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T1 difficulty affects the AB: manipulating T1 word frequency and T1 orthographic neighbor frequency

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Abstract Colored target words were presented with distractor nonwords in a rapid serial visual presentation (RSVP) task. In Experiment 1, the attentional blink (AB) effect on T2 accuracy was larger when T1 was a difficult (low-frequency) word than when it was a high-frequency word. In Experiment 2 the effect of T1 frequency on the AB was replicated in a between-participants design, and the frequency of T1's one-letter different neighbors (e.g., *case*, *bare*, for *care*) interacted with T1 frequency in its effects on T2 accuracy. Experiment 3 confirmed the effect of T1 frequency over 6 T1-T2 lags. The effects of T1 characteristics were sensitively assessed in the AB and were more consistent with resource depletion theories than control-process accounts.

Keywords Visual word identification · Attentional blink · RSVP · Word frequency · Orthographic neighbors

In rapid serial visual presentation (RSVP), stimuli are presented at a rate of approximately ten per second at a single location such that each item masks the preceding item, and participants are required to report on some items at the end of a stream of items. When the task requires participants to identify and report two targets embedded in a stream of distractors, report of the second target is impaired when it occurs at a lag of several items (several hundred ms) after the first target. This decrement occurring at relatively short T1-T2 lags is termed the attentional blink (AB, Raymond, Shapiro, & Arnell, 1992; Shapiro, Raymond, & Arnell, 1994). In experiments with digits and letters as stream items, the AB typically is maximal at lags 2 and 3, and recovers by approximately lag 6. A common phenomenon is "lag-1 sparing," relatively unimpaired T2 identification when T2 is the next item after T1, perhaps reflecting joint processing of the two targets (Maki, Couture, Frigen, & Lien, 1997). Considerable investigation of the AB in experiments with digits, letters and words has indicated partial processing of T2 and the distractors between T1 and T2. For example, in the RSVP task with words, a distractor prior to T2 can associatively prime T2 (Maki, Frigen, & Paulson, 1997). Until recently the most popular accounts of the AB proposed that structural bottlenecks (Jolicoeur, 1998) or processing capacity limitations arising in the identification of T1 limit the completion of the identification of T2. According to one influential theory, T1 exerts its detrimental effects on the consolidation of T2 in working memory (Chun & Potter, 1995). This consolidation appears to be necessary for a stimulus to be consciously identified and available for report. The memory consolidation and bottleneck accounts are examples of "resource-depletion" accounts, so called because they attribute the AB to the processing demands of T1.

Resource-depletion accounts vary in terms of the proposed locus of the effects of the cost of processing T1, but they share the assumption that the AB will increase as the demands of identifying T1 increase.

Recent approaches to explaining the AB have rejected resource depletion in favor of limitations in the cognitive control mechanisms for selecting targets from distractors. For example, on the temporary loss of control (TLC) account, T2 is missed because attending to T1 allows the post-T1 distractors to alter the attentional set that must be maintained to select targets and reject distractors (Kawahara, Kumada, &

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Di Lollo, 2006). In support of this type of theory, when participants are required to report the letters in sequences of three stimuli, there is no AB for the third stimulus (S3) when all stimuli are letters, whereas an AB for S3 is observed when S1 and S3 are letters and S2 is a digit (Di Lollo, Kawahara, Ghorashi, & Enns, 2005). According to TLC, the intervening digit perturbs the attentional set so that it is no longer optimally tuned to letters. However, the role of the distractors in attentional control has been questioned in a recent attentional engagement theory (Nieuwenstein, Potter, & Theeuwes, 2009), according to which the key factor is the absence of a target, which leads to a disengagement of attention and impairs target identification by necessitating the re-engagement of attention. Nieuwenstein et al. found that when the duration of T2 was short, the AB could be observed when a blank screen replaced the distractors between T1 and T2.

The eSTST theory (Wyble, Bowman, & Nieuwenstein, 2009) locates the AB in mechanisms for producing episodic distinctiveness of targets in the RSVP. According to this theory, the AB reflects a cognitive strategy rather than a resource limitation. Multiple targets may be selected for processing but at the cost of episodic distinctiveness and memory for item order. There is competitive regulation of attention, with inhibition of distractor nodes, excitation of target nodes and inhibition of target input to protect consolidation of events in working memory.

A comprehensive theory of attentional selection develops the idea of an attentional gate (Raymond et al., 1992) in a "boost and bounce" mechanism to enhance the selection of targets from distractors (Olivers & Meeter, 2008). This mechanism involves an attentional set to admit targets to working memory and ignore distractors, and it interacts with sensory input to provide feedback to the location of stimulus input based on the category membership of the stimulus. That is, targets get excitatory feedback and distractors get inhibitory feedback. Because of the time course of the rise and decay of feedback activation, both T1 and the T1 + 1 distractor typically are enhanced by the "boost" recruited by T1. Entry of the T1 + 1 distractor to working memory then invokes strong inhibitory feedback on input that persists over several items and causes the AB. The magnitude of the inhibition increases with the difficulty of the target-distractor discrimination.

A key differentiating factor between resource depletion and attentional control theories is the effect of the demands of T1 identification. Changes in T1 difficulty and hence the time taken to identify T1 affect the primary cause of the AB according to resource depletion accounts. By contrast, T1 difficulty has either no effect on the AB or an incidental effect within the attentional control theories. On the TLC account, central processing of T1 results in a relaxation of endogenous control over the configuration of the attentional set. Arguably the difficulty of T1 may affect this loss of endogenous control, although the authors have not discussed this possibility. On the Wyble et al. eSTST theory, the encoding time for T1 might affect the AB, but currently the model assumes a constant encoding time for targets. On the current versions of the attentional engagement and boost and bounce models, there is no obvious mechanism whereby T1 difficulty could affect the AB. The causes of the AB arise after the selection of T1, namely in the loss of attentional engagement caused by events after T1 (engagement theory) or the inhibition of input resulting from the erroneous selection of the T1 + 1 distractor (Boost and Bounce).

The difference between resource depletion and attentional control theories in terms of T1 difficulty effect is made explicit in the Boost and Bounce model (Olivers & Meeter, 2008). The authors note (p. 855) that the Boost and Bounce does not depend upon the processing demands of T1 and thus does not predict an effect of T1 difficulty on the AB.

There have already been a number of investigations of T1 difficulty through manipulations of perceptual, decision and response factors. Surprisingly, as noted by Olivers and Meeter (2008), the studies have not produced definitive evidence about the effect of T1 difficulty. It is known that when the complexity of a decision about T1 increases (e.g., a judgment about identity and size vs. identity only), or the number of alternatives in a choice reaction time task for T1 increases, the AB increases (Jolicoeur, 1999a). However, Ward and colleagues (Ward, Duncan, & Shapiro, 1997) failed to find an effect on the AB of increasing the difficulty of a size judgment about T1 by decreasing the magnitude of size differences among the set of potential T1s. Backward masking of T1 (usually by the following RSVP item) substantially increases the magnitude of the AB (Seiffert & Di Lollo, 1997; Visser, 2007), and it may affect the relationship between T1 difficulty and the AB by curtailing the processing of T1.

Critically, most manipulations of T1 difficulty have either involved changes to the stimulus display or response requirement over levels of T1 difficulty, or they have involved purely perceptual manipulations of T1 difficulty. An exception is a study by Shapiro et al. (1994), which equated the response selection demands and the stimulus display over levels of T1 difficulty by varying the number of potential targets (i.e., target set size). The authors found evidence of only a small and statistically equivocal increase in the AB when T1 was sampled from a set of 25 vs. 3 letters.

