The Locus of the Gratton Effect in Picture-Word Interference

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Abstract

It has been shown that between-trial effects in Stroop-like interference tasks are caused by differences in the amount of cognitive control. Trials following an incongruent trial show less interference, an effect suggested to result from the increased control caused by the previous trial (the Gratton effect). In this study we show that cognitive control not only results in a different amount of interference, but also in a different locus of the interference. That is, the stage of the task that shows the most interference changes as a function of the preceding trial. Using computational cognitive modeling we explain these effects by a difference in the amount of processing of the irrelevant dimension of the stimulus.

Keywords: Picture-word interference; Gratton effect; Cognitive control; Dual-task study (PRP); ACT-R; RACE/A.

Introduction

Picture-word interference is a Stroop-like interference effect that is observed when participants are asked to provide the name of a picture, while they should also try to ignore a word that is inscribed in the picture (e.g., Glaser & Düngelhoff, 1984). The common finding is that reaction times are increased if word and picture bear a categorical relationship, as opposed to when they do not bear a relationship. In addition, reaction times are decreased when word and picture are identical, that is, describe the same object. In many respects, this is analogous to the Stroop effect, in which color naming reaction times are increased for trials in which the word also is a color name, as opposed to trials in which the word is not a color name. Also, in Stroop experiments a decrease in reaction times is found when word and ink color refer to the same color name.

Many theories ascribe the congruency effect – the increased reaction times as a result of a categorical relationship between the word and the picture – to the semantic relation between picture and word (e.g., Glaser & Düngelhoff, 1984; Roelofs, 1992; Van Maanen & Van Rijn, 2007). A word that is a category-member of the picture (e.g., “dog” and a picture of a cat) makes picture naming harder than an unrelated word (e.g., “book” and a picture of a cat), resulting in increased reaction times. In addition, the congruency effect has also been ascribed to a failure to suppress the more automatic word reading response (e.g., Lovett, 2005; MacLeod & Dunbar, 1988). Thus, because it is hard to not read a word, it will interfere with a response on the color or picture, resulting in increased reaction times.

The amount of suppression of the automized reading response has been hypothesized to be under cognitive control (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001). This means that a control mechanism exists that dynamically adapts the amount of suppression of the reading response to the task demands.

For instance, the influence of cognitive control is observed as a between-trial effect in congruency tasks, in which the congruency effect is decreased in trials following an incongruent trial. This effect has been interpreted as an increase in control, resulting from the increased difficulty of the task (Verguts & Notebaert, 2008). Similarly, the congruency effect is increased after congruent trials, suggesting a relaxation in control of the reading response. This particular between-trial effect is referred to as the Gratton effect (Gratton, Coles, & Donchin, 1992).

Experiment

To study the locus of the interference leading to the Gratton effect, we re-analyzed a picture-word interference experiment in a Psychological Refractory Period (PRP) paradigm (Van Maanen, Van Rijn, & Taatgen, submitted). In a PRP design, participants are asked to perform two tasks sequentially. The first task is often relatively simple, whereas the second task is the task of interest (the main task). The interval between the stimulus onsets of the two tasks is manipulated (Stimulus Onset Asynchrony or SOA). A typical finding, known as the PRP effect (Telford, 1931) is a negative correlation between SOA and response latency on the main task. Responses to the first task are typically unaffected by varying the SOA.

The PRP effect has been explained by the assumption that both tasks share a cognitive resource that can only be used by one task at a time (e.g., Pashler, 1994; Welford, 1967). Thus, the second task is delayed because the first task still requires a critical resource, as illustrated by Figure 1. As the interval between the tasks increases, the delay becomes smaller, resulting in a faster main task response.

The PRP design has been used to study the locus of various effects (e.g., for PWI, Dell'Acqua, Job, Peressotti, & Pascali, 2007; for word frequency and age of acquisition effects, Dent, Johnston, & Humphreys, 2008; for the Stroop-effect, Fagot & Pashler, 1992). For PWI, it was found that the locus of interference was located before the singular resource that both tasks share. The reasoning behind this is that a small interval between the first and the second task

