Dynamic Competition and the Cognitive Bottleneck

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Abstract

Limitations seen in dual-task situations have commonly been explained in terms of theories characterized by three discrete stages of information processing (i.e. cognitive bottleneck theory). We take a neural dynamic approach to understanding how the cognitive system processes stimuli within the psychological refractory period paradigm and propose that a capacity limited stage of processing emerges as the natural result of settling competition among presented stimuli as they move from perceptual processing into cognitive stages of processing. Using a new action dynamics methodology, participants respond to stimuli via a Nintendo Wii remote-controlled cursor. Competition within the cognitive system is manifested in the subtle motor movements associated with the trajectories of the participants' responses. It was found that more competition is manifested when stimuli are presented at smaller SOAs than with larger ones and that inhibition is manifested with the larger SOAs.

Keywords: Coordination dynamics; dual-task; competition; psychological refractory period; bottleneck.

Background

Rapidly processing competing stimuli, such as a car cutting you off in traffic as your cell phone rings, is accomplished by the cognitive system via complex nested bouts of perception and action that are coordinated in order to make appropriate decisions. One of the most well known experimental paradigms developed to probe limitations in dual-task paradigms, derived from competing stimuli presented in close temporal proximity, is the psychological refractory period (PRP) paradigm (Welford, 1952).

In the typical PRP design, participants are presented with two stimuli separated by varying stimulus onset asynchronies (SOAs). Usually, a visual stimulus (S1) is followed by an auditory stimulus (S2). Response order is often enforced and participants are instructed to respond to each stimulus by pressing arbitrary keys on a keyboard. The combination of S1 and its response (R1) is referred to as task 1 (T1). The presentation of S2 and its response (R2) is referred to as task 2 (T2). The archetypal finding is that as SOA decreases, and T1 and T2 are thus initiated very close together, RT2 increases (Jentzsch, Leuthold, & Ulrich, 2007; Johnston & McCann, 2006; Ruthruff & Pashler, 2001; Welford, 1952). In other words, the reaction time to T2 is longer in PRP experiments than if T2 were to be completed in isolation.

The cognitive bottleneck theory (CBT) is a commonly accepted theory that attempts to explain the slowing of RT2 (Brisson, & Jolicoeur, 2007; Jentzsch, Leuthold, & Ulrich, 2007; Johnston & McCann, 2006; Sigman & Dehaene, 2006; Vachon & Tremblay, 2006). The CBT posits that information processing resulting in a response requires three discrete stages. The first stage is responsible for perceptual processing, the second stage consists of central operations (e.g., linking of stimulus-response mappings), and the third stage deals with the motor response. The CBT states that the first and third stages can proceed in parallel. However, the second stage is characterized by a passive first-come, first-served serial processor. Therefore, if S2 is presented before S1 has been completely processed by the second stage, S2 must wait for S1 to exit this central stage of processing. For many simple tasks, shortening the SOA to less than 300 ms forces S2 to wait for access to the central processor (Sigman & Dehaene, 2008). This waiting for access to the second stage of processing is thought to be what causes the delayed response times for T2.

However, another approach to explaining RT2 slowing is the idea of dynamic competition. One such model has been proposed by Potter, Staub, and O'Connor (2002) to explain limitations in the attentional blink (AB) paradigm. A notable number of authors have highlighted the similarities between PRP and AB (Corallo, Sackur, Dehaene, & Sigman, 2008; Jolicoeur, 1999; Ruthruff & Pashler, 2001; Wong, 2002). Because of these similarities, it is reasonable to postulate that Potter et al.'s (2002) model could be extrapolated to explain the findings commonly seen in the PRP paradigm. The important difference in the Potter et al. (2002) model from the CBT is that stimuli compete for entrance into a limited capacity stage of processing in an active manner. For example, if S2 is presented before S1 enters the capacity limited stage of processing, the two stimuli will compete for the limited processing resources. Therefore, S2 may be able to "pull" processing resources away from S1.

