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# Flexible and inflexible response components: A Stroop study with typewritten output

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**Abstract**

Two experiments were directed at investigating the relationship between response selection and execution in typewriting, and specifically the extent to which concurrent processing takes place. In a Stroop paradigm adapted from [Logan, G. D., & Zbrodoff, N. J. (1998). Stroop-type interference: Congruity effects in colour naming with typewritten responses. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 978–992], participants typed the names of colour patches with incongruent, congruent, or neutral distractors presented at various stimulus-onset asynchronies. Experiment 1 showed Stroop interference and facilitation for initial keystroke latencies and errors, contrasting with response durations (a measure of response execution) being unaffected by Stroop manipulation. Experiment 2 showed that all three measures were responsive to time pressure; again, Stroop effects were confined to latencies and errors only. The observation that response duration is both flexible under time pressure and protected from response competition, may imply either that response execution is structurally segregated from earlier processing stages, or that encapsulation develops during the acquisition of typing skills.


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## 1. Introduction

Typists value speed. Once fluency is acquired, typing speed remains relatively constant with increasing age (Salthouse, 1986; Uttal & Perlmutter, 1989). Possible performance of up to 200 words per minute (wpm) (Inhoff, 1991) implies a mean interstroke interval as low as 60 ms, which is close to the neural transmission time between the spinal cord and peripheral systems (Norman & Rumelhart, 1983). With such extreme typing speed, motor sequences are likely executed faster than feedback-sensitive central monitoring could influence them. However, most typists perform considerably below that performance level, and under these circumstances it becomes an empirical issue as to how the processing stages of response selection and execution relate to each other.

The issue is amenable to investigation once one asks what resources such medium-speed typists can mobilise whenever they need briefly to attempt to speed up. Let us put the matter in the broadest way, later to narrow it and focus on the task of typing. There are two potential constraints on how mobilisation of resources can be accomplished. One constraint can be formulated in process terms. Speeding up the execution of a complex response may, for example, involve more pre-planning or more sustained attention or to be more vulnerable to intrusion errors, compared with speeding up the initiation of that response (shortening its latency). The second constraint can be formulated in the structural terms of "psychological modularity" (Flombaum, Santos, & Hauser, 2002). The

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repeated practicing of processing and outputting information such as written words or numbers acquired through experience leads to inflexibility which mimics structural modularity in encapsulation and automation (see also Karmiloff-Smith, 1992; Scholl, 1997). In sum, the development of skilled performance may lead to degrees of inflexibility accruing to some response components more than others for two distinct reasons.

A resultant research aim is to identify where in the response sequence such inflexibilities apply, and for what reason. Tang, Critchley, Glaser, Dolan, and Butterworth (2006) recently reported an adaptation of the Stroop paradigm for symbol-initiated numerical judgements in which they successfully identified both constraints in operation. In setting up their study, Tang et al. were able to rely on a great deal of reliable analytic research on number processing. No remotely comparable body of data exists about typing. So, we here undertook to do the research that identifies whether selection and execution of typed responses are equally constrained, leaving it then to a subsequent work to distinguish between process and structural constraints.

The debate over the relative autonomy of response selection and execution in skilled performance can be considered a specific instance of a larger theoretical debate about the characteristics of cognitive processing (see e.g., McClelland, 1979; Sternberg, 1998): According to staged cognitive models, subsequent processing levels are largely independent of each other, whereas in cascaded frameworks, processing at subsequent levels can overlap. More specifically with regard to motoric tasks such as speaking or typing, staged models assume that on initiation of a particular motor response, cognitive processing connected with response selection is no longer necessary for execution; by contrast, cascaded models hold that response selection is still ongoing when response execution has already begun.

A number of findings from linguistic and non-linguistic sequential tasks, such as key pressing, typing, and handwriting, suggest that under certain circumstances, motor programming may occur concurrently with execution. One research approach in this field has centred on the effects of practice in such tasks, which, for instance, appears to reduce the difference in time that it takes to initiate long and short sequences (e.g., Fischman & Lim, 1991; Hulstijn & van Galen, 1983). A possible interpretation is that improving skill in a particular task results in an increasing amount of concurrent processing taking place during execution (e.g., Hulstijn & van Galen, 1983). Regarding handwriting, Portier, van Galen, and Meulenbroek (1990) practiced participants on the production of unfamiliar graphemes. An analysis of changes of movement time of the first three segments showed that practice reduced the movement time of all three segments, but significantly less so in the first segment than in the second and third segments. These findings were taken to suggest that practice resulted in the preparation of later segments of the grapheme being realised more and more concurrent with the real-time execution of the initial segment. Pashler (1994) introduced a paradigm in which participants classified three letters by means of three keypresses, and a preview of the upcoming stimuli was provided. In one study in which single keypresses were compared to double keypresses, the results suggested that in this task, motor programming may have at least partially operated after overt motor behaviour had been initiated.

On the other hand, a number of studies on rapid action sequences in spoken, manual or typed responses which are fully prepared and produced on presentation of a cue (e.g., Sternberg, Knoll, Monsell, & Wright, 1988; Sternberg, Monsell, Knoll, & Wright, 1978) generated evidence broadly suggesting that a representational programme of the entire utterance is generated in the execution of each element in the sequence. This implies that the programme already exists at the time when production of the utterance is initiated. A similar account is suggested by the findings from tasks requiring the generation of sequential keypresses. For instance, Inhoff, Rosenbaum, Gordon, and Campbell (1984) asked participants to respond to letters with a sequence of keypresses, and manipulated stimulus-response compatibility between response hand and side of display. The results suggested that before execution of a response was initiated, the entire response sequence was selected, as evidenced for instance by the finding that S-R compatibility of non-initial keypresses affected latencies. Verwey (1993) used a task that required a rapid movement sequence consisting of three consecutive keypresses in response to visually presented letter stimuli. Even with extensive practice, participants exhibited no tendency to select the third keypress during execution of the earlier keypresses, suggesting that sequence selection and execution were never carried out concurrently. These and other studies indicate that motor programming and behaviour are largely separated from each other.

Shaffer (1973, p. 444) presciently noted that "It should now be beyond controversy that skilled typing depends on simultaneous input and output processing". This approach became formalized for both speech and typing (e.g., Palmer & Pfordresher, 2003): some response-sequence elements remain open to producers' access, other elements run off automatically. Whereas as outlined above, it seems likely that typing at 200 wpm is staged, there is no principled reason why slower fluent typing must similarly be staged. Logan and Zbrodoff (1998) recently reported experiments that have explicitly addressed the relation between response selection and execution in typing. A Stroop paradigm was adopted, and latencies of typed and spoken responses, as well as manual responses with arbitrary mapping of colours to keys, were compared. Participants responded to stimulus colour when the stimulus was neutral (a string of percent symbols presented in, e.g., red), incongruent (e.g., the word *blue* presented in red), or congruent (e.g., the word *red* presented in red) with the response. In all three response modes, latencies displayed