

## Effects of Phonological Length on the Attentional Blink for Words

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The authors tested whether the attentional blink (AB), a deficit in the ability to report a second target appearing within half a second of a first target, may reflect limitations for consolidating visual stimuli into working memory and awareness. Previous research has shown that people are severely limited in the rate that they can identify and report visual events presented in rapid succession. Word length was examined, a variable known to affect verbal working memory. Experiment 1 showed that the AB was modulated by the phonological length of the first target. Phonologically longer pseudowords triggered larger blink deficits. Experiment 2 also demonstrated the word-length effect on the AB using real-world stimuli, anagrams, that controlled for low-level visual differences between conditions. These data support proposals that the AB reflects a difficulty in consolidating information into working memory.

The attentional blink (AB) paradigm demonstrates the rate-limited nature of attention. The AB occurs when the task is to identify two targets presented within a stream of distractors (known as *rapid serial visual presentation* [RSVP]). Attention devoted to the first target (T1) compromises the ability to identify the second target (T2) if it appears within a half second of T1, demonstrating that there are severe limitations in the number of items that we can consciously perceive within a second's time (Broadbent & Broadbent, 1987; Chun & Potter, 1995; Duncan, 1980; Raymond, Shapiro, & Arnell, 1992; Sperling, 1960; Ward, Duncan, & Shapiro, 1996; Weichselgartner & Sperling, 1987).

A variety of models have been offered to explain the AB, and there is now a strong consensus that the AB occurs postperceptually, namely, after initial semantic identification of the input has occurred for all items including those targets unavailable for overt report (Luck, Vogel, & Shapiro, 1996; Maki, Frigen, & Paulson, 1997; Shapiro, Driver, Ward, & Sorensen, 1997; Vogel, Luck, & Shapiro, 1998). The AB is caused by difficulties in encoding visual events into a more durable store (Chun, 1997; Chun & Potter, 1995; Jolicoeur, 1998; Shapiro, Arnell, & Raymond, 1997; Shapiro, Raymond, & Arnell, 1994). An important prediction of some

models is that increasing the difficulty of processing T1 should increase the magnitude and duration of the AB (Chun, 1997; Chun & Potter, 1995; Jolicoeur, 1998). Thus, items that are difficult to encode lead to a larger AB.

But what is difficulty? Task difficulty may arise early in processing, at a perceptual level, because of low signal-to-noise ratios. Task difficulty may also arise at later stages of processing, such as memory consolidation or retrieval interference. Because the AB literature has focused on visual processing, this literature has tended to emphasize perceptual difficulty. For instance, items that are difficult to visually discriminate or are masked lead to a larger blink (Chun & Potter, 1995; Moore, Egeth, Berglan, & Luck, 1996; Raymond et al., 1992). Raymond et al. (1992) demonstrated that the AB was triggered by the presence of an interfering event in the T1 + 1 position, and Chun and Potter (1995) extended these findings by showing that the magnitude of the AB is dependent on the discriminability between T1 and its immediately following item. Masking plays a critical role in modulating T1 processing difficulty with concomitant effects on blink magnitude, and interference can be obtained from either nonpatterned masks (Grandison, Ghirardelli, & Egeth, 1997), metacontrast masks (Seiffert & Di Lollo, 1997), or spatially crowded distractors (Marois, Chun, & Gore, 2000). In summary, variables that degrade the perceptual integrity of a visual event will increase the time it takes to process and consolidate it.

Nonperceptual manipulations of task difficulty can also modulate the AB under certain task situations. For instance, participants typically make unspeeded responses to targets in AB tasks. However, Jolicoeur (1998) showed that changing the response requirements for T1 to a speeded task increased the AB. In addition, increasing the number of first target response alternatives increases the magnitude of the AB in speeded-response tasks (Jolicoeur, 1999). These results suggest that the consolidation bottleneck process in AB consumes central processing resources that must be

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shared with other capacity-limited processes, such as speeded-response selection.