The competition seen in Potter et al.'s (2002) model follows intuitively from neural dynamic approaches to vision and attention, such as Desimone and Duncan's (1995) biased-competition model of visual attention. Instead of a central executive, or spotlight, directing attention around the visual field, their biased competition model purports that attention is an end result of settling representational competition. Desimone and Duncan (1995) suggest that the cognitive system is confronted with competition numerous times between stimulus presentation and the motor response to that stimulus. As each stage of visual processing is traversed the processing becomes more complex and the amount of the visual field a neuron is responsible for increases. As this occurs the stimuli that were presented in those areas must compete with each other for processing resources. Whichever stimulus continually wins the competition for the limited processing resources is the stimulus that is attended to. In this way Potter et al.'s (2002) competition model can be seen as the natural consequence of this competition taking place within the cognitive system at the lowest and most basic levels of information processing as described by Desimone and Duncan (1995).

Taking cognitive competition into consideration is an improvement on the CBT; however, the limitation that both Potter et al.'s (2002) model and the CBT have in common is that they assume that information processing occurs in three discrete, independently operating stages. These models presume that motor commands cannot be programmed until a stimulus has been completely processed by the central operations stage. Given studies on decision-making and motor programming (e.g., Gold & Shadlen, 2000), this assumption is inherently flawed because it portrays the cognitive system as an assembly line, when is better described as an interconnected network of subsystems that perform their individual duties under the influence of continuous updates from these subsystems. Even if CBT is a powerful explanatory account of PRP effects, it must itself be accounted for in terms of emergent properties of cognition and action, in which motor movements materialize as information processing emerges from a continuous coordination of the various subsystems within the cognitive system working in concert (McKinstry, Dale, Spivey 2008; Dale, Roche, Snyder, McCall, 2008). In other words, the central processing of a stimulus and the motor response stages of processing are not mutually exclusive but are, in fact, dynamically linked.

In virtually all dual-task paradigm studies, reaction time is the principle measure used to assess the effects of competition within the cognitive system. In the present work, we hope to contribute to the theoretical debate by considering an action-dynamics methodology that provides a finer-grained detection of cognitive competition than just reaction time alone. In what follows, we summarize this methodology, and describe two experiments using it.

Current Study

The purpose of the experiments presented in this paper is to explore the implicit predictions of the CBT and the competition-based approaches within PRP by tracking the continuous flow of cognition into action. The CBT implies that while the cognitive system is processing a stimulus it cannot process anything else until that stimulus has been completely processed. According to the alternative approaches, there should be a level of competition even during the post-perceptual processing that is typically associated with the CBT approach. In this way, entrance into a limited capacity stage of processing is an active and dynamic process that, we propose, should be manifested as the response unfolds over time.

These assumptions were investigated by way of the basic PRP paradigm. However, instead of arbitrary key presses to indicate responses, participants responded to stimuli using a Nintendo Wii remote. This methodology provides a rich source of arm-movement data that provides insights into the dynamics of cognitive processing (Spivey, Grosjean, & Knoblich, 2005; Dale, Kehoe, & Spivey, 2007).

By allowing participants' to use the Nintendo Wii remote to respond to a cognitive task, Dale et al. (2008) have found that analyses of participants' arm movement trajectories reflect the mental processes that enabled the response. The participants' subtle motor movements within response trajectories are recorded in order to examine how the *decision* unfolds over time. In the case of PRP, because both T1 and T2 here are completed using one response medium (the arm through the Wii remote), there may be influences on the arm's dynamics as stimuli "compete." Specifically, the analyses of the action dynamics data may reveal a subtle signature if S2 can draw processing resources away from S1, or not if the response to the S1 is unaffected by S2 as the CBT predicts.

Experiment 1

The purpose of the first experiment was to investigate whether S2 is able pull processing resources away from S1 while using SOAs that are commonly used in PRP experiments.

Method

Subjects. Participants included 19 (15 females, mean age 20.5) University of Memphis undergraduates from the psychology subject pool who participated for extra credit in their introductory psychology course that self-reported normal or corrected to normal vision and hearing.

Interface display and device. The experiment took place in an oblong laboratory room (3.8 m x 61.8 m). An Epson LCD projector and Apple Mac mini were placed on a small 76 cm high table that stood approximately 2.7 m away from the long wall of the room. The Mac mini's display was projected onto the wall at the end of the room creating a display approximately 1.4 m in width (29.1° visual angle).

