Psychonomic Bulletin & Review
2008, 15 (2), 337-343
doi: 10.3758/PBR.15.2.337

Visual word recognition without central attention: Evidence for greater automaticity with greater reading ability

Eric Ruthruff
University of New Mexico, Albuquerque, New Mexico

Philip A. Allen
University of Akron, Akron, Ohio

Mei-Ching Lien
Oregon State University, Corvallis, Oregon

and

Jeremy Grabbe
University of Akron, Akron, Ohio

The present study examined individual differences in the automaticity of visual word recognition. Specifically, we examined whether people can recognize words while central attention is devoted to another task and how this ability depends on reading skill. A lexical-decision Task 2 was combined with either an auditory or visual Task 1. Regardless of the Task 1 modality, Task 2 word recognition proceeded in parallel with Task 1 central operations for individuals with high Nelson–Denny reading scores, but not for individuals with low reading scores. We conclude that greater lexical skill leads to greater automaticity, allowing better readers to more efficiently perform lexical processes in parallel with other attention-demanding tasks.

Word reading is often regarded as a highly automatic skill. One reason is the well-known Stroop effect: People are slow to name the color in which a word is printed if that word happens to spell a conflicting color name (e.g., "green" in red ink; see MacLeod, 1991). These findings suggest that word reading occurs even when words are irrelevant to the task at hand and people presumably have no intention to read them.

Dual-task paradigms, in contrast, have provided evidence that, at least for younger adults, word reading is not automatic. When one task engages central attentional resources, word reading on another task appears to be delayed (e.g., Lien, Ruthruff, Cornett, Goodin, & Allen, in press; McCann, Remington, & Van Selst, 2000). Interestingly, dual-task studies have provided evidence that word reading is more automatic for older adults than for younger adults, suggesting that word reading is a skill that develops gradually over the life span (e.g., Allen et al., 2002; Lien, Allen, et al., 2006). These differences in word-reading automaticity *between* age groups raise the question of whether there are also differences among individuals *within* an age group. The present study addresses this question.

Word Reading in Dual-Task Paradigms

To assess the automaticity of word reading, McCann et al. (2000) used a dual-task paradigm known as the *psychological refractory period* (PRP) paradigm. This paradigm requires speeded responses to both Task 1 and Task 2. The key independent variable is the time between the stimulus onsets, known as the *stimulus onset asynchrony* (SOA). At long SOAs, where the tasks do not need to be performed simultaneously, one can measure the baseline response time (RT) to Task 1 (RT1) and Task 2 (RT2). One can then use this baseline to measure slowing at short SOAs, where the tasks are presented at almost the same time. Nearly all such studies have revealed a dramatic lengthening of RT2 at short SOAs, a phenomenon known as the *PRP effect* (see Lien & Proctor, 2002, for a review).

A dominant explanation for the PRP effect is the *central bottleneck model*, illustrated in Figure 1. The central assumption is that Task 2 central stages do not overlap with Task 1 central stages. An everyday example is a bank teller who can handle only one customer at a time. If two customers arrive in close succession, the second will experience a "bottleneck delay." Although there is lingering debate about whether people can overlap central opera-

E. Ruthruff, ruthruff@unm.edu

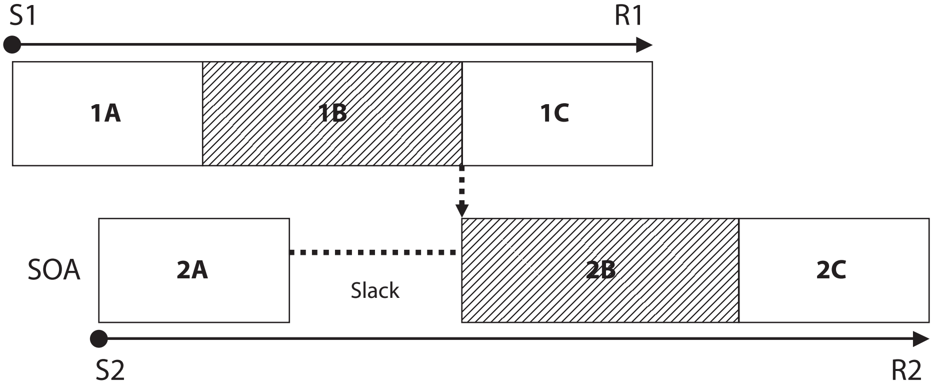


Figure 1. The temporal relations between the processing stages of Task 1 and Task 2 at a short SOA in the psychological refractory period paradigm as suggested by the central bottleneck model. This model assumes that perceptual and response initiation/execution stages of Task 2 can operate in parallel with any stage of Task 1, but the central stages of Task 2 do not start until Task 1 central stages have been completed. Stages 1A, 1B, and 1C are the perceptual, central, and response initiation/execution stages of Task 1, respectively. Stages 2A, 2B, and 2C are the corresponding stages for Task 2. S1, stimulus for Task 1; S2, stimulus for Task 2; R1, response for Task 1; R2, response for Task 2; SOA, stimulus onset asynchrony.

tions under specific conditions (e.g., after practice or when given proper incentives), the central bottleneck model has withstood a barrage of empirical tests under a very wide range of conditions (Lien, Ruthruff, & Johnston, 2006; Pashler & Johnston, 1989; but see Meyer & Kieras, 1997, for a different view). It has held up especially well with novel tasks similar to those discussed below.