However, not all types of difficulty manipulations affect the AB. First, Shapiro et al. (1994) did not observe modulation of the AB when task difficulty was varied by requiring discrimination of the duration of a temporal gap interval. This suggests that the AB is limited to targets that contain visual pattern information (such as letters, words, and pictures). Second, Ward, Duncan, and Shapiro (1997) varied the difficulty of size discrimination for T1 and found that T1 performance varied according to discrimination difficulty, but T2 performance did not. Size discrimination judgment in Ward et al.'s task may have been made subsequent to the formation of a durable representation of the target in working memory. This is consistent with Jolicoeur's (1998, 1999) demonstration that manipulations of response-selection difficulty only affect the AB in speeded, "on-line" tasks. Third, Marois et al. (2000) examined the AB in a task that varied the difficulty of lexical decision on T1 targets that were not perceptually masked. T1 performance varied according to lexical decision difficulty, but this did not affect the AB for T2. Moreover, the lexical decision difficulty manipulation did not activate cortical areas that were shown to be sensitive to perceptual interference manipulations that modulated the AB (Marois et al., 2000; see also Wojciulik & Kanwisher, 1999). Finally, McLaughlin, Shore, and Klein (2001) varied the relative stimulus duration of T1 and the immediately following mask. Although a shorter T1 (and correspondingly longer mask duration) made it harder to detect, this did not produce a larger AB for T2. This provided a new exception to the general finding that perceptual manipulations of T1 difficulty affect AB. In this case, it is possible that the T1 task was so difficult that performance became data limited in the sense that attention could not further improve performance (Norman & Bobrow, 1975). In other words, the same amount of attention may have been allocated to both easy and hard T1 conditions, producing similar T2 performance levels.

On the basis of these various findings, we can hypothesize that the blink is sensitive to only those variables that immediately affect attentional processing between initial sensory registration of a target and consolidation into working memory. The difficulty of tasks that can be performed on representations in working memory, after consolidation has been completed, do not affect T2 performance. In addition, task difficulty in data-limited situations does not influence the AB.

Are there manipulations of nonperceptual factors that may affect the magnitude of the AB in unspeeded T1 tasks? Using a non-AB dual-task paradigm, Jolicoeur and Dell'Acqua (1998) used a task in which participants reported the identity of the first visual target and then responded as quickly as possible to the second target, a tone. Results from this study suggest that short-term consolidation of the first target delays the processing of a second target in a non-AB task. Thus, it seems likely that a manipulation that influences the speed and efficacy of consolidation will modulate the AB.

In this article, we provide further evidence for a consolidation bottleneck process in an AB task. We manipulated phonological word length, a variable known to affect the difficulty or load of verbal working memory (Baddeley, Thomson, & Buchanan, 1975). Increasing the phonological length of words reduces the capacity of working memory. According to Baddeley and Hitch (1974), working memory has an overarching attentional controller

(the central executive) aided by the separate storage buffers of the phonological/articulatory loop and of the visuospatial scratchpad. Evidence for the phonological/articulatory loop comes from the word-length effect, in which immediate memory for a list of long words is poorer than that for short words. The word-length effect is thought to be caused by the longer time needed to subvocally rehearse long words compared to short words, thereby taxing the phonological/articulatory loop subsystem of working memory. In these experiments, word length was typically manipulated by varying the number of syllables. However, the effect can be seen with words varying only in articulatory duration (Baddeley et al., 1975). This suggests that the word-length effect reflects a sensitivity to articulatory length, measured either by number of syllables or by spoken duration. Converging evidence for the phonologically limited capacity of working memory was obtained by Ellis and Hennessey (1980). In their study, Welsh-English bilinguals performed an immediate digit recall task. All participants remembered more English digits than Welsh digits, presumably because Welsh vowel sounds take longer to pronounce than do English vowel sounds. However, if participants were prevented from subvocalization, there was no difference between the English and Welsh digit spans. Thus, subtle differences in phonological word length cause overloading of the articulatory loop of working memory, leading to deficits in immediate recall.

We conjectured that word length may also influence the process of consolidation into working memory.<sup>1</sup> In other words, it may take more time and attentional processing to rapidly encode phonologically long words than short words. If so, the word-length effect should modulate the magnitude of the AB. Specifically, we propose that increasing the phonological length of targets will produce a greater deficit in the AB because processing phonologically long words may consume attentional consolidation mechanisms for a longer duration relative to the processing of short words. Such a result would indicate that one critical bottleneck in processing word stimuli is working memory consolidation. Our study differs from classic working memory studies in that we are interested in the attentional requirements of encoding (or consolidation), not maintenance or retrieval in working memory. A crucial basis for the present work is provided by a recent study by Coltheart and Langdon (1998), who showed that phonological length affects working memory encoding. They demonstrated a word-length effect at high presentation speeds and suggested that at fast presentation speeds, rehearsal is not possible. Thus, the word-length effect can at times be due to a difficulty in consolidating phonological representations in working memory.

Phonological length can be defined in multiple ways (e.g., number of phonemes, articulatory duration, number of syllables), and in our study, we operationally define phonological length as the number of syllables. We varied the phonological length of words and pseudowords, as have previous researchers (e.g., Baddeley et al., 1975; Coltheart & Langdon, 1998).