In the present studies the RSVP targets were words, and we manipulated difficulty by varying the characteristics of words without making any changes to the display, stimulus durations, distractors or response requirements. An additional focus of interest was the utility of the AB paradigm for diagnosing processing difficulty attributable to lexical characteristics. Pronounceable nonword distractors and word targets produce a substantial AB (Maki et al., 1997) and were the items used in the present experiments. Requiring participants to select words among nonword distractors provides some continuity with the lexical decision task (LDT; word-nonword classification), which is the most commonly used test of lexical processing.

Key lexical variables have well-established effects in traditional visual word identification tasks. For example, a word's normative frequency in print has very large effects in the LDT, with response latencies longer for low-frequency than high-frequency words (Monsell, 1991). Word frequency has small but robust effects on the latency to name a printed word (Forster & Chambers, 1973), and on accuracy in perceptual identification of masked words (Wagenmakers, Zeelenberg, & Raaijmakers, 2000). It is likely that the processing cost for rare words is imposed at several stages of lexical processing, including the identification of letter clusters, memory access, retrieval of phonological codes, judgments about word familiarity or meaning, and execution of naming and other responses (Abrams & Balota, 1991; Monsell, 1991; Reichle, Rayner, & Pollatsek, 2003).

Investigations of the attentional demands of word processing have produced clear evidence of a higher processing cost for low- than high-frequency words. For example, when word recognition is performed with a concurrent auditory detection task, responses to the auditory probe are slowed more by low- than high-frequency words (Becker, 1976; Herdman, 1992). The effect of frequency is confirmed by manipulations of word frequency in the Psychological Refractory Period (PRP) paradigm. McCann, Remington, and Van Selst (2000) gave participants an auditory discrimination task followed by a lexical decision task. The increase in lexical decision latencies as the task stimulus onset asynchrony (SOA) decreased was additive with word frequency, suggestive of an effect of frequency on processes affected by the central bottleneck (but see Cleland, Gaskell, Quinlan, & Tamminen, 2006). If frequency had an effect only on perceptual processes occurring prior to word recognition, then the effect of frequency would have decreased as SOA decreased, reflecting "absorption into cognitive slack." Specifically, as the SOA decreases, the waiting time to access central processing for task 2 (LDT) increases, and an increased time cost of pre-central processing in the LDT can be partly absorbed within this waiting time.

The three experiments reported here varied the difficulty of T1 identification in the RSVP by varying the normative frequency of T1, and we observed the consequences for the attentional blink (AB) on a second word target T2. Experiment 2 also examined the orthographic similarity of T1 to other words, a variable thought to affect word identification difficulty.

Experiment 1

In Experiment 1, targets were colored words and distractors were white pronounceable nonwords, following the procedures of Maki et al. (1997). The discrimination of targets and distractors by color meant that effects of word frequency on word-nonword discriminability were unlikely to be the cause of any effect of T1 frequency on the AB. T1 was either a low or high frequency word and T2 was a medium-frequency word. An unequivocal prediction was that low frequency T1s would be less well identified than high frequency T1s (Monsell, 1991). Of critical interest was whether T2 identification would be poorer after a low- than a high-frequency T1.

T2 accuracy in the AB group was compared with that in a control group required to identify only T2, so that the AB effect on T2 could be attributed to the identification of T1. If resource depletion accounts of the AB are correct, then the magnitude of the AB will be larger for low- than high-frequency T1s, evident in a T1 frequency × Group interaction, with no frequency effect on T2 (and no AB) for the control group that was instructed to ignore T1. In addition, in the AB group, the rate of recovery of the AB over increasing T1-T2 lags was predicted to be faster for high- than low-frequency T1s, leading to a T1 frequency x T1-T2 lag interaction.

Method

Participants Thirty-six university students paid \$10 per hour for expenses were randomly assigned to the AB group (n = 18) or the report-T2-only control group (n = 18). The data of an additional three participants tested in excess of counterbalancing requirements for the AB group were deleted on the basis of stimulus list and low T1 accuracy.

Materials and design T1 and T2 were six-letter words, and distractors were 3,120 pronounceable and orthographically acceptable six-letter nonwords selected from the ELP database (Balota et al., 2007). There were 120 high- and 120 low-frequency T1 words. The high frequency words had a median frequency per million of 152 and a minimum of 50 per million in the British National Corpus (BNC, Kilgarriff, 1995), and the low frequency words had a frequency range of .25 to 30 per million (median = 2.6). Orthographic typicality differences were controlled by matching the high and low frequency sets on N, the number of orthographic neighbor words (formed by replacing a single letter in position in a word). The mean N was 1.6 (range 0–8). The T2 words had a frequency range of 0.7 to 125 per million in the BNC database (median = 21). Additional targets and distractors were used for ten practice trials representing the range of lags, T1 frequency and T1 positions in the main list.

Each RSVP trial had 15 items, of which 2 were word targets (T1 and T2) and 13 were nonword distractors. Each participant provided data for 240 trials, 120 at each level of T1 frequency. No word or nonword was repeated within a participant's list. The 120 T1 words within the high and low frequency sets were subdivided into 4 subsets of 30 for allocation to the 4 T1-T2 lags (2, 3, 4 and 6). Within each lag, T1 occurred equally often at positions 4, 6 and 8. Over six lists each T1 word occurred twice at two lags and once at the remaining two lags. The T2 words were divided into four subsets of 60, which occurred twice at each of three lags over the six lists. Within each lag each T2 word occurred once with a high-frequency T1 and once with a low-frequency T1, with T1 position held constant, and with a different T1 word at each lag. The trial sequence was randomized, and ten practice trials were added to the beginning of each list. Within the AB and control groups, three participants were assigned to each list.

Procedure Students saw the displays on a Sony Trinitron E230 monitor running at a resolution of 800 × 600 pixels and with a refresh rate of 85 Hz. They sat at a comfortable distance from the screen and entered their responses on the computer keyboard. Stimulus presentation and response collection was accomplished by a PC running an Eprime program (Schneider, Eschman, & Zuccolutto, 2002), which also presented instructions at the beginning of the session.

The RSVP stream of 15 items was presented in the center of a black screen, with letter strings in 18-point Courier New font. The nonword distractors were white, T1 was aqua (cyan), and T2 was lime green. Participants were asked to give priority to detecting T1, to guess if unsure, and were informed about the length, lexical status and color of T1, T2 and the distractors. Each item was displayed for 106 ms, and there was no discernible pause between the offset of one item and the onset of the next. Each trial was initiated by a fixation cue (+++) that was displayed for 400 ms and followed by a pause of 106 ms. At the end of each stream the prompt W1? was displayed, and the participants typed their responses, using the backspace key to make corrections and the Enter key to terminate their responses. The prompt for T2 (W2?) was displayed immediately after the Enter key was pressed, and termination of the T2 response initiated an inter-trial interval of 106 ms. Trials were presented in 5, 50-trial blocks with a brief rest between blocks. The first block commenced with ten practice trials.

Results

Responses were computer-scored, and misspellings or misordered targets were not accepted. Analyses of the data for the AB group separately were conducted on the proportion of correct T2 responses for trials on which T1 was correct. In analyses involving the AB group and the T2-only control, T2 accuracy was scored without regard to T1 accuracy to facilitate comparison of the groups. Significant effects in analyses of variance (ANOVAs) by participants were confirmed in analyses with items as the random effect. Note that *F2* indicates analysis by items and *F1* indicates by participants. In the standard item analyses accuracy was recorded for each T2 word as a function of condition. In additional item analyses, T2 accuracy in each condition was calculated for each T1 word aggregated over T2 items. Because these analyses by T1 items showed the same results as the analyses by T2 items, they are not reported here or subsequently.

