by rapidly alternating the target item with a string of non-alphanumeric characters (#@&%*). Lists were constructed such that each word target appeared once in each of the SQ (clear vs. degraded) by priming (related vs. unrelated) cells; unrelated prime–target pairs were created by randomly re-pairing primes and targets. Nonwords were generated using the Wuggy software (Keuleers & Brysbaert, 2010) and were counterbalanced across SQ conditions.

PC-compatible computers running E-prime software (Schneider, Eschman, & Zuccolotto, 2012) were used to present stimuli and collect data. Participants were tested individually in sound-attenuated cubicles, sitting approximately 60 cm from the screen. They were instructed to classify letter strings as words or nonwords using the appropriate buttons (apostrophe key for words and A key for nonwords). There were 20 practice trials, followed by eight blocks of 60 trials, with optional breaks between blocks. Stimuli were presented in uppercase 14-point Courier New; primes were in uppercase, whereas targets were in lowercase. All stimuli were presented in white against a black background. Each trial began with a fixation point (+) for 350 ms, followed by a 150-ms prime and another blank screen for 650 ms before the target appeared; this yielded a stimulus onset asynchrony of 800 ms. The target then remained on screen for 4,000 ms or until a response was made. For incorrect responses, a 170-ms tone was played with the target word "Incorrect" displayed in red slightly below the fixation point. All procedures were approved by the National University of Singapore Institutional Review Board (A-14-175), and all participants provided verbal informed consent.

Table 1. Characteristics of items used in Experiments 1 and 2.

Variable	LF	HF	*t* value	*p* value
Primes				
Length	5.21	5.11	0.503	.615
Log SUBTLCD	2.62	3.29	−9.72	<.001
Orth. N	4.00	4.10	−0.18	.861
Phon N.	8.87	10.02	−0.91	.364
OLD20	1.91	1.81	1.34	.181
PLD20	1.74	1.67	0.73	.468
No. of syllables	1.62	1.51	1.26	.211
No. of morphemes	1.21	1.25	−0.66	.508
Targets				
Length	5.35	5.14	1.11	.270
Log SUBTLCD	2.58	3.50	−22.31	<.001
Orth. N	4.27	4.53	−0.42	.674
Phon N.	9.46	10.49	−0.80	.427
OLD20	1.89	1.81	1.21	.227
PLD20	1.69	1.62	0.86	.390
No. of syllables	1.55	1.47	1.05	.294
No. of morphemes	1.26	1.23	0.43	.668
FAS	0.42	0.44	−1.07	.288
BAS	0.40	0.40	−0.30	.764

Log SUBTLCD: log-transformed contextual diversity measure based on subtitles of English films and TV series; Ortho N: number of orthographic neighbours based on a one-letter substitution rule; Phon N.: number of phonological neighbours based on a one-phoneme substitution rule; OLD20: orthographic Levenshtein distance 20, the average of the closest 20 "neighbors" Levenshtein distance which is the minimum number of substitutions, additions, or deletion required to transform one string into another; PLD20: phonological Levenshtein distance 20; FAS: forward associative strength, which is the probability of producing the target given the prime; BAS: backward associative strength, which is the probability of producing the prime given the target.

Results

RT and accuracy to word targets were analysed using analysis of variance (ANOVA) across both participants and items (reported as F_1 and F_2 statistics). In the analysis by subjects, priming, SQ, and frequency served as within-subject factors, and in the items analysis, priming and SQ were within-item factors and frequency was between items.

To avoid the undue influence of outliers in the RT analysis, we implemented the following trimming procedure. First, error trials were removed, followed by any trial that was faster than 200 ms or slower than 3,000 ms. Finally, we removed any RT that was greater than 3 standard deviations from the mean of each degradation condition per subject. This removed an average of 2.8% of the total responses. Finally, we *z*-scored each participant's RT to their individual mean and standard deviation, which has been shown to reduce Type I errors when there are differences in baseline RT across participants or conditions (Faust, Balota, Spieler, & Ferraro, 1999; Hutchison, Balota, Cortese, & Watson, 2008). The mean *z*-scored RTs for each condition and participant served as the primary dependent variable for the ANOVAs. We provide descriptive statistics of the raw RTs in the Supplementary Material for the interested reader.

Table 2. Mean z-scored reaction time and accuracy per condition in Experiment 1.