Note that we are not suggesting that all AB effects are due to the attentional demands of recoding and consolidating visual informa-

<sup>1</sup> We use the term *consolidate* to refer to the process of encoding information into durable working memory. This terminology follows prior convention in the AB literature (Chun & Potter, 1995; Jolicoeur, 1998, 1999).

tion into phonological form. The AB can be triggered by unnameable novel visual shapes, and numerous factors influence the blink without any relevance to phonological codes. We suggest that word length may be one form of difficulty that affects the AB and that it does so because of a verbal working memory encoding bottleneck. We rely on this manipulation to provide converging evidence that consolidation is a critical bottleneck process in the AB, especially for pronounceable words.

### Experiment 1

In an initial pilot experiment, we confirmed a general effect of word length on the AB. The task was to report two green target words appearing in an RSVP stream of black distractor words. The T1 stimuli were either one-syllable or four-syllable words matched for word frequency. The T2 stimuli were two-syllable words, also controlled for frequency. The pilot experiment could not distinguish whether the effect was phonological or visual because syllabic length was confounded with orthographic length. However, longer T1 words led to significantly larger AB, suggesting the possibility of a phonological length effect.

It is difficult to decouple orthographic length and syllabic length using real English words because the two are highly correlated. To overcome these difficulties, we used pronounceable pseudowords in Experiment 1. We created two sets of pronounceable pseudowords (Appendix A) that differed by phonological length but had identical visual lengths, such as *blouthe* and *eclodia*. We defined phonological length by number of syllables and visual length by number of letters. In addition, we included two other conditions that manipulated visual length while controlling for phonological length. The visually short condition had the same number of syllables but fewer letters than the phonologically short condition. The visually long condition had the same number of syllables as the phonologically long condition but more letters.

### Method

**Participants.** Ten paid volunteers participated in the experiment. All of the participants reported normal or corrected-to-normal vision. None were aware of the purpose of the experiment.

**Design and procedure.** Stimuli were pronounceable pseudowords. There were four main conditions: visually short (VS), phonologically short (PS), visually long (VL), and phonologically long (PL). The short pseudowords were one syllable long and the long pseudowords were four syllables long. The four conditions were manipulated by using different sets of T1 stimuli (see Appendix A): 28 one-syllable pseudowords with a mean visual length of 3.5 letters and mean phonemic length of 3.2 (condition VS); 28 one-syllable pseudowords with a mean visual length of 6.8 letters and mean phonemic length of 4.1 (condition PS); 28 four-syllable pseudowords with a mean visual length of 6.8 letters and mean phonemic length of 6.9 (condition PL); or 28 four-syllable pseudowords with a mean visual length of 9.5 letters and mean phonemic length of 8.9 (condition VL). Although we did not manipulate phonemic length, it correlated highly with syllabic length ( $r = .94$ ).

T2 was always a two-syllable real word ( $N = 56$ ) of more than four letters. Because T2 was just a probe, we used real words to make this difficult task more manageable. Each trial consisted of 15 items, 2 targets and 13 distractors. Distractors were randomly drawn from a set of 79 four- or five-syllable pseudowords. T1 was always a one-syllable or four-syllable pseudoword, whereas T2 was always a two-syllable real word. T1 appeared in green, T2 in blue, and the distractor words were always in

black. Because it was important for participants to at least report the first target, we presented T2 in blue, which was less salient than green. This helped participants place more weight on reporting T1. Stimulus presentation was computer randomized. The position of T1 was randomly permuted so that it appeared an equal number of times in Serial Positions 2–5. Three lags between T1 and T2, Lag 2 (stimulus onset asynchrony [SOA] = 294 ms), Lag 4 (SOA = 588 ms), and Lag 8 (SOA = 1,176 ms), were crossed with the five serial positions of T1. One practice block of 20 trials was followed by four experimental blocks of 48 trials each.

Prior to the experiment, there was a familiarization phase in which participants were instructed to slowly scroll through the stimuli word list, pronouncing each pseudoword aloud. Pronunciation was monitored and verbally corrected when necessary. Participants were also instructed to pay attention to the spelling of the pseudowords.

The experiment was self-paced. The participant began each trial by pressing the space bar on the computer keyboard. A fixation dot appeared for 200 ms and then disappeared for 147 ms. The stream of stimuli then appeared successively without interstimulus blanks at the same location for 147 ms each. The sequence was followed by a blank screen for 147 ms, then a screen instructing the participant to report the first target then the second target. No feedback was given.

The experiment was carried out in normal room illumination held constant for all participants. Exactly correct spelling was not necessary for a correct response. Phonologically correct spellings were permissible responses, with vowel replacements allowed.