T1 accuracy (AB group) Accuracy in the AB group on T1 as a function of T1 frequency and T1-T2 lag is shown in Fig. 1, which also shows the standard error of each mean ($SD/\sqrt{n}$). A T1 frequency × Lag ANOVA by participants revealed the expected main effect of T1 frequency, with an accuracy advantage for high over low frequency T1 words, $F1(1, 17) = 60.13$, $MSE = 221$. This effect was confirmed in a T1 frequency ANOVA by items, $F2(1, 238) = 60.21$, $MSE = 314$, $p < .001$. There were no main or interactive effects of T1-T2 lag.

T2 accuracy The effects of lag and T1 frequency are shown in Fig. 2. The means were compared for the AB and control groups in a Group × T1 frequency × Lag ANOVA on T2

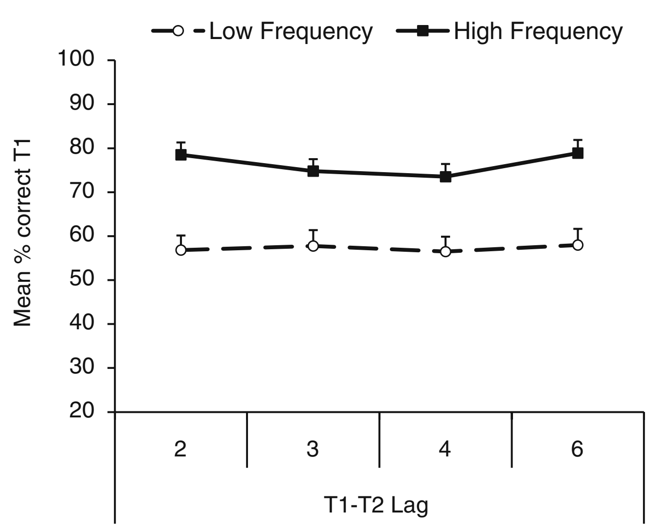

Fig. 1 Experiment 1: Mean percent correct and *SE* for high and low frequency T1s in the AB group

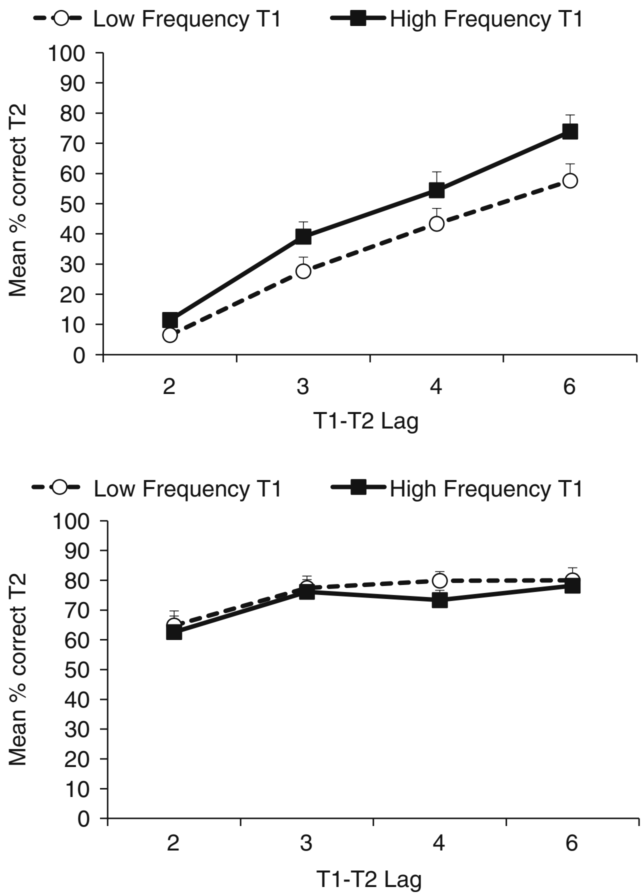

Fig. 2 Experiment 1: Mean unconditionalized percent correct and *SE* for T2 as a function of T1 frequency and T1-T2 lag. The *top panel* shows the group instructed to report T1 and T2 (AB), and the *bottom panel* shows the group instructed to report only T2 (control)

accuracy (scored in the AB group without regard to T1 accuracy). Lag was treated as a between-items factor in item analyses because each T2 was seen at only three of the four lags. Indicative of an AB, there was a significant main effect of group, with superior performance in the control group, (*F1*, *F2* > 40). There also was a substantial effect of lag (*F1*, *F2* > 100) that was qualified by a Group × Lag interaction, *F1*(3, 102) = 35.13, *MSE* = 168, *F2*(3, 716) = 185. 28, *MSE* = 907, *p* < .001. Simple effects of group at each lag confirmed that with the exception of lag 6, at which the group effect was marginally reliable by participants, *F1*(1, 34) = 4.12, *p* = .05, the control group significantly outperformed the AB group at every lag (*p*s < .001). In addition, there was a substantial effect of T1 frequency, *F1*(1, 34) = 13.06, *MSE* = 88, *F2*(1, 716) = 20.47, *MSE* = 564, *p* < .001. Finally, in line with a T1 difficulty effect on the AB, the T1 frequency effect was qualified by a Group × T1 frequency interaction, *F1*(1, 34) = 39.52, *MSE* = 88, *F2*(1, 716) = 48.06, *MSE* = 727, *p*s < .001. As expected, the AB group suffered a large decrement for T2s preceded by low-frequency T1s. Unexpectedly, the control group showed a small advantage for the low-frequency T1 condition over the high-frequency T1 condition. Lag × T1 frequency ANOVAs for each group indicated that the "reverse" frequency effect in the control group was reliable, *F1*(1, 17) = 4.89, *MSE* = 65, *p* = .041, *F2*(1, 716) = 5.17, *MSE* = 611, *p* = .023, as was the advantage for high-frequency T1s in the AB group (*F*s > 35). In addition, T1 frequency interacted with lag in the AB group, *F1*(3, 51) = 3.87, *p* = . 014; *F2*(3, 716) = 2.84, *p* = .037, but not in the control group (*F*s < 1). The T1 frequency × T1-T2 lag interaction in the AB group involved a larger group difference at long than short lags, and thus did not conform with the typical pattern observed, in which groups converge at long lags as the AB is resolved.

T2 data were analyzed in the AB group separately, with T2 accuracy scored only for trials on which T1 was correctly identified. The means are shown in Table 1. A T1 frequency × Lag ANOVA was conducted, with lag again a between-items factor. As in the T2 data not conditional on T1 accuracy, there were substantial effects of T1 frequency and lag (*p*s < .001). The lag × T1-frequency interaction was reliable by items but not by participants (*p* = .17).

Discussion

T1 identification at 67% overall in the AB group was lower than the accuracy of 80% or more reported in typical AB experiments, in which targets are repeatedly sampled from sets of digits or letters, and indicates that the task difficulty was high. Presumably participants require more time to encode unrepeated and moderately infrequent words than letters or digits. Further, the AB is more severe when T1 and T2 come from the same conceptual category (words) rather than different categories (Taylor & Hamm, 1997). The frequency of T1 had the predicted effect on T1 identification, with T1 accuracy in the AB group at 57% and 76% for low- and high-frequency words, respectively. This group showed a large AB effect on T2 accuracy that was not evident in the control group that was not required to report T1. There was a significant main effect of group and a Group × Lag interaction, reflecting a larger group effect at short lags. The difference between the AB and control groups at lag 6 was reliable by items and marginally so by participants (*p* = .05), suggesting that the AB was not fully resolved by lag 6.