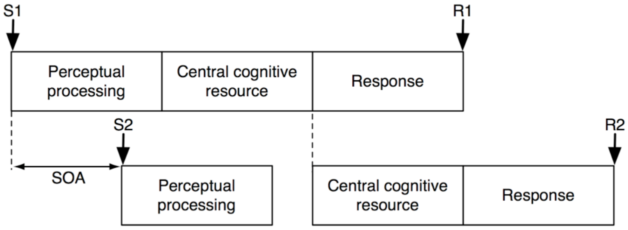

Figure 1: Diagram of the PRP design. The top bar indicates processing of the first task. The bottom bar indicates processing in the second task. S1: stimulus of task 1; S2: stimulus of task 2; R1: response on task 1; R2: response on task 2; SOA: Stimulus Onset Asynchrony

generates a large delay in processing of the second task (referred to as "cognitive slack"), in which the interference that is present in PWI can be resolved. If the interval between the tasks increases, the delay in processing of the second task disappears, and therefore the interference becomes apparent in the reaction times. Following this logic, no congruency effect at small SOAs (but a congruency effect at larger SOAs) would mean a locus before the singular resource, whereas a congruency effect at every SOA would mean a locus after the singular resource. We applied the same reasoning to study which processing stages in a PWI task are affected by cognitive control.

Methods

To study the locus of the Gratton effect in picture-word interference, we re-analyzed the data from a previous experiment (Van Maanen, Van Rijn, & Taatgen, submitted).[1] In this experiment, participants were required to perform a tone classification task and a PWI task concurrently. For the tone classification task, participants had to classify a tone as either low, medium, or high pitch by pressing the b, n, or m keys respectively with the index, middle and ring fingers of the right hand. For the PWI task, participants were required to name an image in which a word was written in the center, and ignore the word. Of each image, three PWI stimuli were created that consisted of the image, with a word written in the center of the image. The words were selected as follows: For the Related condition, category members of the image descriptors were selected. The words for the Unrelated condition were then selected from the CELEX lexical database (Baayen, Piepenbrock, & Van Rijn, 1993), and matched to the related distractors with respect to word length (plus or minus 1 letter) and word frequency (plus or minus 10%). For the Congruent condition, Dutch translations of the most common English picture names were used.

In addition to the Relatedness condition (Related, Unrelated, Congruent), we also manipulated the interval between the tone presentation and the PWI-stimulus presentation (SOA), which could be either 100ms, 350ms, or 800ms. These SOAs were chosen to ensure the PRP effect. Importantly, the correct response order was stressed, to ensure that participants responded to the tone first and to the PWI-stimulus second.

Results

We excluded trials according to the following criteria: Responses that were more than three standard deviations from a participants' mean were excluded (2.1% on the PWI stimulus, and 2.3% on the tone, respectively). Trials in which the responses were in the incorrect order were also excluded (5.3%). Overall, 7.7% of the trials were excluded. In this paper, we will only focus on the effects on the PWI task, and not discuss the effects on the secondary tone classification task.

For each trial, we determined the relatedness between picture and word on the previous trial (Previous). An analysis of variance (ANOVA) showed significant main effects of Relatedness (the congruency effect), and of SOA (the PRP effect), but not of Previous ($F_{Relatedness}(2,42) = 50$, $p<0.001$; $F_{SOA}(2,42) = 104$, $p<0.001$; $F_{Previous}(2,42) = 1.3$, $p=0.28$). However , there was a Relatedness times Previous interaction present ($F_{Relatedness\ x\ Previous}(4,84) = 4.0$, $p=0.005$), representing the Gratton effect. In addition, there was an effect of SOA on the Relatedness condition ($F_{SOA\ x\ Relatedness}(4,84) = 2.5$, $p=0.047$), as well as a significant three-way interaction between SOA, Relatedness, and Previous ($F_{SOA\ x\ Relatedness\ x\ Previous}(8,168) = 3.4$, $p=0.001$).

A visual inspection of the data (Figure 2) shows that the three-way interaction appears as a difference in the congruency effect at the small SOAs (100ms and 350 ms) between the trials directly following a Congruent trial ("post-C" in Figure 2) and the trials following a Related trial ("post-R" in Figure 2). Where the post-C trials do not show a congruency effect at small SOAs ($t<1$), the post-R trials do (paired t-test, $t=3.2$, $df=43$, $p=0.002$). The Gratton effect is visible at SOA=800ms as a smaller congruency effect for post-R trials then for post-C trials.