Within the framework of the central bottleneck model, there are well-established ways of determining which operations are automatic (i.e., do not require limited central resources). The basic approach, known as *locus-of-slack logic*, involves manipulating the duration of a specific stage of Task 2. If this stage occurs *after* the central bottleneck, then the effects should be additive with the effects with SOA (see Figure 2, panel A). However, if this operation can occur *before* the central bottleneck (i.e., is automatic), then the factor effects should decrease markedly at short SOAs (see Figure 2, panel B). In brief, any lengthening of pre-bottleneck stages of Task 2 (Stage 2A in Figure 1) can be absorbed into the cognitive slack generated at short SOAs (for more details, see Pashler, 1994, and Schweickert, 1978).

McCann et al. (2000) applied locus-of-slack logic to the study of visual word recognition with a sample of younger adults. Task 1 was to judge whether a tone was low or high in pitch, and Task 2 was to indicate whether a letter string formed a valid English word (i.e., a lexical decision task). The critical manipulation was whether the Task 2 words were high frequency (appearing often in the English language) or low frequency, a variable thought to influence the duration of word recognition. McCann et al. found roughly constant word frequency effects across SOAs. According to locus-of-slack logic, this finding implies that word recognition was postponed until after Task 1 central stages had finished. In other words, word recognition was not automatic for younger adults (see also Lien, Allen, et al., 2006).

A more recent study by Cleland, Gaskell, Quinlan, and Tamminen (2006) used similar methods but reached the opposite conclusion. However, their data showed only modest deviations from additivity, as had been shown in previous studies. Even at the shortest SOA, the word frequency effect did not disappear, but was still about 70 msec (and was 127 msec at the long SOA) in their Experiment 2, in which words were presented visually (as in McCann et al., 2000). Given the large PRP effect of 259 msec and the assumption that the PRP effect mostly reflects a bottleneck delay, automatic word recognition should have produced nearly complete absorption of word frequency effects into cognitive slack at short SOAs.

Interestingly, older adults show more evidence of automatic word recognition in this paradigm than do younger adults. Allen et al. (2002) found in two separate experiments that word frequency effects nearly disappeared at short SOAs for older adults. Lien, Allen, et al. (2006) later replicated this result with different input modalities on Task 1 (auditory vs. visual). Their conclusion was that older adults, unlike their younger counterparts, are generally able to identify words without central attention. It would appear that word reading is a skill that continues to develop over one’s life span.

The hypothesis that word reading automaticity depends on reading skill raises the question of whether especially skilled younger readers might also benefit from automatic word recognition. Such a finding would help explain why previous studies have found small trends toward reduced word frequency effects at short SOAs: The participants consist of a few “good” readers, for whom word recognition is automatic, and plenty of “poor” readers, for whom word recognition is not automatic.

The present study examined this issue using an extreme-groups design. We first tested the reading ability of a sample of adults, using the Nelson–Denny reading test (Brown, Fishco, & Hanna, 1993) to identify participants with high and low reading ability. We operationalized high reading ability as a percentile score above the 60th percentile and low reading ability as a score between the 20th and 50th percentiles.[1] These two extreme groups then completed dual-task sessions with a lexical decision Task 2.