**Apparatus.** The experiment was conducted on a Macintosh computer. The software used for running the experiments was MacProbe (Hunt, 1994). The word stimuli were presented in 24-point Geneva font on a 17-in. (43.2-cm) monitor. The stimuli were viewed from an average distance of 40 cm. The background was a uniform gray field.

### Results

T1 error rates were significantly different between all conditions, with a main effect of word length,  $F(3, 27) = 159.25, p < .0001$ . Mean T1 performance for the four conditions in order of ascending visual length were VS = 96%, PS = 75%, PL = 58%, and VL = 20%. In separate analyses, we examined how T1 performance was affected by visual length and phonological length. When T1 was visually long, it was more difficult to report, as compared with visually shorter but phonologically similar words: VL versus PL,  $F(1, 9) = 237.88, p < .0001$ ; VS versus PS,  $F(1, 9) = 98.24, p < .0001$ . When T1 was phonologically long, it was also more difficult to report, as compared with phonologically shorter but visually similar words: PS vs. PL,  $F(1, 9) = 12.20, p < .0068$ . Hence as expected, T1 difficulty varied as a function of increasing orthographic and phonological length.

**Phonological word length.** The first analysis examined the effects of phonological length, using the PS and PL conditions that were equated for orthographic length. The results are shown in Figure 1. Correct identification of T1 produced a lag-dependent deficit for reporting T2; thus there was a main effect of lag,  $F(2, 18) = 43.87, p < .0001$ . The main effect of phonological word length was not significant ( $p > .1012$ ), but there was a significant interaction between pseudoword length and lag,  $F(2, 18) = 6.60, p < .0071$ . The significant interaction demonstrates that phonologically long words led to greater AB only at short temporal intervals. The sizes of the word-length effect on the AB were 14%, 16%, and -11%, at Lags 2, 4, and 8, respectively. Long words affected report of T2 only at shorter lags: Lag 2,  $F(1, 18) = 5.34, p < .0329$ ; Lag 4,  $F(1, 18) = 7.80, p < .0120$ ; whereas at the longer Lag 8, performance did not statistically differ between the

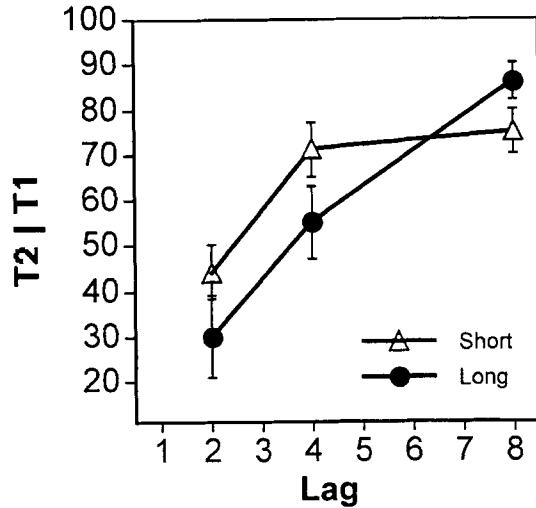


Figure 1. The effect of phonological word length on the attentional blink, controlled for orthographic length: mean T2 performance given T1 performance as a function of time lag in Experiment 1. Error bars represent the standard error of the mean. T1 = first target; T2 = second target.

two conditions. This confirms our hypothesis that processing phonologically long pseudowords engages consolidation mechanisms for a longer duration (Stage 2 processing or visual short-term memory (VSTM) retrieval)—relative to the processing of short pseudowords. Therefore, the AB exhibits a word-length effect.

**Visual word length.** We conducted two comparisons of visual length. The first comparison used the results from the four-syllable conditions, VL and PL, which differed in visual length, in a  $2 \times 3$  two-way factorial analysis of variance (ANOVA), with visual length (short vs. long) and lag submitted as separate independent factors. Mean T2/T1 report performance for the short condition versus the long condition was 39% versus 36%, 66% versus 66%, and 87% versus 63%, for Lags 2, 4, and 8, respectively. Thus, the sizes of the effect on the AB were 3%, 0%, and 24%, respectively. There were main effects of visual length,  $F(1, 9) = 5.45, p < .0444$ , and lag,  $F(2, 18) = 56.76, p < .0001$ . The interaction between visual length and lag was also significant,  $F(2, 18) = 4.87, p < .0204$ . However, pairwise comparisons revealed a significant difference between conditions only at Lag 8,  $F(1, 18) = 16.35, p < .0008$ , which is beyond the typical time range of the AB. Performance did not differ at Lags 2 ( $p > .25$ ) or 4 ( $p > .25$ ). Although it is possible that the results indicate an unusually long AB, this seems unlikely given the lack of a difference at the shorter lags. These results suggest that visual word length does not have a strong impact on consolidation into working memory. This theory is further investigated in our second analysis of visual word length.