Discussion

The lack of a consistent pattern in the responses on the trials following an Unrelated trial (the post-U trials) can be explained by individual differences in how participants adapt their control. Some participants might treat Unrelated trials similar to Congruent trials (because they are both non-conflicting). Other participants might adapt their control on post-U trials similar to the control in post-R trials, following the similarity between related PWI and unrelated PWI stimuli (both incongruent). A mixture of these two strategies could explain the data found for the post-U trials.

The experiment shows that in PWI, the Gratton effect is present as an interaction between congruency and the previous trial. However, for trials immediately following a Congruent trial, the congruency effect disappears at small SOAs, whereas for trials following a Related trial, the effect remains. Similar observations have been interpreted as a different effect locus (e.g., for Stroop and PWI, Dell'Acqua et al., 2007; for word frequency and age of acquisition effects, Dent, Johnston, & Humphreys, 2008). Therefore,

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[1] The submitted manuscript contains an extensive description of the experiment. The manuscript can be downloaded from http://www.ai.rug.nl/~leendert/pubs.

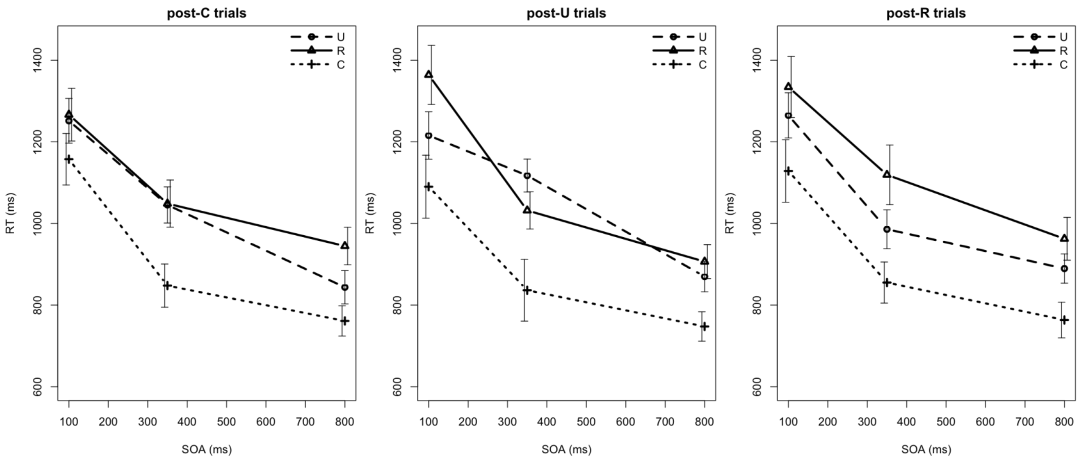

Figure 2: Response times as a function of SOA for the Relatedness conditions. U: Unrelated; R: Related; C: Congruent.

the experiment suggests that the locus of the congruency effect in PWI is influenced by the previous trial. In the following section, we will present a computational cognitive model that accounts for this apparent shift in locus in terms of a difference in processing speed between conditions.

A Cognitive Model of the Gratton Effect

RACE/A

The basis of our computational model of the Gratton effect is a recent model of declarative memory retrieval that we have developed (Van Maanen, 2009; Van Maanen & Van Rijn, 2007; Van Maanen, Van Rijn, & Taatgen, submitted). The model – termed Retrieval by Accumulating Evidence in an Architecture or RACE/A – describes memory retrievals as a sequential sampling process (Ratcliff, 1978). In addition, RACE/A assumes that the dynamics of the retrieval process are constrained by other cognitive processes that co-occur with a particular retrieval process. This aspect is captured by integrating the sequential sampling process in the cognitive architecture ACT-R (Anderson, 2007).

The accumulation process can be characterized by two equations that determine the long-term dynamics and the short-term dynamics of the activation. The short-term dynamics are mediated by the presence or absence of stimuli and spreading activation from other chunks. During a retrieval process, the activation of chunks that match a set of retrieval conditions gradually accumulates until a certain decision criterion (explained below) has been reached. The chunk that has been decided upon is retrieved from declarative memory, and the accumulation of activation stops. Because no new activation is being accumulated, the short-term component of the activation of all chunks decays. The short-term activation dynamics can be represented by a drift, a starting point, and a decision boundary, which will be discussed below.

