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# Electrophysiological Evidence for Parallel Response Selection in Skilled Typists

Gordon D. Logan<sup>1</sup>, A. Eve Miller<sup>2</sup>, and David L. Strayer<sup>2</sup>

<sup>1</sup>Vanderbilt University and <sup>2</sup>University of Utah

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Abundant behavioral and psychophysiological evidence suggests that people cannot select more than one response at a time, as if performance were limited by an immutable bottleneck in which responses must be chosen serially (Osman & Moore, 1993; Pashler, 1994). This observation has been the cornerstone of prominent theories of attention for 60 years (Broadbent, 1958; Pashler & Johnston, 1989; Welford, 1952). Most of the supporting evidence comes from a dual-task procedure known as the psychological refractory period (PRP), in which subjects respond rapidly to two successive stimuli. Researchers sought exceptions to serial response selection by examining practice effects and judiciously choosing stimuli and responses (Hazeltine, Ruthruff, & Remington, 2006; Hazeltine, Teague, & Ivry, 2002), but exceptions are rare, and serial processing of successive tasks is still the best explanation of the PRP effect (Tombu & Jolicoeur, 2004).

Behavioral studies identified the locus of the bottleneck in the process of response selection that chooses between alternative responses (McCann & Johnston, 1992; Pashler & Johnston, 1989). Psychophysiological studies focused on the lateralized readiness potential (LRP), which is recorded from electrode sites on the scalp over the primary motor cortex in the left and right hemispheres. The LRP reflects the difference in activation of responses in subjects' two hands and has been linked directly to response selection (Coles, 1989). Several studies have shown that the LRP is delayed in the PRP procedure, as is response selection (Lein, Ruthruff, Hsieh, & Yu, 2007; Osman & Moore, 1993; Sommer, Leuthold, & Schubert, 2001).

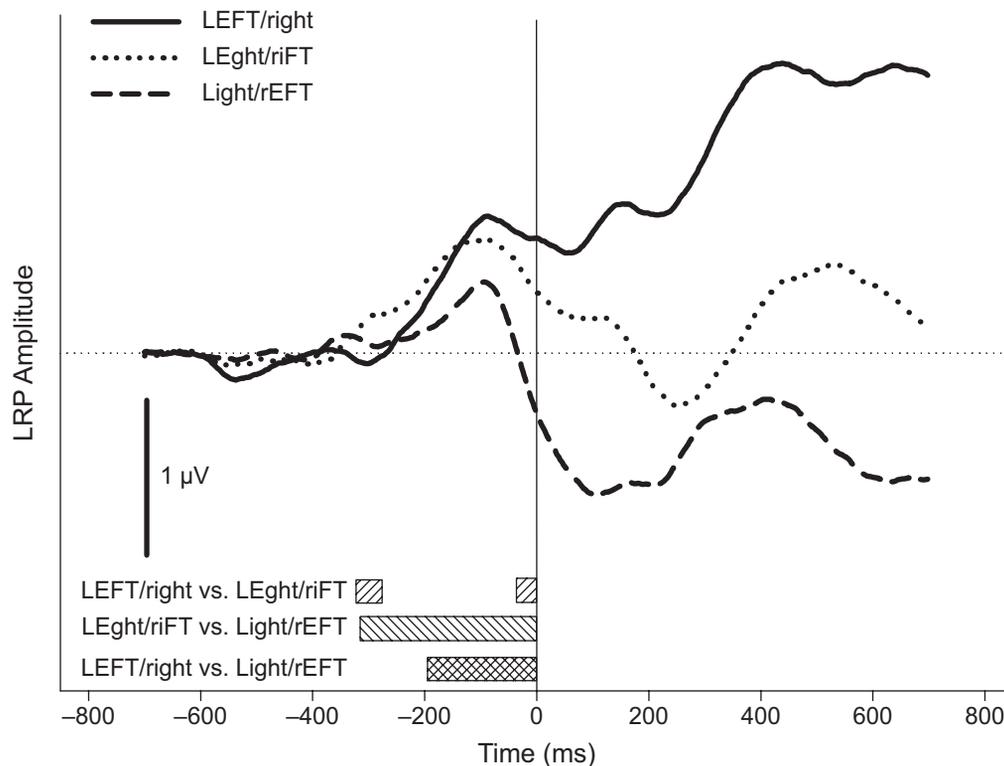
We took a different approach to the question of serial response selection, examining 16 skilled typists who had a mean of 11 years of practice ( $SD = 6.5$  years), reported typing for a mean of 2.5 hr per day ( $SD = 0.6$  hr per day), and typed at a mean of 50.3 words per minute ( $SD = 14.7$  words per minute) on the typing test devised by Logan and Zbrodoff (1998). Behavioral evidence from priming studies (Crump & Logan, 2010; Logan, 2003) and video recordings of finger movements (Flanders & Soechting, 1992) suggest parallel activation of responses in skilled typists, but these effects could occur before or after response selection (Salthouse, 1986).