In the second analysis of visual length, we compared the one-syllable conditions, VS and PS, which differed in visual length. Mean T2/T1 report performance for the VS condition versus the PS condition was 48% versus 44%, 77% versus 71%, and 87% versus 75%, for Lags 2, 4, and 8, respectively. There was a significant effect of lag,  $F(2, 18) = 47.18, p < .0001$ , and a marginally significant effect of visual length,  $F(1, 9) = 4.77, p < .0568$ . However, the interaction between visual length and lag was not significant ( $F < 1$ ). Thus, in both analyses of visual word length,

visually longer words impaired report of T2 in general, but not in a lag-specific manner.

### Discussion

The results from Experiment 1 suggest two findings. First, whereas previous results have shown that there is a visual AB (e.g., Shapiro et al., 1994) and possibly an auditory AB (Arnell & Jolicoeur, 1999; Duncan, Martens, & Ward, 1997; but see Potter, Chun, Banks, & Muckenhoupt, 1998), our results show that there is also a verbal or phonological AB. Unlike the stimuli used in auditory AB studies, the stimuli used in Experiment 1 were visual, but were encoded phonologically. Evidence for a phonological AB was demonstrated by a manipulation that increased the phonological length of words but held the visual length constant. This made T1 processing more difficult and led to a larger AB. Second, we found that increasing the visual length of words makes T1 processing more difficult but does not affect the AB in a lag-dependent manner. When words were extremely long visually, there was a corresponding increase in the AB, but the difference was at long lags rather than short lags. This suggests that visual word length did not affect the consolidation process in AB, which is more capacity limited at shorter lags. Smaller manipulations of visual length only marginally affected the AB and also did not modulate the AB in a lag-dependent manner.

Because T1 performance differed so markedly in the two phonological conditions, we felt that it was necessary to examine whether T1 was somehow differentially affecting T2, apart from the AB. For instance, a short T1 or an unusual letter cluster might serve as some sort of perceptual signal for T2. If so, differential reporting of T2 would result. To ensure that the AB effect was not due to a perceptual difference between conditions, we conducted a standard control condition in which observers were instructed to report only T2.

Seven new volunteers participated in this experiment. The design was identical to Experiment 1 except that only the PS and PL conditions were used, and participants were instructed to report only the second colored target word. T2 error rates did not significantly differ between word length conditions ( $F < 1$ ). Mean T2 performance was PS = 76% and PL = 74%. As expected, there was no difference between the two phonological conditions when only T2 was reported. This replicates Raymond et al.'s (1992) demonstration that an AB is triggered by attending to and processing T1. The lack of a difference in this control experiment demonstrates that the effects of phonological length were not due to any other possible low-level differences in the PS and PL stimuli sets.

### Experiment 2

Experiment 1 demonstrated that the phonological length of T1 modulates the AB, but it is possible that this result is restricted to pseudowords. Although the use of pseudowords controlled for visual length, it is possible that the frequency of certain letter clusters (e.g., *-ough* and *-outhe*) was not controlled for between PS and PL conditions. In addition, unfamiliarity with pseudowords may have contributed to the effect.

To circumvent such potential confounds and to assess the robustness and generality of our results with converging evidence,

we performed another experiment. The stimuli were real-word anagrams. Anagrams are useful because a word and its anagram can have differing syllabic lengths, for instance, *zoned* and *dozen*, but identical low-level visual features. Word frequency was also controlled. Two conditions were tested in the AB paradigm: phonologically short (one-syllable) and phonologically long (two-syllable) words.

### Method

**Participants.** Eighteen paid volunteers participated in the experiment; 2 were excluded for poor performance and failure to follow instructions (less than 15% of T2s reported overall). All of the participants reported normal or corrected-to-normal vision. None were aware of the purpose of the experiment.

**Design and procedure.** The design of Experiment 2 was similar to that of Experiment 1. Stimuli in the two conditions were anagrams. Fourteen T1 stimuli were one-syllable words (PS condition) and 14 T1 stimuli were two-syllable words (PL condition). The mean phonemic length in the PS condition was 3.7 phonemes, and in the PL condition, 4.36 phonemes. These stimuli are shown in Appendix B. Visual length and word frequency was matched across conditions (Thorndike & Lorge, 1944/1972). The T2 stimuli were the same as those used in Experiment 1. Distractors were also the same as in Experiment 1.