Drift Drift in RACE/A is the reflection of the current demands of the environment. Thus, drift is a function of stimuli, as well as the currently active declarative facts. All facts and stimuli, which will collectively referred to as *sources of activation*, continuously spread excitatory activation towards associated chunks. This means that a chunk that has more sources of activation (more evidence) or sources with more activation ("stronger" evidence) will accumulate faster than a chunk with less sources of activation or sources with less activation. In the absence of evidence for a particular chunk, the short-term activation will decay. The drift in RACE/A is also determined by a logistically distributed noise sample, adding stochasticity to the system. These considerations are reflected by Equation 1, which may be referred to as the drift equation (Usher & McClelland, 2001). The drift equation captures the dynamics of short-term activation (*C*) of one chunk (chunk *i*) over time.

$$dC_i = [-\alpha C_i + \beta \sum_j S_{ji} A_j + \varepsilon_i] dt \qquad (1)$$

In this equation, the decay of short-term activation is expressed by α, which should be a value in the range [0,1]. The spreading activation component is a sum of the activation of other chunks (A_j), weighted by the associations that exist with chunk *i* (S_{ji}). Note that this differs from the implementation in ACT-R, in which only the chunks in buffers spread activation. In RACE/A, all chunks may spread activation. The spreading activation component is scaled by a factor β that determines the overall accumulation speed. The noise is expressed by ε_i.

Starting point The starting point of the accumulation reflects the prior probability that a chunk is needed. This is reflected by ACT-R's base-level activation equation (Equation 2, Anderson, 2007), which incorporates the usage history of a chunk. Chunks with a high base-level activation start the accumulation of activation at a higher starting point, and are thus more likely to be retrieved from memory.

$$B_i = \ln\left(\sum_{j=1}^{n} t_j^{-d}\right) \qquad (2)$$

Given that the usage history of the retrieved chunk has been altered (because it has been retrieved recently), the chunk's long-term component is being increased in such a way that it greatly exceeds the current level of short-term activation. For this reason, the net activation of each chunk in the system can be described as

$$A_i = \max(B_i, C_i) \tag{3}$$

indicating that the activation of a chunk is the maximum of the need probability of a chunk (reflected by B_i) and the accumulating evidence for that chunk (reflected by C_i).

Decision Boundary The decision boundary in RACE/A is relative to the activation of competitors in the system. This choice reflects the insight that if multiple memory representations are relevant, responding becomes more difficult (Hick, 1952; Luce, 1986). This is reflected by Equation 4, which expresses the conditions under which a decision will be made. If the activation of a certain chunk (chunk *i* in Equation 4) exceeds the activation of all competitors (*j*, including *i*) by a certain ratio θ (referred to as the decision ratio), then that chunk is retrieved from memory. The ratio between the activation of one chunk and the summed activation of all competitors reflects the relative likelihood of a chunk, and will be referred to as the Luce ratio for that chunk (Luce, 1963). The duration of the retrieval process constitutes the interval between the onset of the retrieval process (when the request for a retrieval is made) and the moment at which the Luce ratio of one chunk exceeds the decision ratio.

$$\frac{e^{A_i}}{\sum_j e^{A_j}} \geq \theta \tag{4}$$

The Model

The model concurrently performs the tone classification task and the PWI task. The tone classification task was modeled using ACT-R's standard auditory perception module. If a tone is presented, the model processes auditory information, and retrieves a memory trace that encodes the appropriate stimulus-response mapping (that is, which button to press given the perceived tone). Finally, the model made a motor response to press the correct button.

When the PWI-stimulus is presented, the model activates conceptual representations in response to the image, and activates a lemma representation in response to the word (e.g., Roelofs, 1992). Because lemmas spread activation to the conceptual representations that relate to them, the presentation of a distractor word causes interference at the conceptual level. The decision boundary that determines retrieval from memory becomes harder to reach for the conceptual representation of the picture, increasing the retrieval time. The different activation levels of the target chunk versus competing chunks determine the latency difference between the related and unrelated PWI conditions. In the related condition, the concepts of the target and the distractor spread activation to each other. This mutual excitation causes both activation values to increase, making it even harder to reach the decision boundary. In the unrelated condition mutual excitation is not present. Therefore, there is less competition and a faster retrieval in the unrelated than in the related condition.

In order to name the image, the relevant concept has to be retrieved from memory. Once a concept has been retrieved, the model initiates a response, but not before the selection of the appropriate tone-to-button mapping for the tone classification response has been retrieved. This ensures that the model displays cognitive slack time in which interference in the first processing stage may be resolved.