	Clear			Degraded		
	LF	HF	FE	LF	HF	FE
z-scored RT						
Unrelated	−0.151	−0.316	0.165	0.582	0.333	0.249
Related	−0.309	−0.458	0.150	0.267	0.102	0.165
PE	0.158	0.142		0.314	0.231	
Accuracy						
Unrelated	0.977	0.991	−0.014	0.947	0.980	−0.033
Related	0.982	0.993	−0.011	0.973	0.990	−0.017
PE	−0.005	−0.003		−0.026	−0.010	

PE: priming effect, FE: frequency effect.

z-scored RT analysis. The mean RTs for each condition are presented in Table 2. The ANOVA revealed large and significant effects of priming ($F_1(1, 191) = 311.38$, $p < .001$, ges = .22; $F_2(1, 238) = 370.31$, $p < .001$, ges = .16), SQ ($F_1(1, 191) = 1{,}551.08$, $p < .001$, ges = .72; $F_2(1, 238) = 3{,}306.54$, $p < .001$, ges = .63), and word frequency ($F_1(1, 191) = 355.01$, $p < .001$, ges = .17; $F_2(1, 238) = 56.34$, $p < .001$, ges = .14).

As expected, the SQ by priming interaction was reliable ($F_1(1, 191) = 45.92$, $p < .001$, ges = .02; $F_2(1, 238) = 49.22$, $p < .001$, ges = .02), indicating that priming was larger for degraded targets compared with clear targets. In addition, there was a significant interaction between frequency and priming ($F_1(1, 191) = 7.37$, $p = .007$, ges = .004; $F_2(1, 238) = 6.11$, $p = .014$, ges = .003), indicating larger priming effects for low-frequency, compared with high-frequency, words. Finally, there was an interaction between frequency and SQ such that there was a larger frequency effect for degraded, compared with clear, targets ($F_1(1, 191) = 7.55$, $p = .007$, ges = .004; $F_2(1, 238) = 6.16$, $p = .014$, ges = .003). Most importantly, these effects were qualified by a three-way interaction that approached significance ($F_1(1, 191) = 3.65$, $p = .06$, ges = .002; $F_2(1, 238) = 4.08$, $p = .04$, ges = .001).

We probed this interaction by conducting follow-up ANOVAs of the SQ by frequency interaction within levels of prime relatedness. The results showed that following related primes: the interaction between SQ and frequency was not significant ($F_1(1, 191) < 1$, $p = .55$, ges < .001; $F_2(1, 238) < 1$, $p = .50$, ges < .001), whereas the interaction was reliable following *unrelated* primes ($F_1(1, 191) = 10.80$, $p = .001$, ges = .010; $F_2(1, 238) = 9.12$, $p = .003$, ges = .008), indicating that the frequency effect was larger for degraded items but only following an unrelated prime.

Accuracy analysis. The ANOVA on proportion correct revealed a large main effect of priming ($F_1(1, 191) = 31.89$, $p < .001$, ges = .02; $F_2(1, 238) = 42.28$, $p < .001$, ges = .01), a main effect of SQ ($F_1(1, 191) = 62.72$, $p < .001$, ges = .04; $F_2(1, 238) = 74.72$, $p < .001$, ges = .02), and a main effect of word frequency ($F_1(1, 191) = 128.42$, $p < .001$, ges = .07; $F_2(1, 238) = 14.15$, $p < .001$, ges = .04). Furthermore, the interaction between SQ and priming was significant ($F_1(1, 191) = 25.57$, $p < .001$, ges = .01; $F_2(1, 238) = 27.12$, $p < .001$, ges = .01), indicating larger priming effects for degraded items. There was also a significant interaction between priming and frequency ($F_1(1, 191) = 9.84$, $p = .002$, ges = .004; $F_2(1, 238) = 8.56$, $p = .004$, ges = .003), such that priming was larger for low-frequency words. Finally, the interaction between SQ and frequency was reliable ($F_1(1, 191) = 24.21$, $p < .001$, ges = .008; $F_2(1, 238) = 16.52$, $p < .001$, ges = .005), reflecting larger frequency effects for degraded stimuli. Once again, the three-way interaction was also significant ($F_1(1, 191) = 5.56$, $p = .02$, ges = .002; $F_2(1, 238) = 6.73$, $p = .01$, ges = .001).