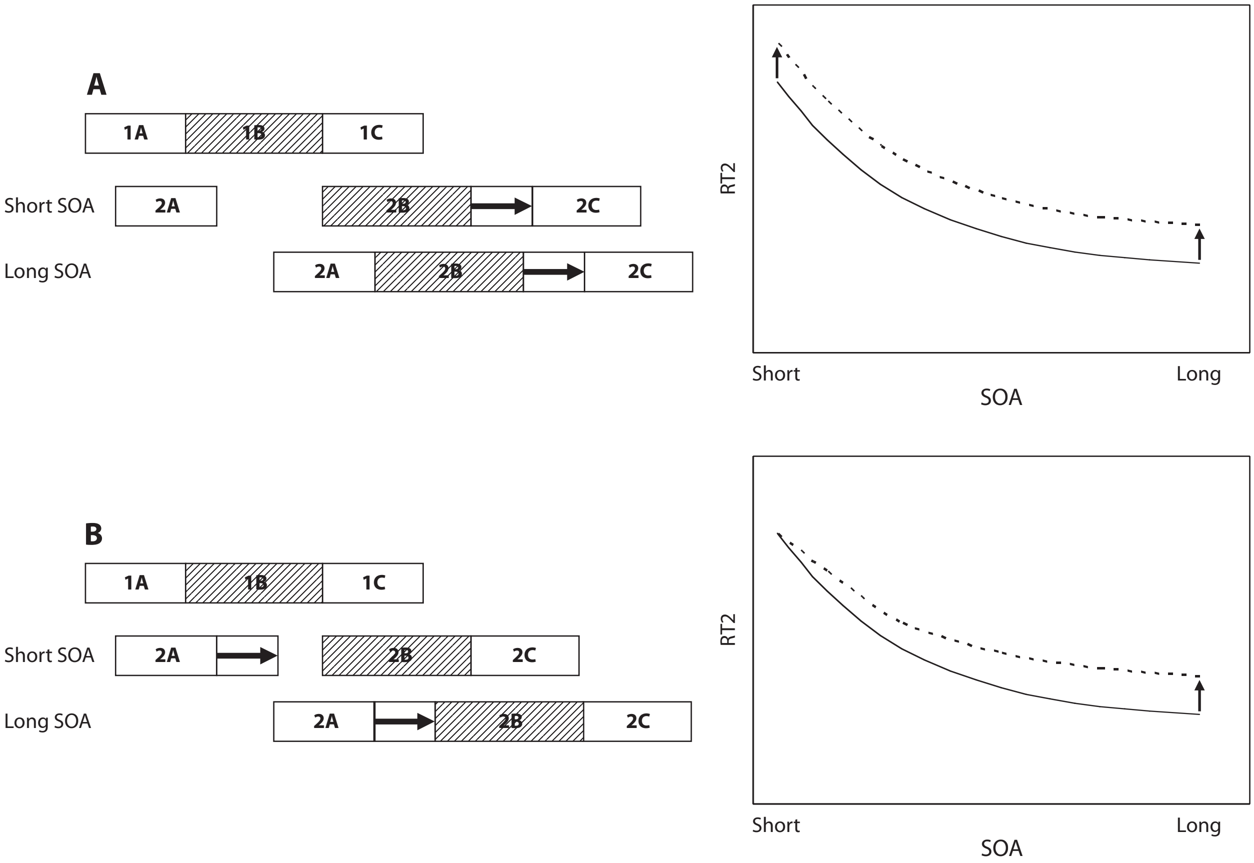


Figure 2. The predictions of the central bottleneck model. Panel A shows that any variable affecting a stage at or after the bottleneck stage would have an additive effect with SOA. Panel B shows that any variable affecting a stage before the bottleneck stage of Task 2 would have an underadditive effect with SOA. Stages 1A, 1B, and 1C are the perceptual, central, and response initiation/execution stages of Task 1, respectively. Stages 2A, 2B, and 2C are the corresponding stages for Task 2. SOA, stimulus onset asynchrony. RT2, response time to task 2.

If the better readers can read words without central attention, their word frequency effects should be greatly reduced at short SOAs (see Figure 2, panel B). The relatively poor readers should show similar word frequency effects at all SOAs (i.e., additivity; see Figure 2, panel A).

METHOD

Participants

A total of 48 undergraduate students (24 high reading ability and 24 low reading ability; mean age = 25 years) at the University of Akron participated in partial fulfillment of a course requirement. All participants had normal or corrected-to-normal vision. They were screened using the Nelson–Denny reading test prior to taking part in the computerized experiments. High-ability readers had scores at the 60th percentile rank or above, and low-ability readers had scores between the 20th and 50th percentile ranks; those with intermediate scores were not asked to participate in the dual-task sessions. The 48 participants falling into these percentile ranges were drawn from an initial pool of 55 students who had taken the reading test. Note that, because we disproportionately sampled high-ability readers (high percentiles), the average reading ability of our sample is somewhat greater than the average in the general population.

Apparatus and Stimuli

Stimulus presentation, timing, and data collection were controlled using IBM-compatible PCs running the E-Prime software package (Schneider, Eschman, & Zuccolotto, 2002). The stimuli and tasks were based on Lien, Allen, et al. (2006). The Task 1 stimulus was always a simultaneous sound (tone or noise) and shape (circle or square). Following Lien, Allen, et al., we manipulated the input modality of Task 1 across sessions. In the auditory Task 1 condition, participants responded to the sound while ignoring the shape. In the visual Task 1 condition, participants responded to the shape while ignoring the sound. This methodology ensured that the stimuli in the auditory and visual Task 1 conditions were identical. The visual condition has the advantage of having no need to switch attention between auditory and visual modalities; the auditory condition has the advantage of minimizing peripheral conflicts (i.e., conflict for visual processors). The shape was an unfilled circle (6 cm in diameter) or square (6 cm sides). At a typical viewing distance of 55 cm, both shapes subtended horizontal and vertical visual angles of 6.23º. The auditory stimulus was either a pure tone or white noise (similar to a hissing sound).