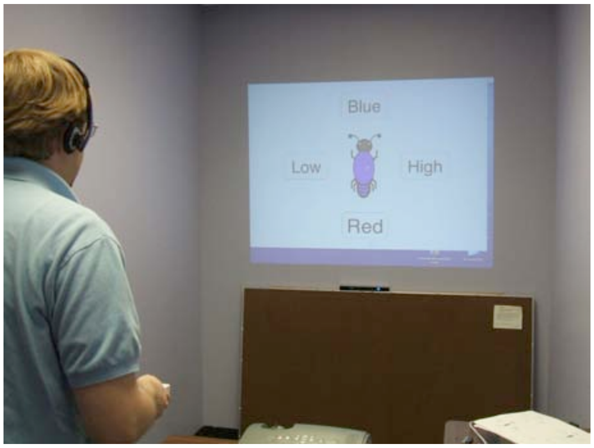

Figure 1: Experimental environment and interface.

Participants interacted with the experimental program by using the Nintendo Wii remote. Standing behind the small table, participants held the Wii remote in their right hand that was approximately lined up with the projector's lens. The Wii-remote interfaced with the Apple mini computer via a Blue-tooth transfer protocol called DarwiinRemote (2006, Hiroaki Kimura). A Nyko infrared emitter at the base of the projected screen provided the remote with a frame of reference so that arm movements mapped isomorphically onto x,y pixel-coordinate movements (see Figure 1).

Procedure. In a basic PRP design, participants performed a visual discrimination task (T1) and an auditory discrimination task (T2). Perceptual judgment tasks were chosen because previous work has suggested that they are subject to the PRP (Johnston & McCann, 2006). For each trial, S1 was an image of a bug (2.4° visual angle) that varied in color from red to blue (i.e., saliently red, ambiguously red, ambiguously blue, saliently blue). T1 was to determine whether the presented bug was more red than blue or vice versa. At varying SOAs (150 ms, 500 ms, 999 ms), a tone (S2) would be played via headphones. There were four levels of tone pitch that varied between low and high (300Hz, 500Hz, 700Hz, 900Hz). T2 was to categorize the pitch of the tone as high or low.

At the beginning of each trial a central fixation point (2.7° visual angle) and four response boxes (2.8° visual angle) were displayed on the screen. Above and below the central fixation point were response boxes labeled "blue" and "red" respectively. To the left and right of the central fixation point were response boxes labeled "low" and "high" respectively (see Figure 2). To begin each trial, participants clicked the central fixation point. At that time S1 would replace the fixation point and then be followed by S2.

In previous PRP studies, participants responded to each stimulus with different hands (Jentzsch, Leuthold, & Ulrich, 2007; Johnston & McCann, 2006; Ruthruff & Pashler, 2001). In the current experiment, responses to both stimuli were conducted through the participants' right hand only. Requiring participants to respond to both stimuli through a single modality increased competition within the cognitive system for that modality. Participants were instructed to respond by moving the Wii remote-controlled mouse cursor and clicking on the appropriate response boxes that corresponded to S1 and S2 as quickly and as accurately as possible. Response order was not fixed. Participants were told to respond in the order of their perceptual decisions. Feedback was provided by the presentation of either a green check mark (to indicate a correct response) or a red "X" (to indicate a wrong response) in the selected response box. The trial ended once a correct response to both stimuli was selected (see Figure 2).

The instructions were explained to each participant prior to an 8 trial practice stage during which they were allowed to ask clarification questions about the experimental procedures. The researcher initiated the experiment and left the room once the participant verbally acknowledged clear understanding of the procedures.

During each session, participants went through 5 blocks of 48 trails. In each block every combination of bug color, tone pitch, and SOA was displayed exactly once in random order. Participants completed 240 total trials that lasted approximately 20 minutes. MATLAB was used to develop the experimental program, produce the tone stimuli, and sample the Wii-remote-controlled cursor movements as streaming x-y coordinates.