As before, we probed this interaction by analysing the SQ by frequency interaction separately for related and unrelated primes. This interaction was marginally significant following related primes ($F_1(1, 191) = 3.87$, $p = .05$, ges = .004; $F_2(1, 238) = 2.87$, $p = .09$), but the interaction was much larger following unrelated primes ($F_1(1, 191) = 19.83$, $p < .001$, ges = .01; $F_2(1, 238) = 17.70$, $p < .001$, ges = .01).

Discussion

The critical first step of this research project was to demonstrate the three-way interaction among SQ, priming, and word frequency can be obtained in LDT as such a complex pattern might be difficult to replicate. Importantly, the interaction was significant in our data and took the same form as that shown by Scaltritti et al. (2013) in the speeded word naming task. Specifically, the standard additive relationship between SQ and frequency was obtained following related primes but became interactive following unrelated primes. Before discussing the implications of this effect, we first turn to our primary questions of interest. Specifically, will the three-way interaction be eliminated by a reduction in the proportion of related primes and will this reduction influence both the Priming × SQ interaction as well as the Priming × Frequency interaction?

Experiment 2

Participants

In total, 239 new participants were recruited from the same source as in Experiment 1. All had normal or corrected-to-normal vision and participated in exchange for course credit or payment. Thirty-one participants were excluded because their mean RTs exceeded 1,000 ms and/or their mean accuracy rate was below 80%, leaving 208 participants.

Stimuli and procedure

The stimuli and task procedures were identical to those of Experiment 1, with the sole exception that the proportion of targets that were preceded by a related prime was reduced from .50 to .25. To facilitate comparison with Experiment 1, we ensured that the same related primes were contributing to the condition mean across both experiments. To achieve this, we included a set of buffer words that were all preceded by unrelated primes. As these items served only to balance out the lists, they were discarded and never analysed. RTs were trimmed in the same manner as Experiment 1, which removed 2.9% of total word responses.

Results

z-scored RT analysis. The three main effects, priming ($F_1(1, 207)=146.82$, $p<.001$, ges=.08; $F_2(1, 238)=141.89$, $p<.001$, ges=.07), SQ ($F_1(1, 207)=1{,}029.86$, $p<.001$, ges=.67; $F_2(1, 238)=2{,}891.49$, $p<.001$, ges=.62), and frequency ($F_1(1, 207)=416.73$, $p<.001$, ges=.16; $F_2(1, 238)=66.03$, $p<.001$, ges=.15), were all significant.

Furthermore, the priming by SQ interaction was significant ($F_1(1, 207)=19.06$, $p<.001$, ges=.008; $F_2(1, 238)=13.46$, $p<.001$, ges=.006), indicating priming effects were larger for degraded items. In addition, the SQ by frequency interaction was reliable by subjects but not by items ($F_1(1, 207)=4.62$, $p=.03$, ges=.002; $F_2(1, 238)=2.39$, $p=.12$, ges=.001); frequency effects were slightly larger for degraded items. Finally, the priming by frequency interaction was significant ($F_1(1, 207)=5.25$, $p=.02$, ges=.003; $F_2(1, 238)=4.55$, $p=.03$, ges=.002), with larger priming effects for low-frequency, compared with high-frequency, targets. Importantly, unlike Experiment 1, the three-way interaction was not significant ($F_1(1, 207)<1$, $p=.35$, ges<.001; $F_2(1, 238)<1$, $p=.41$, ges<.001) (condition means are provided in Table 3).

Accuracy analysis. In the analysis of accuracy rates, the main effects of priming ($F_1(1, 207)=20.70$, $p<.001$, ges=.008; $F_2(1, 238)=13.09$, $p<.001$, ges=.006), SQ ($F_1(1, 207)=90.53$, $p<.001$, ges=.07; $F_2(1, 238)=141.78$, $p<.001$, ges=.06), and word frequency ($F_1(1, 207)=87.62$, $p<.001$, ges=.04; $F_2(1, 238)=12.71$, $p<.001$, ges=.04) were significant. The priming by SQ interaction was also significant ($F_1(1, 207)=10.\ 91$, $p=.001$, ges=.004; $F_2(1, 238)=9.\ 24$, $p=.003$, ges=.003), indicating larger priming effects for degraded items, as was the priming by frequency interaction ($F_1(1, 207)=5.78$, $p=.02$, ges=.002; $F_2(1, 238)=3.21$, $p=.07$, ges=.002), indicating larger priming effects for low-frequency words. Finally, the frequency by SQ interaction was also significant ($F_1(1, 207)=11.97$, $p<.001$, ges=.005; $F_2(1, 238)=9.50$, $p=.002$, ges=.004), such that frequency effects were larger for degraded items. There was no evidence for the presence of a three-way interaction ($F_1(1, 207)<1$, $p=.90$, ges<.001; $F_2(1, 238)<1$, $p=.90$, ges<.001).