T1 frequency was expected to have an impact on T2 identification primarily in the AB group. Consistent with this expectation, there was a reliable Group × T1-frequency interaction in the analyses involving the groups. The surprising result from this analysis was that in contrast to the disadvantage for the low-frequency T1 condition in the AB group, there was a very small but reliable advantage for the low-frequency T1 condition in the control group. This

Table 1 Experiment 1: Mean percent correct T2/T1 and standard deviations for the AB group

	T1-T2 Lag							
	Two		Three		Four		Six	
T1 frequency	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Low	6.36	7.81	28.89	22.06	46.49	25.91	60.57	26.80
High	13.14	14.80	40.84	22.60	58.93	25.64	76.97	22.60

unexpected reverse frequency effect was mainly evident at lag 4. Given the counterbalancing of items, this result cannot be attributed to an item confound. The most plausible explanation is that the effect is located not at T2 identification but at T2 report. When participants attempted to prepare their T2 response it is possible that sometimes they were able to recall T1 and T2, and were not sure which was which. It is likely that the low frequency T1s were more easily rejected as unlikely T2s, given the distinctiveness of low frequency words (Glanzer & Ehrenreich, 1979).

With respect to T2 accuracy for the AB group separately, there was a highly reliable mean difference of 12 percentage points between the high- and low-frequency-T1 conditions. Given that the scores for the analysis of the AB group separately were calculated as a proportion of the number of trials on which T1 was correct, the disadvantage for T2s following a low-frequency rather than a high-frequency T1 cannot be attributed simply to indirect effects of failure to identify T1, or differences in the number of trials on which successful identification of both T1 and T2 was possible. Floor compression in the AB group for T2 at lag 2 is evident in the low mean accuracy and the small *SD* of 12.2 compared with at least 23 at remaining lags. Given this finding it is not surprising that a Lag × T1-frequency interaction was not consistently observed for the AB group, and that the interactive pattern did not take the form of a larger deficit for low- than high-frequency T1s at short lags compared with long lags, in line with the well established trajectory of the AB. The larger frequency effect at longer lags reflects the high task difficulty and the fact that the AB persisted over relatively long lags.

In summary, Experiment 1 provided clear evidence that T1 frequency affects the AB, with the AB group but not the control group showing a larger deficit in T2 accuracy when T1 was low-frequency than when it was high-frequency. As noted, a latency and accuracy disadvantage for low- compared to high-frequency words is well established in the word identification literature (Monsell, 1991), confirming that low-frequency words are more difficult to identify, and low frequency words interfere more than high frequency words with concurrent tasks (Herdman, 1992). The effect of T1 difficulty did not depend upon changes to the task or the spatial, perceptual or temporal characteristics of the stimulus display. The results for T1 frequency are entirely consistent with resource depletion accounts of the AB, and less easily reconciled with attentional control theories such as the Boost and Bounce theory of Olivers and Meeter (2008), and the attentional engagement theory (Nieuwenstein et al., 2009), according to which the AB arises from events occurring after T1 selection. Experiment 2 investigated both T1 frequency and the effects of orthographic similarity of a word to other words, a lexical variable whose influence on visual word identification in English is not clearly established. Additionally, measures were taken to eliminate the floor compression observed in Experiment 1.

Experiment 2

A key lexical variable for distinguishing hypothesized mechanisms of lexical processing is a word's orthographic similarity to other words. Orthographic similarity has most typically been operationalized in terms of a word's orthographic neighbors, the words that can be formed by replacing one letter in position in the word (e.g., *case*, *care*, *come*, *dame*, for *came*). Considerable attention has been devoted to establishing the effect of the number of neighbors (N, Coltheart, Davelaar, Jonasson, & Besner, 1977), as well as the frequency of neighbors, on responses to a word in the LDT and naming and perceptual identification tasks. In interactive activation models (Grainger & Jacobs, 1996) neighbor-word units are activated by virtue of sharing letters with a to-be-identified word. As a result there may be priming at the letter level, but also competitive inhibition among activated word units. Higher frequency neighbors have stronger inhibitory influences than low frequency neighbors (Davis & Lupker, 2006).

The outcomes of experiments in which neighbor variables have been manipulated have been inconsistent, as summarized in reviews by Andrews (1997) and Mathey (2001). A partial resolution of the empirical inconsistency comes from observations that the effect of neighbor variables depends on word frequency, with a benefit more likely for low frequency words (Andrews, 1989; Sears, Hino & Lupker, 1999). A recent study suggested that word frequency reversed the direction of N effects: In hierarchical regression analyses of LDT latencies for 2,428 words in young adults, N was associated with decreased response latencies for low frequency words and increased latencies for high frequency words (Balota, Cortese, Sergent-Marshall, Spieler, & Yap, 2004). Furthermore, an unpublished study from the present laboratory showed that word frequency interacted with summed neighbor frequency in the LDT in a manner similar to that found by Balota et al. (2004) with N. Plausibly, lexical-level competitive effects are offset in more slowly processed low frequency words by a neighbor benefit earlier in the identification sequence, for example, in the processing of shared letter clusters.

In Experiment 2 a strong manipulation of orthographic neighborhood was achieved by maximizing the difference between summed neighbor frequency and allowing N to vary along with neighbor frequency. In addition we again varied T1 word frequency, taking care to match neighbor variables over frequency.

In order to keep the number of trials to a manageable number for participants, T1 frequency was varied between participants. Given that the AB was clearly demonstrated in Experiment 1, the report-T2-only control group was dropped from Experiment 2. In order to reduce the high task difficulty observed in Experiment 1, the duration of each RSVP item was increased to 129 ms. Because of a scarcity of items, the critical neighbor sets were assigned to the T1 role only at lags considered likely to be within the region of the AB, namely lags 2 and 4. A third lag (6) was used to assess the trajectory of the AB. T1 words at lag 6 varied in frequency but not orthographic neighbor frequency, and thus they were excluded as fillers from the analyses of neighbor effects.

For Experiment 2 it was predicted that high neighbor frequency of T1 would facilitate T1 identification when T1 was of low frequency and inhibit T1 identification when T1 was of high frequency. However inhibitory effects of neighbor frequency and N are the norm in perceptual identification (see the review by Mathey, 2001), and we suspected that differential effects of guessing might obscure the predicted result for T1. Given previous evidence that neighbor word guesses are common (Snodgrass & Mintzer, 1993) and likely to be high in frequency (Broadbent & Broadbent, 1975), guesses for low-frequency words are more likely to be incorrect. This is especially so if the low-frequency words also have high neighbor frequency, and thus many potential guesses. For high-frequency words, a high-frequency neighbor guess has a chance of being correct. To assess these assumptions, the incorrect guesses made by participants to T1 were examined.

With respect to the AB, we expected from a consideration of lexical processing demands that the interaction of T1 neighbor frequency with T1 frequency would accordingly affect T2 accuracy. That is, T2 accuracy would be higher after high- than low-frequency T1s, with an inhibitory effect of high neighbor frequency when T1 was high frequency and a facilitatory effect when T1 was low frequency. It follows that this also is the pattern of results predicted by resource depletion accounts of the AB. By contrast, the most obvious prediction from the attentional control theories is that T1 neighbor frequency would not affect the AB. For models according a major role to the target-distractor discrimination, such as the Boost and Bounce model (Olivers & Meeter, 2008) and the TLC (Kawahara et al., 2006), any effect of neighbor frequency would operate through its effects on wordlikeness, with low neighbor frequency words being less wordlike and more like nonword distractors. However, given that targets and distractors were colored differently in the present studies, a word's orthographic neighborhood was expected to play only a minor role in discrimination. Thus, on these models, high neighborhood density was expected to have a null or facilitatory effect on target identification.

Method

Participants Forty-eight introductory Psychology students participated. They were randomly assigned to the high frequency group (High, $n = 24$) or the low frequency group (Low, $n = 24$). The data were discarded for one additional participant who could not discriminate the target colors, and an additional three data sets collected in excess of counterbalancing requirements were selected for removal on the basis of list and low T1 accuracy.