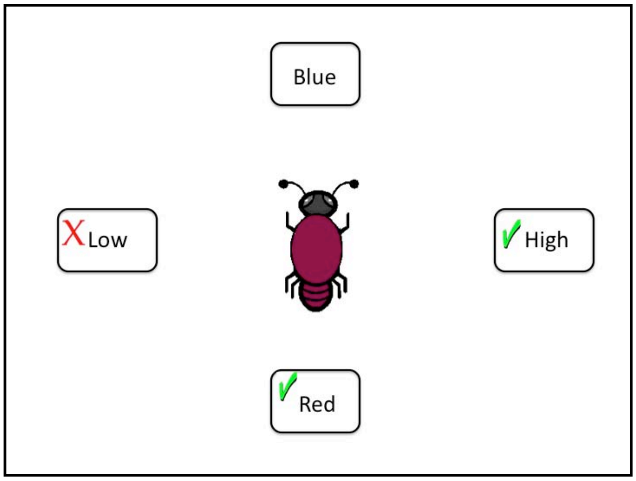

Figure 2: Feedback and the experimental interface.

Measures. The Wii remote is not fixed on a surface (as in computer-mouse studies, Spivey et al., 2005; Dale et al., 2007). This causes constant subtle fluctuation in the held out hand. We therefore use a pixel radius to define an "escape" region. The amount of time it took for participants to initiate a movement by moving the cursor out of a 50-pixel escape region around the central fixation point served as a measure of latency. Previously, Dale et al. (2008) used a 100-pixel escape region. However, for the smaller experimental display presented here it was found that a 100-pixel escape region was too conservative. We calculated the 50-pixel latency period for task T1 in milliseconds, producing *latency for T1*. How long it took for a response to unfold over time served as a second measure. *Response time for T1* was measured from the onset of S1 until a correct T1 response was selected. This reflects the amount of time the hand is in motion towards a selection. *Response time for T2* was measured from the T1 response selection (or presentation of S2, whichever came first) to the selection of a correct T2 response.

Since T1 responses required only vertical movements, deviations along the x-axis served as a measure of whether S2 affected T1 responses. For example, if the highest tone (responded to towards the right response option) is presented before or during movement, x-axis fluctuation towards the right may be observed. These x-axis deviations during T1 responses were analyzed at 50 ms intervals after the response trajectories exited the escape region. If response movements capture cognitive competition, then any x-coordinate deviation present in the evolving trajectories should reflect the tone response box's direction.

Results

A 3 (SOA: 150, 500, 999) x 2 (bug: salient vs. ambiguous) x 2 (tone: salient vs. ambiguous) linear mixed effects model was constructed for each of the measures (using MIXED procedure in SPSS, with subjects as a random factor). All trials involving any incorrect response were removed prior to analysis. Unless otherwise noted, only effects significant at the .05-level are reported. All other main effects and interactions not mentioned were not significant.

T1 latency was significantly reduced for saliently colored bugs by approximately 37 ms. Similarly, RT1 and RT2 were significantly lowered by ambiguous stimuli by approximately 122 ms and 72 ms respectively. Also, lower SOAs induced faster reaction times for both tasks by approximately 80 ms for T1 and 160 ms for T2. These findings are displayed in table 1.

Table 1: Results of basic movement measures.

DV	T1 Latency M (ms), F	T1 RT M (ms), F	T2 M (ms), F
Ambig.	510, 32.3***	1,446, 64.3***	705, 49.3***
Salient	473	1,324	633
150ms		1,356, 11.9***	609, 106.8***
500ms		1,361	625
999ms		1,427	774

*** $p < .001$

Deviations along x-axis. We added an additional predictor to the mixed models in this analysis. We factored in a variable reflecting how long the subjects had to process the T2 stimulus prior to latency movement (which we termed *competition latency*). There was a significant main effect of this competition latency on the x-axis deviations at 50 ms into the T1 response $F(1, 3{,}428.8) = 7.525$, $p < .01$. It continued to be significant every 50 ms until 200 ms into the T1 response and again at 300 ms. There were also significant interactions between competition latency and SOA as well as significant three-way interactions among competition latency, SOA, and sound type (i.e. whether S2 was a high or low pitch tone). The significant findings are listed in table 2. The three-way interactions are graphed at 50 ms and 250 ms into the T1 response trajectory in Figure 3.

Table 2: x-axis deviation results.