In both the auditory and visual Task 1 conditions, the Task 2 stimulus was a word or nonword presented inside the circle or square. Each letter, presented in lowercase, was approximately 0.8 cm in height and 0.6 cm in width. At a viewing distance of 55 cm, each letter subtended a visual angle of 0.83º × 0.63º. Each participant completed two dual-task sessions: one for the auditory Task 1 condition and one for the visual Task 1 condition. (The order was counterbalanced across participants.) Each session used a separate word list, so words or nonwords were never repeated across sessions. For more details regarding the construction of the word lists, see the Methods and Appendixes of Lien, Allen, et al. (2006).

Design and Procedure

The design and procedure were similar to those in Lien, Allen, et al. (2006). Each participant performed two practice blocks. The first included 32 trials with a constant 1,500-msec SOA, and the second included 72 trials with the same set of SOAs that had been used in the experimental blocks. Each participant then received 432 regular trials divided into 6 blocks of 72 trials each.

In each trial, the fixation cross appeared in the center of the screen for 500 msec and then disappeared for 100 msec. The Task 1 stimulus (S1) was then presented: The auditory stimulus was sounded for 100 msec, and the shape appeared in the screen center until response. The Task 2 stimulus (S2; a string of letters) followed S1 after one of six SOAs (50, 100, 300, 500, 700, or 900 msec, randomly selected within blocks) and remained until a response was recorded.

In the auditory Task 1 condition, participants pressed the "z" key with their left middle finger when they heard a tone and the "x" key with their left index finger when they heard white noise. In the visual Task 1 condition, participants pressed the "z" key with their left middle finger when they saw a circle and the "x" key with their left index finger when they saw a square. For Task 2, participants pressed the "n" key with their right index finer if the letter string formed a word and pressed the "m" key with their right middle finger if the letter string formed a nonword.

Participants were instructed to respond to S1 immediately (to discourage response grouping) before responding to S2 and to respond as quickly and accurately as possible to both tasks (while maintaining at least 90% accuracy). Feedback regarding incorrect responses was presented visually for 1,200 msec.

Analyses

Since the word frequency variable applied only to word stimuli, we did not include nonword trials in the data analyses. S1 type (tone/noise in the auditory Task 1 condition and circle/square in the visual Task 1 condition) and session (first vs. second) had little effect and therefore were not included in the final analyses. The independent variables submitted to the ANOVA were group (high vs. low reading ability), S1 modality (auditory vs. vocal), S2 word frequency (high vs. low), SOA (50, 100, 300, 500, 700, and 900 msec), and participants. We adjusted *p* values using the Greenhouse–Geisser epsilon correction for nonsphericity.

RESULTS

Trials were excluded if the RT for either task was less than 100 msec or greater than 3,000 msec (0.57% of trials). Trials were also excluded from RT analyses if the response to either task was incorrect. The resulting mean RTs and proportions of errors (PEs) are shown in Table 1 for Task 1 and Table 2 for Task 2. Figure 3 shows overall mean RT as a function of word frequency and SOA. Figure 4 shows the same data, but separately for the high and low reading ability groups.

Task 1 RT and PE

Mean RT1 was faster for participants with high reading ability (658 msec) than for those with low reading ability (794 msec) [$F(1,46) = 8.62$, $MS_e = 612{,}236$, $p < .01$]. There was also a gradual increase in mean RT1 as SOA decreased [$F(5,230) = 12.53$, $MS_e = 17{,}617$, $p < .001$]. Tombu and Jolicœur (2003) noted that such an effect is consistent with capacity-sharing between central processes (as opposed to a strict bottleneck). However, the effect of SOA on RT1 is also consistent with a modest amount of response grouping at short SOAs—withholding the Task 1 response so it can be emitted with the Task 2 response—and with perceptual interference between tasks. The SOA effect was significantly more pronounced when S1 was visual than when S1 was auditory [$F(5,230) = 4.62$, $MS_e = 5{,}537$, $p < .001$]. These patterns were stronger for those with low reading ability, resulting in a significant three-way interaction between S1 modality, SOA, and group [$F(5,230) = 2.52$, $MS_e = 5{,}537$, $p < .05$]. The three-way interaction between word frequency, SOA, and group was also significant [$F(5,230) = 2.48$, $MS_e = 11{,}931$, $p < .05$]. For the high reading ability group, the word frequency effect on Task 1 was −10, 0, 1, 17, −16,

Table 1
Mean Response Times (in Milliseconds) and Proportions of Errors on Task 1 for the High Reading Ability Group and the Low Reading Ability Group As a Function of Stimulus Onset Asynchrony (SOA: 50, 100, 300, 500, 700, and 900 msec), Stimulus Modality (Auditory–Visual vs. Visual–Visual), Stimulus 2 Lexicality (Word vs. Nonword), and Stimulus 2 Word Frequency (High vs. Low)