Both T1 and T2 appeared in green, whereas the distractor numbers were always in black. The position of T1 was randomly permuted so that it appeared an equal number of times in Serial Positions 2–5. Seven lags between T1 and T2, from Lag 1 (no intervening items, SOA = 107 ms) to Lag 7 (SOA = 749 ms), were crossed with the four serial positions of T1. As in Experiment 1, the experiment began with a familiarization phase in which participants were instructed to slowly scroll through the target word list. Next, they performed one practice block of 20 trials, followed by four experimental blocks of 56 trials each. Feedback was provided in the form of high-pitched beeps, and the data were scored as in Experiment 1.

### Results

Performance on T1 and T2 given T1 were considered separately and submitted to separate  $2 \times 7$  two-way ANOVAs with condition (short vs. long length) and lag (1–7) as factors. Measures of T2 performance were based only on trials in which T1 was correctly identified. Correct identification of T1 produced the typical AB effect. Figure 2 shows the proportion of trials in which T2 was correctly reported given correct report of T1. The important comparison is between the PS and PL conditions as a function of lag. The standard AB effect was found in the main effect of lag,  $F(6, 90) = 45.08, p < .0001$ . Also, long words increased the size of the blink, shown in the main effect of phonological length,  $F(1, 15) = 8.22, p < .0117$ . The size of the word-length effect on the AB was 1.3%, 6.6%, 8.6%, 3.1%, –3%, 1.5%, and .04% at each lag, respectively. However, the interaction between lag and word length was not significant ( $F < 1$ ). We tested to determine whether an interaction would be more apparent if data was combined across the early lags (2–4) and later lags (5–7), excluding Lag 1. This interaction approached significance,  $F(1, 90) = 3.37, p < .0697$ .

Mean correct report performance on T1 regardless of T2 performance was 92% for the PS condition and 92% for the PL condition ( $F < 1$ ). To further analyze the T1 data, we split it into two groups: those who had lower T1 performance in the PL condition as compared with the PS condition ( $N = 8$ ), and those whose T1 performance was equal or higher in the PL condition as

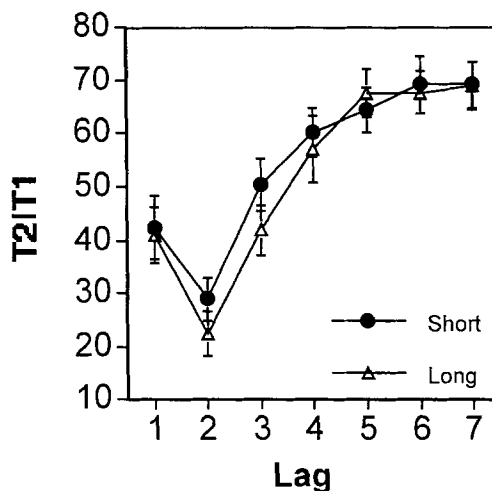


Figure 2. The effect of phonological word length on the attentional blink: mean T2 performance given correct T1 as a function of lag in Experiment 2. Error bars represent the standard error of the mean. T1 = first target; T2 = second target.

compared with the PS condition ( $N = 8$ ). We analyzed their AB data separately. This analysis showed that only participants who had difficulty reporting the phonologically longer words in the T1 position showed an effect of condition on the AB,  $F(1, 7) = 9.96, p < .0160$ . The participants who showed no impairment on phonologically long words in the T1 position did not show an effect of condition in the AB,  $F(1, 7) = 1.37, p > .25$ . Both groups showed the standard lag effect (both  $ps < .0001$ ). These data suggest that the AB is modulated by the difficulty of processing T1.

### Discussion

These data from Experiment 2 provide converging evidence that the AB is modulated by phonological length, because the anagram stimuli controlled for orthographic features, visual word length, and certain phonemic features. Analysis of the T1 data showed that when T1 processing was difficult, there was a larger AB, but it was not larger when T1 processing was easy. This may reflect the differential use of phonological versus visual strategies for processing targets. Some participants may have processed the word stimuli by an orthographic route, relying more heavily on visual features of the word than on phonological features. This strategy would lead to similar performance across conditions because visual features were similar across conditions.