Time into T1 response movement	Competition latency (F)	Competition latency x SOA (F)	Competition latency x SOA x S2 (F)
50 ms	7.5**		
100	9.2**		
150	7.2**		3.6*
200	5.1*	3.7*	4.6*
250		3.8*	5.1**
300	3.3*	3.4*	4.7**
350			3.4*

* $p < .05$, ** $p < .01$

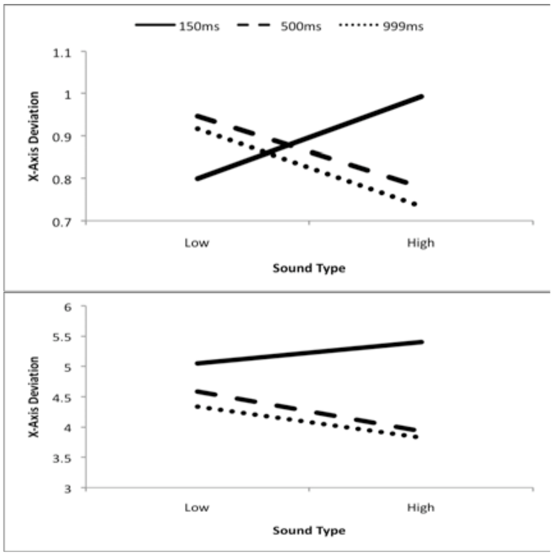

Figure 3: Mean x-axis deviation at 50 ms (top) and 250 ms (bottom) into T1 response trajectory. Higher x-axis deviation reflects more rightward movements (movements towards high-tone responses).

Discussion

The data from the current study are in line with previous studies that show that task difficulty is manifested in response trajectories (Dale et al., 2008). Contrary to most PRP results, we found that as SOA decreased, RT1 and RT2 also decreased. One explanation for this finding could be that participants took as much time as they were allotted to process S1 and that the presentation of S2 cued them to initiate a S1 response. This is likely unique to our study due to our collapsing of T1 and T2 into one response mode.

The findings of the x-axis deviation analysis show (relative) movement in the direction of the correct response to S2 at the shortest SOA, but away from the correct response at the longer SOAs. This occurs as soon as 50 ms into the T1 response movement. This finding suggests that S2 is being processed very early into the T1 response, and competing with it, resulting in a pull toward the correct T2 response at the shortest SOA. The pull away from the correct T2 response at longer SOAs may be indicative of active inhibition. Previous work by McSorley, Haggard and Walker (2006) has shown that saccade trajectories also show a similar pattern of deviation toward a distractor when the saccade latency is less than 200 ms and away from the distractor when the latency is more than 200 ms, indicating active inhibition. In an effort to evaluate whether these effects would be evident using shorter SOAs, a second experiment was conducted.

Experiment 2

The second experiment used SOAs that more closely resembled those used by Potter et al. (2002). We predicted that this adjustment would enhance competition and therefore participants' response trajectories would exhibit more x-axis deviation, reflecting potentially concurrent S2 processing.

Method

Subjects. Participants included 19 (11 females, mean age 19.3) University of Memphis undergraduates from the psychology subject pool who participated for extra credit in their introductory psychology course that self-reported normal or corrected to normal vision and hearing.

Procedure. Procedures for experiment 2 were identical to experiment 1 except that the SOAs used were 30 ms, 100 ms, 200 ms.

Results

As in the previous experiment, a 3 (SOA: 30, 100, 200) x 2 (bug: salient vs. ambiguous) x 2 (tone: salient vs. ambiguous) linear mixed effects model was constructed for each of the measures (using MIXED procedure in SPSS, with subjects as a random factor). Unless otherwise noted, only effects significant at the .05-level are reported. All other main effects and interactions not mentioned were not significant.

T1 latency was significantly reduced for saliently colored bugs by approximately 16 ms. Similarly, RT1 and RT2 were significantly lowered by ambiguous stimuli by approximately 176 ms and 46 ms respectively. The previous effect of SOA from Experiment 1 was not retained. These findings are displayed in table 3.

Table 3: Results of basic movement measures.

DV	T1 Latency M (ms), F	T1 RT M (ms), F	T2 M (ms), F
Ambig.	529, 4.4*	1,420, 75.8***	666, 10.7***
Salient	513	1,244	620

* *p* < .05, *** *p* < .001

Deviations along x-coordinate. There was a significant main effect of competition latency on the x-axis deviations at 50 ms into the T1 response F(1, 3,428.8)= 6.06, *p* < .05. It continued to be significant every 50 ms until 300 ms into the T1 response. There were also significant interactions between competition latency and SOA as well as significant three-way interactions among competition latency, SOA, and sound type. The significant findings are listed in Table 4. The three-way interactions are graphed at 50 ms and 550 ms into the T1 response trajectory in Figure 4.