	SOA											
	50		100		300		500		700		900	
	M	*PE*	*M*	*PE*	*M*	*PE*	*M*	*PE*	*M*	*PE*	*M*	*PE*
High Reading Ability Group												
Auditory–Visual Condition												
Nonword	724	.027	680	.022	630	.030	633	.026	651	.019	656	.027
High-frequency word	707	.044	694	.023	650	.026	628	.021	661	.012	655	.017
Low-frequency word	677	.049	688	.047	670	.025	646	.019	639	.021	662	.026
Visual–Visual Condition												
Nonword	737	.056	700	.054	650	.017	628	.024	634	.022	664	.022
High-frequency word	707	.049	650	.037	635	.040	621	.035	648	.012	647	.012
Low-frequency word	716	.042	658	.050	617	.028	637	.012	639	.019	644	.035
Low Reading Ability Group												
Auditory–Visual Condition												
Nonword	826	.044	844	.038	768	.039	775	.023	788	.025	780	.021
High-frequency word	818	.038	846	.062	800	.032	771	.014	773	.012	790	.028
Low-frequency word	881	.038	825	.043	817	.035	768	.024	752	.028	831	.024
Visual–Visual Condition												
Nonword	891	.055	851	.046	762	.027	755	.018	721	.024	750	.019
High-frequency word	842	.060	827	.042	744	.028	768	.019	750	.028	741	.026
Low-frequency word	890	.071	855	.035	768	.019	722	.021	739	.012	728	.026

Table 2
Mean Response Times (in Milliseconds) and Proportions of Errors on Task 2 for the High Reading Ability Group and the Low Reading Ability Group As a Function of Stimulus Onset Asynchrony (SOA: 50, 100, 300, 500, 700, and 900 msec), Stimulus Modality (Auditory–Visual vs. Visual–Visual), Stimulus 2 Lexicality (Word vs. Nonword), and Stimulus 2 Word Frequency (High vs. Low)

	SOA											
	50		100		300		500		700		900	
	M	*PE*	*M*	*PE*	*M*	*PE*	*M*	*PE*	*M*	*PE*	*M*	*PE*
High Reading Ability Group												
Auditory–Visual Condition												
Nonword	1,034	.090	946	.085	775	.089	714	.071	675	.078	675	.088
High-frequency word	957	.033	900	.042	714	.042	616	.037	603	.028	564	.021
Low-frequency word	951	.074	933	.091	781	.129	686	.103	637	.100	637	.107
Visual–Visual Condition												
Nonword	1,035	.087	950	.076	777	.079	709	.071	670	.070	669	.082
High-frequency word	949	.042	841	.026	729	.040	643	.051	600	.028	563	.031
Low-frequency word	968	.074	892	.075	747	.089	699	.090	665	.121	633	.119
Low Reading Ability Group												
Auditory–Visual Condition												
Nonword	1,171	.109	1,157	.118	934	.120	835	.121	785	.093	765	.104
High-frequency word	1,093	.040	1,057	.035	870	.053	742	.042	679	.035	651	.016
Low-frequency word	1,182	.112	1,084	.066	934	.121	799	.114	741	.114	736	.105
Visual–Visual Condition												
Nonword	1,203	.119	1,112	.103	891	.099	836	.083	764	.099	760	.089
High-frequency word	1,072	.042	1,015	.042	812	.033	748	.021	689	.028	646	.033
Low-frequency word	1,154	.092	1,094	.088	857	.116	791	.119	738	.124	731	.089

and 2 at the 50-, 100-, 300-, 500-, 700-, and 900-msec SOAs, respectively. For the low reading ability group, the effect was 55, 4, 21, −25, −16, and 13 msec at the 50-, 100-, 300-, 500-, 700-, and 900-msec SOAs, respectively (see Table 1). The above results tentatively suggest that the low reading ability group was more likely to group responses together at short SOAs. This hypothesis explains why this group showed an exaggerated effect of SOA on mean RT1 and an effect of Task 2 word frequency on RT1 at the shortest SOA.

PE1 increased as SOA decreased [$F(5,230) = 17.34$, $MS_e = 0.0017$, $p < .001$]. The three-way interaction between group, SOA, and modality was also significant [$F(5,230) = 2.48$, $MS_e = 0.0016$, $p < .05$] (see Table 1). No other effects were significant.