Materials and design All words and nonwords were four letters in length. The neighbor statistics and frequency counts (per million) were taken from the British National Corpus (Kilgarriff, 1995). The critical word set consisted of 128 words of which half were high frequency (median 227.4, range 97–6,753) and half were low frequency (median 4.6, range 1.1–10.5). Within each frequency set there were two frequency-matched sets of 32 words, one high and one low in the frequency of orthographic neighbors (4-letter words differing from a word in one letter preserving position). Neighbor frequency was operationalized as the summed frequency of neighbors and the frequency of the highest frequency neighbor. On average a high summed frequency was associated with high neighbor density (many neighbors), and a low summed frequency was associated with low neighbor density. Table 2 shows the mean number of neighbors, the summed frequency of neighbors, and the frequency of the highest frequency neighbor. Within neighbor sets, the neighbor variables were well matched over sets that differed in target frequency (all item Fs < 1).

One hundred sixty-two words with a mean frequency of 30.3 (range of 0.3–118.7) were selected for T2. The T2 items had a mean of 8.4 orthographic neighbors with a mean summed neighbor frequency of 582.

Table 2 Experiment 2: Mean number (N) and mean summed frequency (SF) of orthographic neighbors and mean frequency of the highest-frequency neighbor (MaxF)

Target frequency	Neighbor condition	N	SF	MaxF
High	High	12.06	2245	1545
High	Low	4.31	55	35
Low	High	12.34	2450	1703
Low	Low	4.18	50	33

An additional 98 word pairs served as T1 and T2 on 80 filler and 18 practice trials. These items were similar in frequency to the neighbor sets but covered a wide range of neighbor frequencies intermediate between the high and low neighbor frequency ranges. The fillers allowed an examination of the trajectory of the AB by adding a longer T1-T2 lag containing filler targets that was unlikely to be vulnerable to the AB. They also decreased the salience of the neighbor frequency manipulation. Pronounceable non-words (N = 2,132) were selected from nonwords in the English Lexicon Project database that have a mean accuracy of at least 50% in the human data (Balota, et al., 2007). As in Experiment 1, each stream had 2 colored word targets and 13 nonword white distractors.

Four counterbalanced lists were constructed for each T1-frequency-group. The 64 T1s for each group were cycled through T1-T2 lags 2 and 4 and T1 positions 6 and 8, so that within each neighbor condition in each list there were 8 items in each lag-position combination. Over the four lists each T1 occurred once in each of the four lag-position combinations. The 80 filler pairs were cycled through lags 2 and 4 (16 pairs each) and an additional lag condition, lag 6 (48 pairs). Thus collapsing over item sets and excluding practice trials, there were 48 pairs at each lag. The filler pairs were allocated to T1 positions 6 and 8 and an additional position (4) so that in the total trial set (excluding practice) each T1 position (4, 6 and 8) was paired equally often with each lag (2, 4 and 6).

Sixty-four words were selected randomly from the T2 item set to be paired with the T1s varying in neighbor frequency. These 64 T2 words were used for this purpose in the 4 high- and the 4 low-frequency lists. For each T2 word, the lag, T1 position and T1 neighbor condition was fixed over the eight lists, but over the eight lists each T2 appeared with a different T1 word, four of which were high-frequency and four low-frequency. The remaining T2 words were assigned to filler and practice trials, with T1 position fixed for each filler T2 over lists, but with lag varying over 2 values and T1 different in each list.

The trial sequence was randomized in each list, and 18 practice trials representing the frequency, lag and T1 positions for the list were added to the beginning of each list.

Procedure The procedure was as in Experiment 1 with the following exceptions. The duration for each item in the RSVP stream was increased to 129 ms, blocks were 54 trials long, participants were instructed that targets and distractors had a length of 4 letters, and the number of practice trials was increased to 18.

Results

Lags 2, 4 and 6: T1 and T2 accuracy in combined neighbor and filler item sets The data for the three lags were analyzed by participants only because of unequal cell sizes in the items analyses. T1 accuracy pooled over lags 2, 4 and 6 was 93% for high-frequency words and 87% for low frequency words. A T1-T2 lag × T1 frequency ANOVA confirmed the frequency effect on T1 accuracy, $F1(1, 46) = 14.33$, $MSE = 89$, $p < .001$. There was no effect of lag and no interaction. A second analysis on T2 accuracy examined the course of the AB for the total item set over the three T1-T2 lags. T2 accuracy was recorded only for the trials on which T1 was correctly identified. Figure 3 shows T2 accuracy given T1 correct as a function of lag and T1 frequency. A T1 frequency × T1-T2 lag ANOVA with T1 frequency as a between-participants factor revealed significant main effects of T1 frequency and lag, with T2 accuracy higher when T1 was high-frequency, $F1(1, 46) = 13.34$, $MSE = 294$, $p < .001$, and T2 accuracy higher with increasing T1-T2 lag ($F1 > 100$). In addition there was a reliable T1 frequency × Lag interaction, $F1(2, 92) = 6.85$, $MSE = 123$, $p < .002$. The interactive pattern was in the direction expected for Experiment 1, with the frequency effect larger at lag 2 than at lags 4 and 6. This result, together with the higher overall accuracy in Experiment 2, indicates that we were successful in reducing the floor compression observed in Experiment 1.

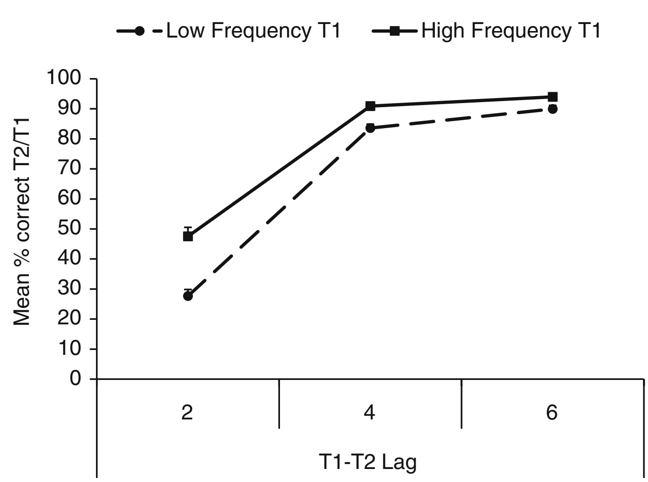

Fig. 3 Experiment 2: Mean percent correct and *SE* for T2 on trials on which T1 was identified, pooled over the neighbor-frequency and filler items, as a function of T1 frequency and T1-T2 lag

Lags 2 and 4: T1 accuracy as a function of neighbor frequency and frequency Figure 4 shows T1 accuracy as a function of neighbor frequency for the high- and low-frequency-T1 groups. T1 accuracy was analyzed in a T1 frequency (high vs. low) × T1-T2 lag (2 vs. 4) × Neighbor frequency (high vs. low) mixed design ANOVA with T1 frequency as the single between-participants factor. Accuracy was superior for high over low-frequency T1s, $F1(1, 46) = 8.30$, $MSE = 181$, $p = .006$; $F2(1, 124) = 16.42$, $MSE = 117$, $p < .001$. The main effect of neighbor frequency, lower accuracy for high neighbor frequency, was reliable by participants and marginally so by items, $F1(1, 46) = 5.85$, $MSE = 50$, $p = .02$; $F2(1, 124) = 3.36$, $MSE = 117$, $p = .069$. There were no effects involving T1-T2 lag and no interactions.

Errors to T1 were 3-5 letter words on 66% of trials, and more word neighbors were given for T1s that were high in neighbor frequency (55%) than low in neighbor frequency (30%). Unexpectedly, the mean frequency of guesses was higher in frequency when T1 was high-frequency (mean = 102 per million) than when T1 was low-frequency (mean = 51 per million), as confirmed in an items analysis treating all responses as different items, $F2(1, 749) = 25.41$. This unexpected result suggests that participants used information about item familiarity in their guesses. The important result for the interpretation of neighbor frequency effects was that, as expected, many more guesses were higher than the median frequency of the target words for low-frequency T1s (77%) than for high-frequency T1s (3%). This difference was similar within levels of T1 neighbor frequency and was significant in a T1 frequency × T1 neighbor frequency ANOVA by items, $F2(1, 78) = 6.97$, $MSE = 1728$, $p = .01$. Thus guessing a higher frequency neighbor of T1 was likely, and this strategy would be most likely to produce an error when T1 was low in frequency and high in neighbor frequency.