In processing the PWI response, the model first retrieves a lemma representation that encodes the syntactic information associated with the desired response, than it retrieves a motor program to articulate the desired response. Thus, to complete the task the model needs to do three memory retrievals.

Simulation Results

The model is similar to a previous model of a PRP study of PWI (Van Maanen, Van Rijn, & Taatgen, submitted). However, in the current model we manipulated the speed of word processing relative to the speed of picture processing. Following Botvinick et al. (2001) we assumed that a previous conflict trial leads to more cognitive control, leading to more suppression of the reading response. Thus, high control in the model means a low value for the parameter controlling word processing speed. On the other hand, if the previous trial was congruent, we assume a relaxation of control, resulting in less suppression of the reading response and a high value of the parameter that controls word processing speed (low control).

Figure 3 presents the model behavior for high and low control, respectively. Similar to the pattern in the data (Figure 2), the model shows no interference effect for the high control condition (analogous to the post-R trials), whereas it shows an interference effect for the low control condition (analogous to the post-C trials). In our simulations we ignored the post-U condition from the experiment, since we assume that behavior in that condition was a mixture of behavior from post-C trials and post-R trials.

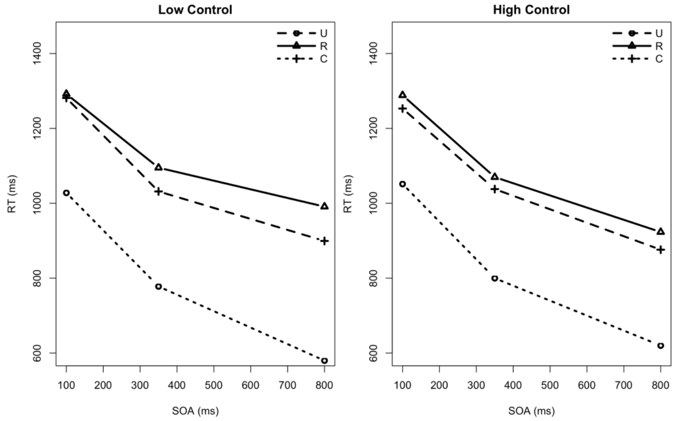

Figure 3: Simulation results for low control (left) and high control condition (right). R: Related; U: Unrelated; C: Congruent.

The explanation for this effect follows directly from the dynamics of the activation of the chunks (conceptual and lemma information) in the model. Retrieval times for the concept and lemma information are determined by the activation ratio (the Luce ratio) between the chunks. Thus, a high Luce ratio in favor of the relevant chunk (the one associated to the correct response) leads to a fast retrieval. A high Luce ratio is reached by a large difference in processing speed fo the two stimulus dimensions, hypothesized to reflect high control (Figure 4, High Control). A high ratio in favor of the irrelevant chunk, or a low ratio in favor of the relevant chunk leads to slower retrievals. The competition between chunks results from mutual excitation of the competing chunks. Therefore, strong competition results in high activation of the competing chunks, and also in a high activation difference (Figure 4, Low Control). As a result, a subsequent retrieval of the same chunk will be faster, because the starting points of accumulation of activation of the competing chunks differ more than at the start of the first retrieval. A similar argument can be constructed for chunks that are strongly associated, as are the concept chunks and lemma chunks in our model. An initial concept retrieval already influences the activation at the start of the subsequent lemma retrieval.

Figure 5 presents the activation dynamics of four chunks in the model over time. the top panel (Low control) presents a prototypical model run in which the word processing speed is high, the bottom panel (High control) presents a model run in which the word processing speed is low. Figure 5 illustrate how a fast retrieval in the first stage of the PWI process may lead to a slow retrieval in the later stages, resulting in a shift of the overall interference pattern.

Discussion & Conclusion

Although we implemented the effect of more cognitive control as a lower speed of word processing relative to picture processing, we make no claims on the exact mechanism. Besides actual slower perceptual processing, another possibility could be that more cognitive control results in active inhibition of the undesired response. However, similar to our current implementation this would result in less competition, and our results would not differ.