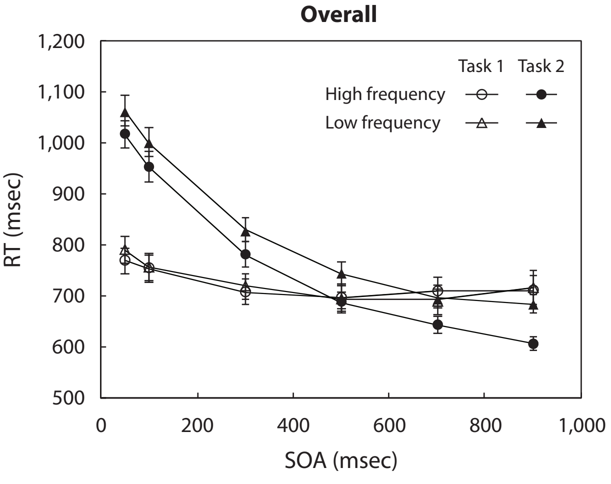
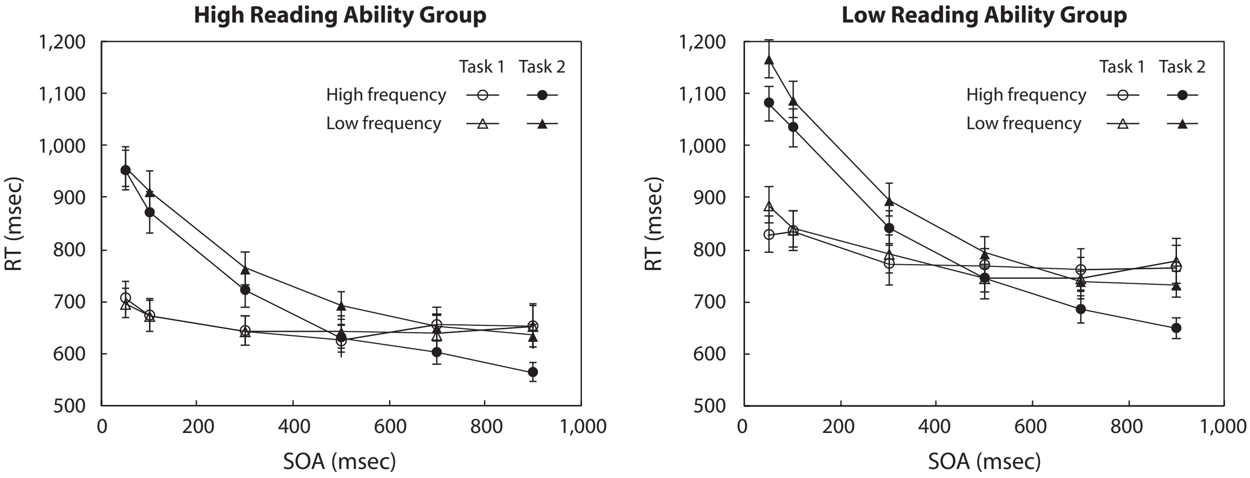


Figure 3. Mean response time (RT) for Task 1 and Task 2 as a function of stimulus onset asynchrony (SOA; 50, 100, 300, 500, 700, and 900 msec) and Stimulus 2 word frequency (high vs. low). Error bars represent the standard error of the mean, calculated on the basis of the between-subjects variance in that condition.

Task 2 RT and PE

Mean RT2 was shorter for participants with high reading ability (746 msec) than for participants with low reading ability (871 msec) [$F(1,46) = 10.54$, $MS_e = 428{,}719$, $p < .01$]. In addition, mean RT2 increased as SOA decreased (RT2 = 1,041, 977, 806, 716, 669, and 645 msec at the 50-, 100-, 300-, 500-, 700-, and 900-msec SOAs, respectively) [$F(5,230) = 385.48$, $MS_e = 13{,}657$, $p < .0001$]. The overall PRP effect was 396 msec. The PRP effect was larger for participants with low reading ability (434 msec) than for participants with high reading ability (357 msec) [$F(5,230) = 4.89$, $MS_e = 13{,}657$, $p < .001$]. This increase in the PRP effect was expected, given that mean RT1 was longer for participants with low reading ability. Although the PRP effect was similar for the auditory and visual S1 conditions (398 and 393 msec, respectively), the two-way interaction between SOA and S1 modality was statistically significant [$F(5,230) = 2.90$, $MS_e = 6{,}863$, $p < .05$].

The critical test in this experiment concerned the interaction between word frequency and SOA as a function of reading ability. Overall, mean RT2 was 55 msec shorter when S2 was a high-frequency word (781 msec) than when it was a low-frequency word (836 msec) [$F(1,46) = 139.31$, $MS_e = 6{,}775$, $p < .001$]. Averaged across the high and low reading ability groups (see Figure 3), the interaction between word frequency and SOA was not significant [$F(5,230) = 1.47$, $MS_e = 4{,}804$, $p = .2113$], replicating McCann et al. (2000). Nevertheless, participants with high reading ability showed a greater reduction in word frequency effects at short SOAs than did participants with low reading ability [$F(5,230) = 2.48$, $MS_e = 4{,}804$, $p <$



High Reading Ability Group

Low Reading Ability Group

Figure 4. Mean response time (RT) for Task 1 and Task 2 for the high reading ability group and the low reading ability group as a function of stimulus onset asynchrony (SOA; 50, 100, 300, 500, 700, and 900 msec) and Stimulus 2 word frequency (high vs. low). Error bars represent the standard error of the mean, calculated on the basis of the between-subjects variance in that condition.