Discussion

The effects of SOA in the reaction time findings of Experiment 1 were not replicated in Experiment 2. This is presumably due to that fact that the shortened SOAs of Experiment 2 didn't allow participants the luxury of extra processing time.

In the Experiment 1 inhibition was not evident at the 150 ms SOA. Interestingly, in Experiment 2 inhibition of the T2 response was observed with the 100 ms SOA. Although the time course of inhibition is not consistent, in both experiments the shortest SOA yielded a pull toward the distracting S2 while the longer SOAs seemed to indicate active inhibition.

Table 4: x-axis deviation results.

Time into T1 response movement	Competition latency (F)	Competition latency x SOA (F)	Competition latency x SOA x S2 (F)
50 ms	6.06*	4.41*	7.6***
100	6.5*	6.7**	6.4**
150	5.6*	6.6***	4.0*
200	5.7*	4.6**	3.5*
250	6.6**		3.6*
300	4.6*		3.1*
350			3.1*
400			3.4*
450			3.7*
500			3.2*
550			3.1*

* *p* < .05, ** *p* < .01

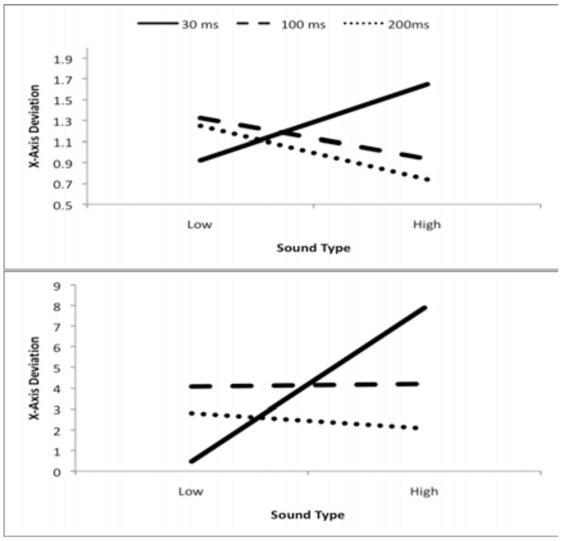

Figure 4: Mean x-axis deviation at 50 ms (top) and 550 ms (bottom) into T1 response trajectory.

General Discussion

The investigations discussed in this paper explored how two stimuli presented within a dual-task paradigm compete with each other and how the unfolding of the responses to the presented stimuli reflect not only task difficulty but may also be indicating an interesting pattern of active inhibition. The results are preliminary but promising insights toward developing more fine-grained access to the time course of decision competition. They do, however, have a number of limitations. Most notably, the extent to which the stimuli competed with each other could have been hampered because in both experiments S1 was a constant stimulus but S2 was only presented briefly. While this is characteristic of most PRP experimental designs adjusting the presentation duration of S1 to equal that of S2 may enhance competition among the stimuli. Also, reducing the size of the response boxes is another factor that could be adjusted in order to provide more fine-grained action dynamics data. Participants were able to make ballistic-like responses in our task because target regions were large enough to accommodate speed over placement accuracy.

Admittedly, these simple aspects of our task may have sharply influenced the competition observed. In general, the findings were robust in the x-axis deviations in the T1 response trajectories, suggesting competition and possibly active inhibition. As shown in the past (Shin, Cho, Lien, & Proctor, 2007) the cognitive bottleneck is a not “finicky.” It works to robustly predict responding even in more natural decision competition situations (Levy, Pashler, & Boer, 2006).

Our position is that to the extent that the cognitive bottleneck exists, it is less a structural limitation and more an emergent quality of the cognitive system because it breaks down under certain circumstances (Brisson & Jolicoeur, 2007). Importantly, our talk of supporting one theory over another is an oversimplification, when another conceptual strategy is quite possible: CBT and competitive theories may be integrated by identifying the contexts in which one or the other holds (cf. Dale, 2008; Navon & Miller, 2002). The data we present here are another step towards identifying its boundaries.

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