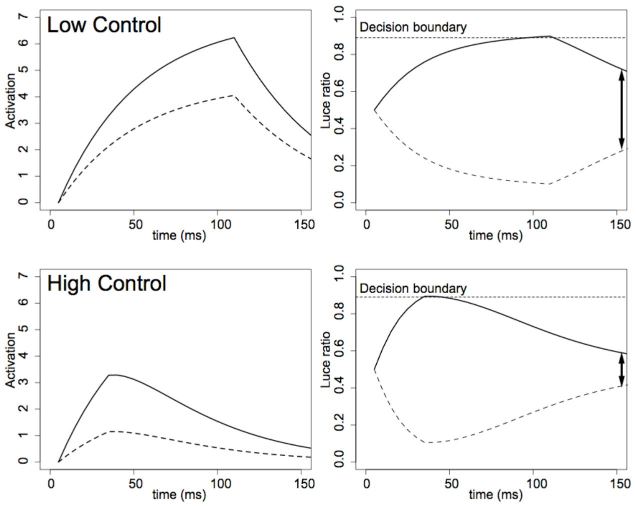

Figure 4: The activation dynamics in RACE/A.

Analogy with Stroop and PWI

The results from our study show a remarkable analogy with the results from experiments that studied the difference between the Stroop effect and PWI. Dell'Acqua et al. (2007) found an early locus of interference in PWI, similar to the post-C condition in our experiment. By contrast, Fagot and Pashler (1992) found a late locus of interference in the Stroop task, similar to our post-R condition. In a previous study, we explained this difference by a difference in processing speed between colors and images (Van Maanen & Van Rijn, 2008; Van Maanen, Van Rijn, & Borst, submitted). The cognitive models in that study showed that both Fagot and Pashler's data and Dell'Acqua et al.'s data could be explained by one model that maintained a lower processing speed for color information than for picture information.

Our current results suggest that it may not be the speed of perceptual processing per se that is important in shifting the locus of interference, but rather the difference in speed between the two stimulus dimensions (words and pictures for PWI). In the current model, the processing speed of the word and picture differed more for the low control than for

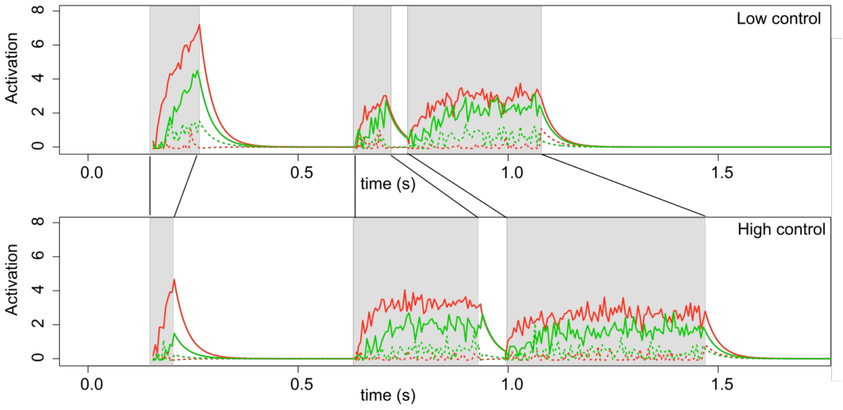

Figure 5: A simulated trial for the low control condition (top) and the high control condition (bottom). The grey areas indicate the duration of every memory retrieval during a trial.

the high control condition. This was explained by more suppression of the reading response in the high-control condition. In the Stroop/PWI model, the processing speed for the PWI condition differed more than for the Stroop condition. This was explained by the faster processing of colors than of pictures, and hence a greater difference in processing speed between words and pictures in PWI than between words and colors in Stroop.

Conclusion

The experiment demonstrated that the Gratton effect is not only present as a difference in interference effect size after Congruent and Related trials, but also entails a shift in the locus of the interference. The absence of observable interference at small SOAs in the post-C trials suggests that the locus of interference in those trials is in an early processing stage, but is absorbed in the cognitive slack time that is created by the PRP design. The presence of observable interference in post-R trials suggest that the locus of interference is late, after the bottleneck that is created by the PRP design.

Our simulations suggest a mechanism for this shift in locus. The simulations show that if the speed with which words are processed is high, the locus of interference is early, whereas a low processing speed for words results in a late locus. The processing speed for words was hypothesized to be under cognitive control, where an increase in control leads to a decrease in word processing speed, and vice versa. These results suggest that the specifics of the stimulus determine the magnitude and spacing of interference over the entire task, a result which may be extended to the Stroop/PWI literature as well.

Acknowledgments

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