.05]. Follow-up analyses showed that the interaction between the word frequency effect and SOA was significant only for the high reading ability group [$F(5,115) = 3.02$, $MS_e = 4{,}159$, $p < .05$]; their word frequency effect was 6, 42, 42, 63, 50, and 72 msec at the 50-, 100-, 300-, 500-, 700- and 900-msec SOAs, respectively (see Figure 4, left panel). For participants with low reading ability, the word frequency effect was 85, 53, 54, 50, 55, and 85 msec at the 50-, 100-, 300-, 500-, 700- and 900-msec SOAs, respectively [$F(5,115) = 1.25$, $MS_e = 5{,}348$, $p = .3046$] (see Figure 4, right panel). This pattern did not depend on whether S1 was auditory or visual ($F < 1.0$), as was also found by Lien, Allen, et al. (2006). The critical interaction between group, SOA, and word frequency was also significant when comparing only the shortest and longest SOAs (50 vs. 900 msec) [$F(1,46) = 6.78$, $MS_e = 4{,}055$, $p < .05$].

PE2 was higher for low-frequency words (.101) than for high-frequency words (.035) [$F(1,46) = 170.48$, $MS_e = 0.0074$, $p < .0001$]. In addition, PE2 was slightly lower at short SOAs than at long SOAs [$F(5,230) = 2.44$, $MS_e = 0.0041$, $p < .05$]. This SOA effect was more pronounced for low-frequency words than for high-frequency words [$F(5,230) = 3.73$, $MS_e = 0.0036$, $p < .01$] (see Table 2). No other effects were significant.

DISCUSSION

Previous PRP studies suggested that word reading for younger adults requires central attention, based on a nearly additive relationship between word frequency and SOA (Allen et al., 2002; Lien, Allen, et al., 2006; McCann et al., 2000). On the other hand, these studies consistently showed a slight underadditive interaction, hinting at partial automaticity (see Cleland et al., 2006). The present study evaluated the hypothesis that the overall data actually contain a mixture of participants with high reading ability, for whom word recognition is automatic, and participants with low reading ability, for whom word recognition is not automatic.

The aggregate data of the present study (Figure 3) closely resemble the aggregate data of previous studies—approximate additivity with a slight trend toward underadditivity—typically taken as evidence for the nonautomaticity of word recognition. When individual differences are considered, however, a qualitatively different picture emerges (Figure 4). The high reading ability group showed strong underadditivity between word frequency and SOA on RT2 (about 92% absorption at the shortest SOA), whereas the low reading ability group showed no interaction between word frequency and SOA (0% absorption). Thus, according to locus-of-slack logic, the high reading ability readers generally recognized words automatically (without central attention), whereas the low reading ability readers did not.

Interestingly, those with low reading ability performed Task 1 (the auditory task) more slowly than did those with high reading ability at all SOAs and produced a larger PRP effect (by 77 msec). One plausible explanation is that the low reading ability group needed to devote more of their pretrial preparation to the word task (Task 2) in order to compensate for their low reading ability, and thus were less prepared for Task 1. In any case, note that the relatively poor readers showed less reduction of Task 2 word frequency effects at short SOAs, even though they actually had more cognitive slack time into which to absorb the frequency effects.

Relation to Other Studies

Studies of cognitive aging have also provided evidence for the importance of individual differences in reading ability. Allen et al. (2002) and Lien, Allen, et al. (2006) found that older adults showed a much stronger underadditive interaction between word frequency and SOA than did younger adults. These studies suggest that, due to far greater cumulative experience with lexical processing, older adults have developed greater automaticity of lexical access than "typical" younger adults. This is a rare example in which an aspect of cognitive performance actually improves with advancing age. Taken together, the present study and the cognitive aging studies support the broader hypothesis that word recognition automaticity depends on reading skill, regardless of how that skill was achieved.

Recently, Reynolds and Besner (2006) proposed that word frequency affects both orthographic processing (assumed not to require central attention) and phonological recoding (assumed to require central attention). This conjecture could explain why Task 2 word frequency effects are often partially underadditive with SOA. Although plausible, this hypothesis by itself does not explain why underadditivity is stronger for those with high reading skill.

Varieties of Attention

The present study examined whether word reading requires *central attention*, which can be loosely defined as general purpose resources used for all central operations (e.g., decision making, response selection, and memory retrieval). There is empirical evidence that this variety of attention is distinct from input attention (or *spatial* attention), which involves the selective processing of specific locations or objects (see Johnston, McCann, & Remington, 1995). Although input attention and central attention are distinct, they both appear to be critical for normal word recognition. In the case of input attention, there is evidence that relatively little semantic word processing takes place for words outside the focus of spatial attention (see, e.g., Stolz & Stevanovski, 2004; for a comprehensive review, see Lachter, Forster, & Ruthruff, 2004).

Given that input attention (like central attention) is critical for word recognition, it is natural to ask whether the automaticity of this variety of attention also depends on reading skill. To the best of our knowledge, no studies have yet investigated this issue.