The word-length effect was smaller in Experiment 2 than in Experiment 1. A  $t$  test between AB effect sizes at Lag 2 found no difference,  $t(24) = 0.685, p = .373$ , but the difference approached significance at Lag 4,  $t(24) = 2.064, p > .053$ . In addition to the difference between processing pseudowords and real words, we think the most likely explanation for the smaller effect size in Experiment 2 is that the syllabic differences were small. Coltheart and Langdon (1998) found a difference of 7–12% between recall of one-syllable words as compared with four-syllable words, using similar presentation speeds. The results of Experiment 2, which used one-syllable differences, were at the low end of this spectrum (a decrement of approximately 8% at Lags 2 and 3). The AB effect

in Experiment 1, which used three-syllable differences, was slightly larger (14% at Lag 2) than what Coltheart and Langdon reported. These results converge to suggest that syllabic length correlates predictably with target encoding difficulty and the magnitude of interference on T2.

### General Discussion

The AB demonstrates a fundamental property of human information processing, that there are severe limitations in the number of items that humans can consciously report within a second's time (Broadbent & Broadbent, 1987; Chun & Potter, 1995; Duncan, 1980; Raymond et al., 1992; Sperling, 1960; Ward et al., 1996; Weichselgartner & Sperling, 1987). Our experiments suggest that the word-length effect modulates the AB. A phonologically longer T1 target produced more interference for reporting a second word appearing within half of a second. This effect was due to the phonological length of the stimuli, because we varied syllabic length of pronounceable pseudoword stimuli that were controlled for visual orthographic length. Phonologically long words (or pseudowords) may engage attentional mechanisms for target consolidation into verbal working memory, creating a larger reporting deficit for T2, relative to phonologically short words.

Taken together, these results suggest that the temporal limits on the ability to report words or alphanumeric stimuli may be partially due to verbal working memory constraints. We now consider how existing models of the AB are constrained by the present findings. As described in the introduction, most models of the AB propose that capacity limitations exist at the stage of consolidating a target into a more durable representation. This is described as a Stage 2 consolidation process (Chun & Potter, 1995), central interference (Jolicoeur, 1998), or visual short-term memory retrieval interference (Raymond, Shapiro, & Arnell, 1995). Although there is tight agreement that the capacity-limited process occurs after the target stimulus has been initially identified (Chun & Potter, 1995; Luck et al., 1996; Maki et al., 1997; Shapiro, Driver, et al., 1997; Vogel et al., 1998), there is weaker consensus on how to characterize processes between initial identification and report.

Chun and Potter (1995) proposed that a manipulation that affects the difficulty of T1 processing will affect Stage 2 and the resulting blink magnitude. A critical factor that influences Stage 2 processing is the perceptual integrity of the target. Manipulations that decrease the visibility of the target will increase the duration and magnitude of the blink (Chun & Potter, 1995; Grandison et al., 1997; Marois et al., 2000; Moore et al., 1996; Raymond et al., 1992; Seiffert & Di Lollo, 1997). However, other factors may affect T1 processing difficulty without an impact on the blink. Ward et al. (1997) and Shapiro et al. (1994) have argued that task difficulty should not affect the magnitude of the AB. Both contrasting views are likely to be correct in that task difficulty of T1 will modulate the AB in some situations and not in others. If so, identifying the conditions that produce T1 difficulty effects on the AB should help illuminate the mechanisms involved.

The results of our experiments suggest that the AB for wordlike letter strings or digits involves a capacity-limited process used for consolidating phonological codes into verbal working memory. Our finding that a nonperceptual variable influences T1 processing difficulty and an accompanying blink corroborates other studies. For instance, Jolicoeur (1999) showed that when the response to

T1 was speeded, increasing the number of response alternatives increased the magnitude of the AB. Our data present a new difficulty effect that can be observed in an unspeeded T1 task.

We believe that varying phonological length affects translation and consolidation processes rather than increases interference for maintenance or retrieval processes in working memory per se. The lag effect in the AB allows examination of the time course of interference that supports this claim. The phonological length manipulation only affected T2 performance when it appeared within around 500 ms of T1. At the longest lag (Lag 8, SOA = 856 ms), no effects of phonological length were obtained. If this effect was due to interference or competition within working memory (as in the standard word-length effect), then we should have observed a difference at longer lags also.

Alternative explanations exist for these data, but do not affect the general conclusion that the word length of T1 affects the consolidation bottleneck process of the AB (Stage 2 of Chun and Potter's, 1995, two-stage model). Until now, we assumed that the T1 word length manipulation was directly affecting the encoding process into working memory. However, it is also possible that an independent subvocalization routine or the process of generating phonological codes may be sensitive to word length. Modulation of the AB would occur if any of these processes draw central resources away from the encoding process for T1.<sup>2</sup> Although we consider these alternative hypotheses to be less likely, our experiments cannot rule them out. These alternative processing architectures are still consistent with our claim that increasing syllabic length affects the consolidation of visual stimuli that are recoded phonologically.