Table 3. Mean z-scored reaction time and accuracy per condition in Experiment 2.

	Clear			Degraded		
	LF	HF	FE	LF	HF	FE
z-scored RT						
Unrelated	−0.146	−0.338	0.191	0.483	0.273	0.210
Related	−0.262	−0.396	0.134	0.310	0.125	0.185
PE	0.116	0.058		0.173	0.148	
Accuracy						
Unrelated	0.979	0.992	−0.013	0.949	0.973	−0.024
Related	0.984	0.991	−0.007	0.963	0.980	−0.017
PE	−0.005	0.001		−0.014	−0.008	

PE: priming effect, FE: frequency effect.

Discussion

Importantly, the reduction in the RP appeared to eliminate the three-way interaction obtained in Experiment 1. However, a small two-way interaction remained between SQ and word frequency. A return to additivity following a reduction in RP was taken to be one signature of the retrospective prime retrieval mechanism being "turned off." The fact that these variables continue to interact in the current experiment might suggest that participants are still occasionally retrieving the prime context (perhaps probabilistically rather than deterministically) as some of the primes were indeed useful.

Furthermore, we failed to fully replicate Stolz and Neely (1995) in that we obtained a reliable interaction between priming and SQ even in the .25 RP condition. Given our substantially larger sample size, it is entirely possible that we simply had more power to detect very small interactions. We address this concern by conducting a final analysis in which we combine the data across experiments and utilise RP as an additional between-subjects factor. This will allow us to more directly determine whether the RP is moderating the SQ by frequency interaction. As the primary goal of this analysis involves the influence of RP, only interactions that include this variable will be discussed.

Cross-experiment comparison

z-scored RT analysis

As expected, the four-way interaction among frequency, SQ, priming, and experiment was significant ($F_1(1, 398)=4.07$, $p=.04$, ges=.001), reflecting the significant three-way interaction in the .50 condition and lack thereof in the .25 condition as described above. Moreover, RP moderated the priming by SQ interaction ($F_1(1, 398)=3.95$, $p=.048$, ges=.001), indicating the interaction was smaller in the .25 condition (effect=.07) than in the .50 condition (effect = .12). Not surprisingly, RP interacted with priming ($F_1(1, 398) = 30.95$, $p < .001$, ges = .01), such that priming was smaller in the .25 condition (effect = .12) compared with the .50 condition (effect = .21). Finally, the interaction between RP and SQ was also marginally significant ($F_1(1, 398) = 3.66$, $p = .06$, ges = .003), indicating that the degradation effect was slightly smaller in the .25 condition (effect = .58) compared with the .50 condition (effect = .63). No other interactions involving RP were significant.

General discussion

The current series of experiments investigated how a list-wide variable, specifically the RP, moderates the joint relationship among three theoretically key variables in the LDT. This study produced three primary patterns regarding this relationship. First, when the RP was .50, there was a three-way interaction among SQ, semantic priming, and word frequency, such that SQ and frequency were additive following related primes but overadditive following unrelated primes. Second, the three-way interaction was eliminated when the proportion of related primes was reduced to .25, although there remained a small two-way interaction between SQ and frequency, contrary to expectations. Finally, RP significantly reduced (but did not eliminate) the priming by SQ interaction but had no effect on the relationship between priming and word frequency. We discuss the implications of each of these patterns in turn.

To our knowledge, this is the first study to show a three-way interaction among these three variables in LDT and represents a straightforward extension of the Scaltritti et al. (2013) results. Similar to that earlier study, the current results yielded a significant interaction between SQ and frequency following unrelated primes, but additive effects following related primes. Scaltritti et al. (2013) suggested this pattern is a signature of degraded target conditions triggering a retrospective reliance on prime context (see also Balota, Yap, Cortese, & Watson, 2008; Thomas et al., 2012). Specifically, when a target is degraded and thus difficult to resolve, participants retrieve the prime word to facilitate making the word/nonword decision. When the prime is related, responses to degraded targets are sped up, which eliminates the interaction. More importantly, this mechanism is sensitive to list-wide conditions, such as the proportion of related primes. When we reduced the RP to .25, the three-way interaction was eliminated. This strongly suggests that the prime reliance process can be turned off or at least deemphasized when the prevailing experimental conditions do not incentivize its use.