To address response selection, we examined LRPs recorded while typists typed words with keystrokes distributed between their left and right hands. We used three sets of 60 three- to five-letter words taken from Logan (2003). In each set, half of the words began with a left-hand keystroke and half began with a right-hand keystroke. One set (LEFT/right) consisted of words (e.g., *rest*) that required all keystrokes to be made by one hand. The second set (LEght/riFT) consisted of words (e.g., *swim*) that required the first two keystrokes to be made by one hand and the remaining keystrokes to be made by the other hand. The third set (Light/rEFT) consisted of words (e.g., *dump*) that required the first keystroke to be made by one hand and the remaining keystrokes to be made by the other hand. The LRP measures the difference in activation of responses in the two hands. If typists select keystroke responses in parallel, then the amplitude of the LRP for the first keystroke should decrease systematically from LEFT/right to LEght/riFT to Light/rEFT words, as progressively more keystrokes are activated in the opposite hand. If typists select keystrokes serially, then the LRP for the first keystroke should not differ between word sets.

Words were presented one at a time, and the typists typed them quickly and accurately. Mean response time was short and did not vary much between word sets (LEFT/right:  $M = 662$  ms,  $SD = 80$  ms; LEght/riFT:  $M = 666$  ms,  $SD = 84$  ms; Light/rEFT:  $M = 656$ ,  $SD = 84$  ms). Mean interkeystroke interval (IKSI) was also short (LEFT/right:  $M = 197$  ms,  $SD = 30$  ms; LEght/riFT:  $M = 171$  ms,  $SD = 41$  ms; Light/rEFT:  $M = 163$  ms,  $SD = 37$  ms). Accuracy was high (LEFT/right:  $M = 89.7\%$ ,  $SD = 7\%$ ; LEght/riFT:  $M = 90.5\%$ ,  $SD = 7\%$ ; Light/rEFT:  $M = 92.6\%$ ,  $SD = 5\%$ ). LRPs locked to the first keystroke were computed for correct responses as the difference between C3 and C4 electrode sites (international 10–20 system; Jasper, 1958; C4 – C3 for first keystrokes in the left hand, and C3 – C4 for first keystrokes in the right hand). These LRPs are plotted in Figure 1.

## Corresponding Author:

Gordon D. Logan, Department of Psychology, Vanderbilt University, Nashville, TN 37203  
E-mail: gordon.logan@vanderbilt.edu



**Fig. 1.** Grand-average lateralized readiness potential (LRP) amplitudes response-locked to subjects' first keystroke for three sets of words. Sets consisted of words in which all letters are typed with one hand (LEFT/right), the first two letters are typed with one hand and the other letters are typed with the other hand (LEght/riFT), or the first letter is typed with one hand and the other letters are typed with the other hand (Light/rEFT). Results above the dotted horizontal line are associated with contralateral activation of the motor cortex elicited by typing the first letter in each word. The hatched bars inset in the figure indicate the points at which significant differences ( $p < .05$ , based on  $t$  tests) occurred between LRPs for the comparisons shown.

The test of serial and parallel response selection requires isolating the LRP to the first keystroke. For Light/rEFT words, we estimated the onset of the LRP for the second keystroke (the first opposite keystroke) by adding the IKSI (163 ms) to the onset of the LRP for LEFT/right words ( $-246$  ms); this yielded  $-83$  ms. We observed significant differences between LRPs to LEFT/right and Light/rEFT words at  $-194$  ms, before the predicted onset. This finding is contrary to serial response selection. For LEght/riFT words, the first opposite keystroke was the third. We estimated the onset of the third keystroke LRP by doubling the IKSI (342 ms) and adding the result to the LRP onset for LEFT/right words; this yielded 96 ms. We observed significant differences between LRPs to LEFT/right and LEght/riFT words at  $-32$  ms. This finding is contrary to serial response selection.

The first-keystroke LRPs may be contaminated by LRPs from subsequent keystrokes that are faster than average. To rule out this possibility, we repeated the analysis but omitted trials with the fastest 25% of the IKSI. The LEFT/right LRP was significantly different from the Light/rEFT LRP at  $-174$  ms and significantly different from the LEght/riFT LRP at  $-28$  ms. Both these differences emerged before the estimated onset of the first opposite keystroke—a result inconsistent with serial response selection.

The present electrophysiological evidence and the previous behavioral evidence for parallel response selection in skilled typing contrast sharply with the abundant electrophysiological and behavioral evidence for serial response selection in the PRP procedure. Typing differs from the PRP in several respects. The most important may be the level of practice. Few PRP studies train subjects for more than 20 hr of practice. Our typists had nearly 10,000 hr of practice, which qualifies them as experts (Ericsson, Krampe, & Tesch-Römer, 1993). The words that our typists typed have considerably more structure than the random sequences of lights and tones in typical PRP experiments. Extensive practice may allow typists to take advantage of this structure to select successive keystrokes in parallel.

Many studies of expertise address small populations of specialists who practice rare skills, so it is tempting to dismiss their abilities as atypical. However, typing is extremely common in modern culture. The level of skill seen in our typists is typical of college undergraduates and is likely to be characteristic of readers of this article. Theories of attention and performance must be reconciled with the complexities of skilled performance, even if this means abandoning theories that have dominated the field for 60 years.

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The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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