It is also important to note that the AB is not always driven by the attentional requirements of consolidating phonological codes. As reviewed earlier, the AB is modulated by the perceptual integrity of the target and the demands of consolidating this information into a more durable format (Chun, 1997; Chun & Potter, 1995). In addition, consolidation of keyboard symbols or random polygon shapes, which are difficult to recode phonologically, has been shown to consume central processing resources, so it seems likely that these would produce AB (Jolicoeur & Dell'Acqua, 1997, 1998). Phonological encoding is simply one mechanism that might affect the AB bottleneck; it is not the only mechanism. Our point is simply that when phonological codes are activated and used to encode visual information into verbal working memory, the overall length of these codes will affect performance. This is consistent with earlier proposals stating that phonological variables may come into play when these codes are recruited by the task (Bavelier, 1994; Bavelier & Potter, 1992). For example, Bavelier (1994, Bavelier & Potter, 1992) has reported that phonological similarity between visually dissimilar targets affected target report performance in repetition blindness.

Our demonstration of a word-length effect in the attentional blink parallels the findings by Baddeley et al. (1975) and Ellis and Hennessey (1980) that showed that longer phonological word lengths create larger working memory deficits. Our results are also consistent with the finding that longer word lengths impair recall of word lists even at fast presentation speeds (Coltheart and

<sup>2</sup> We thank Ed Vogel for suggesting this.

Langdon, 1998). We demonstrated that processing and consolidating longer trains of phonological codes produces larger attentional interference on a secondary task. This suggests that the word-length effect extends to target consolidation of visual information into working memory. These results also support the proposal that a phonological route is used in reading when the material requires much attention, such as pseudowords, irregular words, or low frequency words (Carr, 1986; Papp & Noel, 1991). If participants were relying on only the visual route to encode the words, we would expect no modulation of the AB from the phonological length of T1. Consistent with this hypothesis, unpublished data from our lab revealed that participants exhibited no modulation of the AB from pictorial T1 stimuli with labels of different syllabic length (e.g., the flag for the country Chad compared with the flag from the country Mozambique). Participants may have used a strategy of encoding the novel shapes visually and labeling them off-line after the stimuli were encoded in working memory.

In summary, working memory and attention may have many points of contact; our experiments demonstrate that one such convergence point is the placing of information into a more durable store. Attentional limitations for reporting multiple visual targets reflects a bottleneck for consolidating information into working memory and hence for availability for conscious report (Chun & Potter, 1995).

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Appendix A

Pseudowords Used in Experiment 1

| Condition |         |      |            |
|-----------|---------|------|------------|
| PS        | PL      | VS   | VL         |
| spheam    | eclodio | gnat | altosentie |
| blouthe   | akidian | knae | feveticcoe |
| browthe   | alabato | nok  | bendestery |
| cliethe   | alidisy | phie | colonetta  |
| creatch   | aramico | phic | carbonelli |
| drouth    | aritepa | chem | deckobetic |
| flairch   | atipia  | spee | exlorione  |
| fleathe   | balaria | spou | fillacolio |
| flouthe   | colinio | sot  | hendritote |
| choushe   | olipeta | sove | trilalatto |
| frouthe   | epizity | stek | hinnerlato |
| glought   | exominy | ster | ladication |
| greath    | exorion | stug | malegetron |
| kneave    | fevetia | sust | marometer  |
| knouthe   | impenia | spem | malimatie  |
| phlysse   | jelario | bot  | neckilodio |
| phylche   | melidio | brot | paratrezza |
| spheane   | opatomy | clie | peekrology |
| spleight  | oripio  | cret | quadritogo |
| splought  | ripatio | drut | redditomy  |
| spootch   | regidio | flah | refinistan |
| spouve    | semioro | feth | reggipetto |
| steache   | ubicolo | foth | rentorious |
| streaff   | utology | cosh | semigennoe |
| strought  | uzonia  | fue  | terremotoe |
| strouse   | impetia | gug  | exominight |
| wrouse    | icantio | wruv | seminiffio |
| wrouve    | pitanio | wrus | stipinorio |

Note. PS = phonologically short; PL = phonologically long; VS = visually short; VL = visually long.

Appendix B

Anagrams Used in Experiment 2

| Short words | Long words |
|-------------|------------|
| grease      | agrees     |
| loin        | lion       |
| fringe      | finger     |
| rinse       | siren      |
| dice        | iced       |
| break       | baker      |
| aide        | idea       |
| live        | evil       |
| tide        | edit       |
| brief       | fiber      |
| freak       | faker      |
| trace       | react      |
| trout       | tutor      |
| zoned       | dozen      |

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