It is important to note that using the speeded naming task, Scaltritti et al. (2013) obtained additivity between SQ and frequency when related primes were completely removed (Experiment 2). In contrast, our results showed a very small interaction persists between SQ and frequency when the RP was reduced to .25. This suggests that in lexical decision, retrospective reliance on prime context may be engaged probabilistically, rather than deactivated completely, even when primes are only rarely related to the target. This is consistent with reliable interactions between priming and both SQ and frequency in Experiment 2; priming effects became larger as targets became more difficult to resolve, either due to stimulus degradation or being lower in frequency. Moreover, it is important to note that the SQ × Frequency interaction was very small and only significant in the by-subjects analysis and should therefore be interpreted with a degree of caution. Of course, the cross-experiment comparison clearly indicates that the SQ by priming interaction was much smaller in the .25 RP condition compared with the .50 condition, consistent with a de-emphasis on the prime retrieval mechanism.

Alternatives to retrospective prime retrieval

We have emphasised retrospective prime retrieval as the key mechanism underlying the three-way interaction in Experiment 1. Such a process is supported by Thomas et al. (2012), who showed that an interaction between SQ and priming is only obtained when there is a backward associative relationship between the prime and the target; additivity prevails when the prime–target relationship is only forwardly associated. Despite this strong evidence, some alternative explanations of the present findings are worth considering. Specifically, it is accepted that there are at least three possible loci of the semantic priming effect (Neely, 1991): (1) spreading activation from the prime word to related words in memory, (2) a prelexical, expectancy-generation process (Becker, 1980), and (3) postlexical mechanisms including a semantic matching process (Neely, Keefe, & Ross, 1989) or plausibility checking (Norris, 1986). Although an expectancy-based mechanism is often invoked to explain RP effects (Hutchison, 2007), Stolz and Neely (1995) discounted this mechanism as a plausible explanation for the SQ by priming interaction. Hence, as this interaction is a major focus of the present work, we will only consider spreading activation as an alternative to retrospective prime retrieval in explaining the SQ by priming by RP interaction.

The SQ by priming interaction under .50 relatedness conditions can be accommodated by assuming that the feedback from the semantic level disproportionally facilitates processing of degraded stimuli. Furthermore, it is assumed that the low relatedness condition modulates the degree of feedback from the semantic system to the letter level (Stolz & Neely, 1995), which then reduces the magnitude of the SQ by priming interaction, suggesting the feedback from the semantic level is somehow throttled. Intuitively, this would be beneficial as the feedback from unrelated primes would actually interfere with processing on the majority of trials.

Thus, both retrospective prime retrieval and throttling of spreading activation could accommodate the SQ by priming by RP interaction. In an attempt to separate these accounts, it is important to consider the final main finding of the present study. Specifically, even though the priming by frequency interaction was itself significant in Experiment 2, the combined analysis revealed that RP had no influence on the priming by frequency interaction. Thus, regardless of the exact mechanism underlying the SQ by priming by RP interaction, one can reasonably ask why RP did not exert an influence on the frequency by priming interaction. Importantly, the throttling account would appear to have difficulty accommodating the lack of an interaction among priming, frequency, and RP.

Specifically, to account for the full range of effects obtained from the present experiments, the lexical processing system would have to be able to selectively throttle the activity between specific layers as a function of the RP. That is, the RP by priming by SQ interaction suggests the feedback from the semantic system to the letter level is constrained presumably due to the low probability of related primes. The same mechanism can account for frequency by priming (e.g., semantic information facilitates processing of low-frequency words), reflecting the interactivity between lexical and semantic levels. In contrast to SQ, the frequency by priming interaction is left intact when the RP is reduced (as evidenced by the fact that RP does not modulate the frequency by priming interaction). Assuming that throttling of activity among processing layers can indeed be this selective, it is not immediately clear that such a mechanism is even adaptive. Specifically, the feedback from unrelated primes (which are the majority of trials when the RP is low) would still interfere with activation at the lexical level (in addition to the letter level), and hence, it would make sense to also constrain the feedback from semantics to the lexical level. Of course, this would reduce the priming by frequency interaction, a pattern that was not observed in the current data.