Lags 2 and 4: T2 accuracy as a function of T1 frequency and T1 neighbor frequency Figure 5 shows T2 accuracy as a function of T1 frequency, T1 neighbor frequency and T1-T2 lag. A T1-T2 lag × T1 frequency × T1 neighbor frequency ANOVA with T1 frequency as the single between-participants factor was conducted on the percentage of trials with T1 correct on which T2 was correct. There was a significant main effect of lag (*F*s > 300), with T2 accuracy at 87% for lag 4 and 35% for lag 2. Replicating Experiment 1, there was a robust main effect of T1 frequency, with T2 accuracy at 68% after a high frequency T1 and at 54% after a low frequency T1, $F1(1, 46) = 11.87$, $MSE = 714$, p < .001; $F2(1, 60) = 59.34$, $MSE = 98$, $p < .001$. The interaction of lag and T1 frequency also was reliable, $F1(1, 46) = 5.97$, $MSE = 372$, $p = .018$; $F2(1, 60) = 13.06$, $MSE = 98$, $p < .001$, reflecting a larger frequency effect at lag 2 than lag 4. There was no main effect of T1 neighbor frequency.

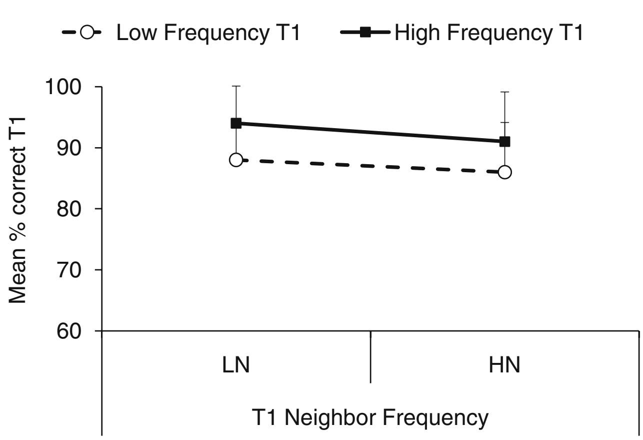

Fig. 4 Experiment 2: Mean percent correct and *SE* for T1 as a function of T1 frequency and T1 neighbor frequency

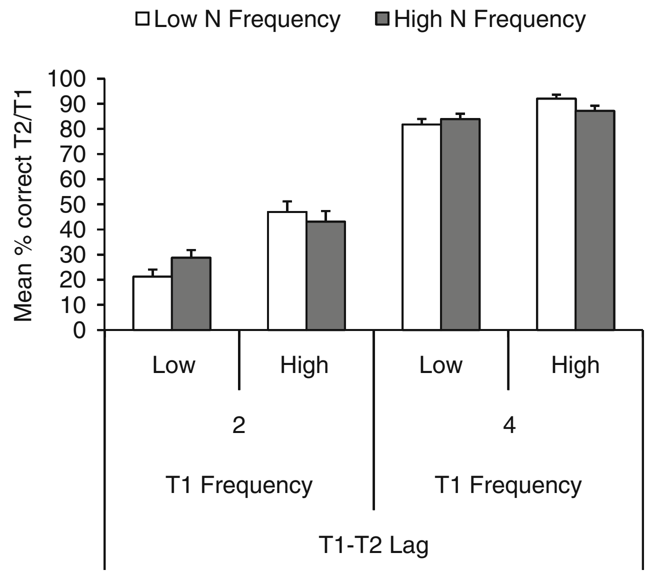

Fig. 5 Experiment 2: Mean percent correct and *SE* for T2 when T1 was correct, as a function of T1-T2 lag, T1 frequency, and T1 neighbor frequency

The only other significant effect was the predicted two-way interaction of T1 neighbor frequency with T1 frequency, $F1(1, 46) = 16.05$, $MSE = 83$, $p < .001$, $F2(1, 60) = 6.93$, $MSE = 98$, $p = .011$, with a 5 percentage points decrease for high-frequency-N with high frequency T1s, and a 5 percentage points increase for high-frequency-N with low frequency T1s. Simple effects analyses showed that both the decrement in accuracy with high-frequency-T1s and the increment in accuracy with low-frequency T1s were reliable by participants but not items, $F1(1, 23) = 5.94$, $p = .023$, $F2(1, 60) = 1.66$, $p = .20$; and $F1(12, 23) = 8.28$, $p = .008$, $F2(1, 60) = 2.15$, $p = .15$, respectively.

Discussion

Frequency effects In Experiment 2 changing to four-letter words and increasing the presentation duration of items in the RSVP largely abolished the floor compression that was evident in Experiment 1. The substantial effect of T1 frequency observed on T1 and T2 accuracy in the AB group of Experiment 1 was replicated. Additionally there was an interaction of T1 frequency and T1-T2 lag on T2 accuracy, with a larger frequency effect at the lag at which the AB was expected to be maximal; that is, the shortest lag. Thus this result indicates that the magnitude of the AB was affected by the frequency of T1. Clearly, word frequency affects an aspect of lexical processing that is compromised in the AB phenomenon. T1 frequency produced an effect of 12 percentage points in T2 accuracy in both the current experiment (over lags 2, 4 and 6) and in the AB group in Experiment 1 (lags 2, 3, 4 and 6). The effect of T1 frequency on T2 accuracy is robust, and it does not appear to be highly sensitive to the overall level of T1 or T2 accuracy.

Neighbor frequency effects In line with previous results in the perceptual identification task, there was a tendency for high neighbor frequency to inhibit identification of T1 at both frequencies (cf. Mathey, 2001), although in separate analyses there was no evidence for an effect for low-frequency T1s ($F1$, $F2 < 1$). As suggested previously, guessing would have differentially disadvantaged low frequency T1s with many and high-frequency neighbors. Analyses of participants' word errors to T1 showed that a majority of guesses were words of higher frequency than the median frequency of T1, and that orthographic neighbor guesses were common, especially to T1s with high neighbor frequency and density.

Most importantly, the effect of T1 neighbor frequency on T2 accuracy was significantly moderated by T1 frequency in the predicted direction, namely a neighbor benefit with low frequency T1s and neighbor impairment with high-frequency T1s. The neighbor effects within levels of T1 frequency were reliable by participants but not by items. It appears that the effects in the item analyses were restricted by ceiling compression at lag 4 and floor compression at lag 2 for some items. The finding of differential neighbor effects as a function of word frequency is consistent with effects of the number of neighbors observed in multiple regression analyses of item means in the LDT by Balota et al. (2004).

Experiment 3

Experiments 1 and 2 established an effect of T1 frequency on the AB, but in some ways the results were atypical of contemporary studies of the AB with letter and digit stimuli. In Experiment 1 presumed floor compression produced an atypical interaction of T1 frequency and T1-T2 lag, with the AB not resolved by the longest lag. In Experiment 2 the effect of T1 frequency was revealed in the expected interaction of T1 frequency and T1-T2 lag, but atypically, T1 difficulty was manipulated between groups. Experiment 3 confirmed the effect of T1 frequency on the AB by examining the interaction of T1 frequency and lag in a single group over 6 T1-T2 lags at the temporal parameters used in Experiment 2. It was expected that the AB would be resolved by lag 6, and that there would be Lag × T1 frequency interaction indicating a steeper AB for low frequency T1s. Also, we examined whether T2 accuracy would be higher at lag 1 than lag 2, although this "lag-1 sparing" effect is observed in only about half of published AB studies (Visser, Davis & Ohan, 2009).