Limitations

Note that we did not manipulate reading ability. We simply took advantage of natural variation in the population. It is highly likely the high and low reading ability groups differ in more ways than just reading ability (e.g., crystallized intelligence). It is even conceivable that some of these differences—not reading ability, per se—caused the observed differences in the automaticity of word recognition. Nevertheless, we believe that the most plausible cause for the apparent differences in the automaticity of word recognition between groups is the difference in reading ability.

Conclusions

The present results suggest that caution is required when interpreting aggregate data. Although the average reader cannot recognize words without central attention, the most skilled readers, due to greater experience or greater inherent ability, apparently can. We conclude that, as word recognition skill reaches a certain point, individuals are capable of performing word recognition in parallel with other attention-demanding tasks (i.e., automatically).

AUTHOR NOTE

Correspondence concerning this article should be addressed to E. Ruthruff, Department of Psychology, 1 University of New Mexico, MSC03 2220, Albuquerque, NM 87131 (e-mail: ruthruff@unm.edu).

REFERENCES

Allen, P. A., Lien, M.-C., Murphy, M. D., Sanders, R. E., Judge, K. S., & McCann, R. S. (2002). Age differences in overlapping-task performance: Evidence for efficient parallel processing in older adults. *Psychology & Aging*, **17**, 505-519.

Brown, J. I., Fishco, V. V., & Hanna, G. S. (1993). *Nelson–Denny Reading Test.* Itasca, IL: Riverside Publishing.

Cleland, A. A., Gaskell, M. G., Quinlan, P. T., & Tamminen, J. (2006). Frequency effects in spoken and visual word recognition: Evidence from dual-task methodologies. *Journal of Experimental Psychology: Human Perception & Performance*, **32**, 104-119.

Johnston, J. C., McCann, R. S., & Remington, R. W. (1995). Chronometric evidence for two types of attention. *Psychological Science*, **6**, 365-369.

Lachter, J., Forster, K. I., & Ruthruff, E. (2004). Forty-five years after Broadbent (1958): Still no identification without attention. *Psychological Review*, **111**, 880-913.

Lien, M.-C., Allen, P. A., Ruthruff, E., Grabbe, J., McCann, R. S., & Remington, R. W. (2006). Visual word recognition without central attention: Evidence for greater automaticity with advancing age. *Psychology & Aging*, **21**, 431-447.

Lien, M.-C., & Proctor, R. W. (2002). Stimulus–response compatibility and psychological refractory period effects: Implications for response selection. *Psychonomic Bulletin & Review*, **9**, 212-238.

Lien, M.-C., Ruthruff, E., Cornett, L., Goodin, Z., & Allen, P. A. (in press). On the nonautomaticity of visual word processing: Electrophysiological evidence that word identification requires central attention. *Journal of Experimental Psychology: Human Perception & Performance*.

Lien, M.-C., Ruthruff, E., & Johnston, J. C. (2006). Attentional limitations in doing two tasks at once: The search for exceptions. *Current Directions in Psychological Science*, **15**, 89-93.

MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin*, **109**, 163-203.

McCann, R. S., Remington, R. W., & Van Selst, M. (2000). A dual-task investigation of automaticity in visual word processing. *Journal of Experimental Psychology: Human Perception & Performance*, **26**, 1352-1370.

Meyer, D. E., & Kieras, D. E. (1997). A computational theory of executive cognitive processes and multiple-task performance: Part 2. Accounts of psychological refractory-period phenomena. *Psychological Review*, **104**, 749-791.

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin*, **116**, 220-244.

Pashler, H., & Johnston, J. C. (1989). Chronometric evidence for central postponement in temporally overlapping tasks. *Quarterly Journal of Experimental Psychology*, **41A**, 19-45.

Reynolds, M., & Besner, D. (2006). Reading aloud is not automatic: Processing capacity is required to generate a phonological code from print. *Journal of Experimental Psychology: Human Perception & Performance*, **32**, 1303-1323.

Schneider, W., Eschman, A., & Zuccolotto, A. (2002). *E-Prime reference guide*. Pittsburgh, PA: Psychology Software Tools.

Schweickert, R. (1978). A critical path generalization of the additive factor method: Analysis of a Stroop task. *Journal of Mathematical Psychology*, **18**, 105-139.

Stolz, J. A., & Stevanovski, B. (2004). Interactive activation in visual word recognition: Constraints imposed by the joint effects of spatial attention and semantics. *Journal of Experimental Psychology: Human Perception & Performance*, **30**, 1064-1076.

Tombu, M., & Jolicœur, P. (2003). A central capacity sharing model of dual-task performance. *Journal of Experimental Psychology: Human Perception & Performance*, **29**, 3-18.

NOTE

1. We decided to not sample readers below the 20th percentile for fear that they would often be unable to recognize the low-frequency words.

(Manuscript received December 31, 2006;
revision accepted for publication July 23, 2007.)