For these reasons, we believe the retrospective prime reliance account to be the most parsimonious explanation. However, this account also needs a mechanism to explain the lack of a priming by frequency by RP interaction. It is possible that modulations in retrospective prime retrieval as a function of RP are mainly seen when there is difficulty in early letter-level processing, that is, when the system is still struggling with mapping the letter string to an underlying lexical representation. When this initial process is relatively slow, the prime context is retrieved and utilised, conditioned upon the overall utility of the prime context (i.e., RP). However, the rate of accumulation of activity at the lexical level (modulated by word frequency) is apparently not monitored in the same way. Rather, variations in retrospective prime retrieval due to difficulty at the lexical level may instead be mediated by individual differences in skilled lexical processing. For example, Yap, Tse, and Balota (2009) showed that skilled lexical processors (based on vocabulary knowledge) produced additive effects of priming and frequency, whereas less skilled processors exhibited the standard overadditive interaction. Thus, for skilled lexical processers (i.e., high vocabulary), there is no need to engage in retrospective retrieval, and priming can be based on prospective (spreading activation) mechanisms that are not sensitive to RP. Because the participants in the present two experiments were drawn from the same pool and are therefore comparable on lexical processing fluency,[2] it is not surprising that the priming by frequency interaction is of comparable magnitude for the two samples.

Regardless of the lexical proficiency, letter-level disruption caused by stimulus degradation is problematic for all readers, prompting consistent engagement of retrospective prime retrieval (a process which is moderated by the RP). Of course, future research is needed to further disentangle these two processes. For example, a strong test of retrospective prime reliance would be to manipulate the prime–target relationship (Thomas et al., 2012), such that it is easier to generate the prime given the target (backward associative strength, which moderates retrospective mechanisms) than to generate the target given the prime (forward associative strength, which moderates prospective mechanisms).

Alternatives to IA

Thus far, we have interpreted our findings within the IA framework; however, it is important to consider whether alternatives to IA would also accommodate the present findings without assuming ancillary mechanisms such as prime retrieval. One such model is presented by Plaut and Booth (2000) in which the effects of variables such as priming are governed by a sigmoidal input–output function. Thus, additive or interactive effects could be obtained depending on where one is on the sigmoid function. One simply needs to assume that variables such as RP selectively change the shape of this function (see Masson & Kliegl, 2013, for other variables that might change the shape of this function). Despite the appealing simplicity of such a model, a lively debate in the field has questioned whether this model can adequately capture the full range of additivity and interactivity that has been shown in the empirical literature (Borowsky & Besner, 2006).

Limitations

There are a few limitations to the current work that warrant mention. First, although the four-way interaction among RP, SQ, priming, and frequency was significant, the three-way interaction within Experiment 1 was marginal ($p = .06$ by subjects and $p = .04$ by items). Therefore, the results of Experiment 1 in isolation should be interpreted carefully. However, it is also important to note that the four-way interaction that included RP was also significant, indicating the patterns across Experiments 1 and 2 were indeed reliably different. Second, manipulations of RP are typically confounded with what is called the "nonword ratio" (Neely et al., 1989). This ratio refers to the probability that the target is a nonword given that the prime and target are unrelated. As the proportion of related primes increases, the likelihood of a target nonword given an unrelated prime also increases. Thus, our results could entirely be driven by nonword ratio effects rather than RP. However, for purposes of the present study, and the finding that processing adapts as a function of list-wide manipulations, the distinction between RP effects and nonword ratio effects is not critical.

Conclusion

The present results replicate a theoretically critical three-way interaction among SQ, priming, and word frequency in LDT and extend them to include an RP manipulation. The fact that RP affects some, but not all, of the observed effects points to a remarkably adaptive lexical processer that can dynamically adjust to optimally meet task demands given the experimental context.

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Supplementary Material

The Supplementary Material is available at: qjep.sagepub.com

Notes

1. This mechanism is similar to Neely's (1977) semantic matching process whereby once the target is processed, the participant checks for a relationship between the prime and the target. As only words can be related to prime, such a check process can bias a word response in the lexical decision task and thereby speed response times (RTs). However, it is not clear how this would facilitate speeded word naming; hence, we use the term prime retrieval throughout.
2. Indeed, the two groups were very closely matched on vocabulary knowledge ($p = .31$) and spelling ability ($p = .77$), as, respectively, reflected by performance on the Shipley Institute of Living Scale (Shipley, 1940) and Andrews and Hersch's (2010) spelling recognition task.

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