Method

Participants Twenty-four introductory Psychology students participated.

Materials and design All words and nonwords were four letters in length. The neighbor statistics and frequency counts (per million) were taken from the British National Corpus (Kilgarriff, 1995). The critical word set consisted of 144 words of which half were high frequency (median 244.6, range 80–4,392) and half were low frequency (median 4.8, range 1.9–10.6). The frequency sets were matched on the number of orthographic neighbors (mean = 8.4) and their summed frequency (mean = 947.9)

One hundred forty-four words with a mean frequency of 30.5 (range of 1.8 - 119.7) and a mean of 8.4 orthographic neighbors were selected for T2. An additional 16 word pairs with similar characteristics and were selected for T1 and T2 on 16 practice trials. Distractors were pronounceable non-words ($N = 2,080$) selected from the English Lexicon Project database, as in Experiment 2 (Balota, et al., 2007).

T1s of each frequency were placed equally often at positions 4 and 6 within each lag, and there were 12 trials at each T1 frequency at each of the T1-T2 lags 1, 2, 3, 4, 5 and 6. Four lists were constructed in which each T1 word occurred twice at two lags (1 and 4, 2 and 5, or 3 and 6) and with four different T2 words. Similarly each T2 occurred twice at each of two lags, once with a low-frequency T1 and once with a high-frequency T1. No target or distractor was repeated within a list. The trial sequence was randomized in each list, and 16 practice trials were added to the beginning of each list.

Procedure The procedure was as in Experiment 2. As previously, T1 was cyan and T2 was lime green.

Results

T1 accuracy as a function of lag is shown in Table 3. T1 frequency (high vs. low) × Lag (1 to 6) ANOVAs by participants and items (with lag treated as a between-item

Table 3 Experiment 3: T1 accuracy (% correct) as a function of T1 frequency and T1-T2 lag

T1 frequency	T1-T2 Lag					
	One	Two	Three	Four	Five	Six
High	86	90	92	90	90	93
Low	76	72	76	76	75	82

effect) revealed a significant effect of T1 frequency, with accuracy higher for high-frequency T1s, $F1(1, 23) = 41.95$, $MSE = 334$, $F2(1, 276) = 59.87$, $MSE = 234$. There was no significant effect of Lag and no Frequency × Lag interaction.

T2 accuracy on trials on which T1 was correct is shown in Fig. 6. In view of the evidence for lag-1 sparing (T2 accuracy higher at Lag 1 than at Lag 2), the trajectory of the AB was assessed over Lags 2 to 6 in T1-frequency × Lag ANOVAs. Because each word occurred at only 2 lags, lag was treated as a between-item factor in the analysis by items. There were significant effects of T1 frequency, $F1(1, 23) = 65.32$, $MSE = 199$, $F2(1, 235) = 49.73$, $MSE = 411$, and Lag, $F1(4, 23) = 78.63$, $MSE = 293$, $F2(4, 235) = 73.97$, $MSE = 598$. The T1-frequency × Lag interaction was significant by participants, $F1(4, 92) = 4.02$, $MSE = 161$, and approached significance by items, $F2(4, 235) = 2.23$, $MSE = 411$, $p = .066$. An additional items analysis was conducted for the lags capturing the resolution of the AB and having a within-items variation of lag (namely, lags 3 and 6). In this analysis the T1-frequency × Lag interaction was significant, $F2(1, 47) = 8.27$, $MSE = 380$. A final comparison was conducted for Lags 1 and 2 to assess the lag-l sparing effect (see Fig. 6). The sparing effect was confirmed, with T2 accuracy higher at Lag 1 than Lag 2, $F1(1, 23) = 4.81$, $MSE = 367$, $F2(1, 94) = 3.99$, $MSE = 888$.

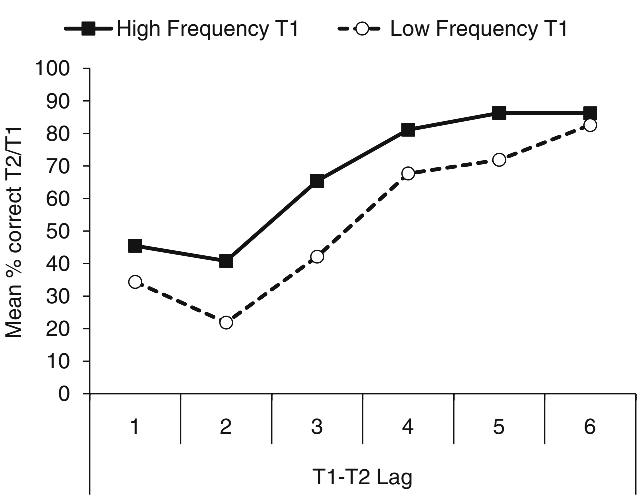

Fig. 6 Experiment 3: Mean percent correct and *SE* for T2 when T1 was correct, as a function of T1-T2 lag and T1 frequency

Discussion

In contrast to traditional AB studies with items repeatedly sampled from small sets of letters and digits, the present RSVP trials were composed of items sampled only once from large item pools, and targets were words and distractors were nonwords. Nevertheless, the typical trajectory of the AB was evident in T2 accuracy over lags 2 to 6. Furthermore, there was a small lag-1 sparing effect, with T2 accuracy higher at lag 1 than at lag 2. The results for the AB collapsed over T1 difficulty replicated those found by Maki et al. (1997) with word targets and nonword distractors.

As in Experiments 1 and 2, the normative word frequency of T1 had a substantial impact on both T1 accuracy and on the magnitude of the AB. The effect of T1 frequency on the trajectory of the AB was confirmed in a significant T1-frequency × Lag interaction over lags 2 to 6. The consistency of this result over individual words was supported by a significant T1-frequency × Lag interaction in within-item analyses at lags 3 and 6, and a marginally significant interaction over lags 2 to 6 when lag was a between-items factor. Because T1 frequency was varied within participants, Experiment 3 confirms that the AB was affected by trial to trial changes in the difficulty of identifying T1.

General discussion

Overview Varying T1 difficulty by varying the normative frequency of T1 produced the predicted effects on T1 and T2 accuracy and the AB. In Experiment 1 the AB group that identified T1 and T2 showed a deficit in T2 accuracy when T1 was a low frequency word, but no such deficit was found for the control group that identified only T2. This result confirms an effect of T1 difficulty on the AB. In Experiments 2 and 3, the effect of T1 frequency on the AB was confirmed in AB groups by a T1 frequency interaction with T1-T2 lag. Variation in the frequency and size of T1's orthographic neighborhood was expected to affect the AB differentially as a function of T1 frequency, with different effects on T1 difficulty for high- and low-frequency T1s. Consistent with predictions, increasing orthographic neighbor frequency was associated with a decrement in T2 accuracy when T1 was high-frequency and an increment in T2 accuracy when T1 was low-frequency.

Implications for the AB The effect of T1 manipulations on the AB was achieved without changing the nature of the distractors, the format of the stimulus display or the response requirement. The effect of T1 frequency in Experiment 1 was confirmed to have its locus in the AB by a comparison with a control group not identifying T1. In Experiment 2 neighbor variables were manipulated only for lags clearly within the

AB, and presumably for this reason the small effects of neighbor frequency did not interact with lag.

The implications of the T1 frequency effect for theories of the AB depend upon whether the theories apply equally to the traditional digit and letter stimuli and to the more complex stimuli used here. Experiment 3 and previous studies of the AB with word targets (e.g., Maki et al., 1997; Martens, Wolters, & van Raamsdonk, 2002) and other complex stimuli (Raymond & O'Brien, 2009) suggest that the AB takes a similar form over a variety of target types. However, because the theories have mainly addressed the findings with simple, highly familiar stimuli such as digits and letters, it must be acknowledged that the additional encoding demands of words may be somewhat beyond the scope of some theories of the AB.

The effects of T1 frequency on the AB in the three experiments are clearly consistent with resource depletion models that attribute the AB to the demands of processing T1. These models include structural bottleneck accounts of the AB (Jolicoeur, 1999a) and two-stage models, the most well known being that of Chun and Potter (1995). On the latter model the extra time taken to consolidate T1 for report delays and perhaps prevents the consolidation of T2. Word frequency has a natural role in this model in that it plausibly affects the first stage, accessing a word in memory, and perhaps also the second stage, consolidation of a word's phonology or orthography for report.

By contrast, T1 difficulty has no clear role in attentional control theories, primarily because for these theories the locus of the AB effect is in processes instigated after T1 identification is completed or largely completed. In particular, the effects of T1 word frequency do not support the prediction of the Boost and Bounce model that T1 difficulty does not affect the AB (Olivers & Meeter, 2008). Olivers and Meeter noted interpretational issues with previous demonstrations of T1 difficulty effects on the AB, arising because the post-T1 mask was changed to make T1 identification more difficult, or task or location switches were required between T1 and T2. In the present studies these problems do not apply; T1 masking conditions were identical over levels of T1 difficulty, T1 and T2 were words in the same location, and participants were required merely to identify T1 and T2. Similarly, the attentional engagement theory (Nieuwenstein et al., 2009) accords no direct role in the AB to the time taken to identify T1. Therefore the effect of T1 difficulty poses challenges for these theories as a comprehensive account of the AB. As noted, however, the theories largely address findings with letter and digit targets rather than the present findings with word targets. Modifications of these theories might take the form of a delay in the initiation of the inhibition of distractors, or a delay in attentional disengagement, as a result of prolonged processing time for T1.

The present results also pose difficulties for the Temporary Loss of Control (TLC) account of the AB, which emphasizes the role of the T1 + 1 distractor in perturbing control over the endogenous task set configuration to select the targets from the stream of distractors (nonwords, Di Lollo et al., 2005). The effect of T1 frequency might be reconciled with this account by assuming that the increased difficulty of identifying low-frequency words increases the destabilisation of the control over the system configuration. However, this acknowledgement of a role of T1 processing load in the AB is a problem given that the authors have rejected resource depletion theories.

The eSTST model of Wyble et al. (2009) has not addressed T1 difficulty effects. It is possible that encoding time could be added as a parameter for more complex targets of the kind used here. As a result more slowly encoded items (low frequency words) would have delayed consolidation as distinct events in working memory (tokenisation), and thus the period of inhibitory influence on attention to subsequent targets that occurs during tokenization would be prolonged.

In models in which distractors play a key role in the AB, notably the Boost and Bounce (Olivers & Meeter, 2008) and the TLC (Di Lollo et al., 2005), it might be argued that T1 frequency exerts its effects on the discriminability of T1 and the distractors, with low frequency T1s being more similar to nonword distractors than are high-frequency words. In a similar vein, high neighbor frequency may reflect an increase in the orthographical typicality of words and a decrease in the similarity between T1 and the nonword distractors. According to Olivers and Meeter (2008), if T1 is more discriminable from the distractors then the inhibition recruited by the T1 + 1 distractor is reduced and thus the AB is less severe. On the TLC theory, the control over the configuration of the attentional set may be easier when target-distractor discriminability is high.

The obvious objection to the above suggestion is that targets were colored differently from distractors in all of the present experiments. Any effect of T1-distractor discriminability can be expected only when selection by color is ineffective. Further, in all experiments we controlled the orthographic similarity of high and low frequency words to other words by matching frequency sets on orthographic neighbor variables. Experiment 1 used six letter words, which have few orthographic neighbors. Consequently we applied a recent similarity metric devised by Yarkoni, Balota, and Yap (2008) from the Levenshtein distance, which is based on the number of operations required to change one word into another. Orthographic and phonological distinctiveness scores, based on the 20 most similar words for each word, were obtained for 239 of the 240 T1 words used in Experiment 1. Phonological distinctiveness of T1 was associated with a decrease in both T1 accuracy, $r = -.14$, and T2 accuracy, $r = -.25$. Orthographic distinctiveness was associated with lower T2 accuracy, $r = -.20$, and had no association with T1 accuracy. However, when the distinctiveness measures were entered as covariates in the item analyses of T1 accuracy, and also in analyses of T2 accuracy by T1 item, there was no change in the results for word frequency. Thus it is unlikely that the T1 frequency effect on the AB was observed because low frequency T1s were more orthographically or phonologically confusable with nonwords than were high frequency words.

Furthermore, the neighbor frequency effects in Experiment 2 could not be explained in terms of increases in word-nonword discriminability with increasing neighbor frequency. There was an effect on T1 accuracy in the opposite direction, with high neighbor frequency decreasing the accuracy of high-frequency T1s. Additionally, a neighbor effect on target discriminability cannot explain the T1 neighbor frequency × T1 frequency interaction on T2 accuracy, indicating a neighbor benefit for low frequency targets and a deficit for high frequency targets.

Implications for visual word identification Assessing the effects of T1 characteristics on identification accuracy for a later target (T2) removes the effects of lexical variables on guessing strategies directed at T1, and allows a clear assessment of their effects on the difficulty of lexical processing. Thus the AB paradigm used here has an advantage over the perceptual identification task, and provides a useful accuracy-based complement to the latency measures obtained in the traditional lexical tasks, lexical decision and speeded naming. It has proved to be a sensitive assessor of the effects of orthographic neighborhood frequency.

The results of Experiment 2 support the conclusions of Balota et al. (2004) that typically neighbors decrease response latencies for low frequency English words whereas they increase response latencies for high-frequency words. Neighbor benefits may reflect improvements in the efficiency of lexical access, or phonological activation from orthography (Seidenberg & McClelland, 1989), by virtue of the increase in activation of grapheme or phoneme units shared by the target with neighbor words. On the other hand, neighbor deficits suggest competitive inhibition by activated neighbor words, as developed in interactive activation models (Grainger & Jacobs, 1996). Balota et al. (2004) examined the number of neighbors, whereas in the present work neighbor frequency was the primary variable, with a concomitant variation in the number of neighbors. Taken together with previous results (Pollatsek, Perea, & Binder, 1999), the present results suggest that both neighbor frequency and the number of neighbors are important factors in orthographic similarity effects.

In the context of word reading research, word frequency is a robust marker of the amount of word learning and of the quality of memory representations of words that serve reading and spelling (Burt & Tate, 2002). Memory access for high frequency words is rapid and accurate as a result of repeated processing of the orthography and the links between orthography, phonology and meaning. Thus word frequency may be an index of the attentional demands of several aspects of lexical processing, including letter cluster identification, memory access and retrieval of orthographic or phonological responses.

Conclusion The strong effect of word frequency on the AB observed here is consistent with evidence that frequency sensitive processing of words is subject to the central bottleneck (McCann et al., 2000), and more generally, with the resource depletion theories according to which the demands of identifying T1 are primarily responsible for the AB (Chun & Potter, 1995; Jolicoeur, 1999b). The combined effects of T1 frequency and neighbor frequency cannot easily be reconciled with the Boost and Bounce theory in its present form (Olivers & Meeter, 2008) or with other approaches that attribute the AB to attentional control processes facilitating the selection of targets. With respect to lexical processes, the present studies suggest that the effects of lexical variables on visual word identification may be sensitively assessed in the AB paradigm with nonword distractors. Future research in the RSVP in readers varying in skill may illuminate the processing demands of word identification and their limitations on performance under time pressure.

Author Note Experiment 1 was conducted by the second and third authors as part of an undergraduate research apprenticeship.

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