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COGNITIVE CRUISE CONTROL: INVESTIGATING HOW CONTEXT AFFECTS THE MOMENTUM OF COGNITIVE CONTROL

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COGNITIVE CRUISE CONTROL: INVESTIGATING HOW CONTEXT AFFECTS THE MOMENTUM OF COGNITIVE CONTROL

By

Kristy Marie Tapp

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DEDICATION

This thesis is dedicated to my dad, Richard Snyder, who taught me by example the crucial importance of character, integrity and working diligently to refine the one's raw potential. And to the rest of my family, who continue to support me while I pursue my goals.

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I'd like to thank Rick Dale, for his support and guidance throughout this project and for providing me the opportunity, knowledge, and the tools necessary for completing this research; and for being an all-around awesome advisor. I'd also like to thank Nick Duran, Ryan Morehead, Jenny Roche and all the Cognition and Integrated Action Laboratory members for their invaluable input.

ABSTRACT

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In the present studies a coordination dynamics perspective is taken to explore the interplay of perception and action in a continuous dual-task paradigm. Two experiments will be conducted using an action-dynamics methodology, through tracking response trajectories with the Nintendo Wii remote, which allows for analysis of how a response unfolds over time. The real-time data (i.e., the response trajectories) are expected to reflect an intriguing pattern of cognitive competition as attention adapts to trial context. The purpose of this work is twofold: a) exploring whether attention/cognitive control is best characterized in terms of its structural limitations (i.e., bottleneck) or its flexible, dynamic properties and, b) investigate if any patterns emerge in the response trajectories that may be indicative of the cognitive system adjusting to conform to the unique combination of experimental parameters.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Every decision we make, whether it is determining which job to apply for or just deciding to pick up a cup of coffee, is possible because the cognitive system coordinates the processing of the numerous stimuli we are constantly bombarded with, giving rise to complex nested bouts of perception and action (Kelso, 2002; Van Orden, Holden, & Turvey, 2003). Information processing and ultimately higher-level cognitive processes never occur within a vacuum but are instead modulated by numerous factors such as context and current goals. In order to make any decision and subsequently act on it, the cognitive system must settle on a current goal, reconcile the competition among seemingly countless stimuli, and elect to initiate an appropriate response. All the while it must be flexible enough to inhibit unexpected distractors, such as a dog jumping into your lap as you reach for that coffee.

Historically, attempts to formulate theories of such cognitive control have focused on explaining dual-task limitations of the cognitive system. The classic theories, most notably the cognitive bottleneck theory (CBT), were built on the single key assumption that the cognitive system conducts processing through an assembly line of discrete, serial stages (for recent discussion see: Brisson & Jolicoeur, 2007; Jentzsch, Leuthold, & Ulrich, 2007; Johnston & McCann, 2006; Sigman & Dehaene, 2006; Vachon & Tremblay, 2006). The CBT has been shown to predict responding in natural decision competition situations (Levy, Pashler, &

Boer, 2006), but it originally sought to describe the pattern of results elicited by 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). Responding to the two stimuli typically requires arbitrary key presses in response to different tasks, from relatively low-level perceptual decisions (Johnston & McCann, 2006), to higher-level cognitive decisions such as numeral identification (Sigman & Dehaene, 2008). The common finding is that if the second stimulus (S2) is presented within 300 ms of the first stimulus (S1), the response to S2 is delayed (Sigman & Dehaene, 2008). Moreover, the reaction time to S2 is longer in PRP experiments than if it were to be completed in isolation.

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. According to the CBT the first and third stages can proceed in parallel. However, a passive first-come, first-served serial processor characterizes the second stage. Therefore, while the central stage is processing S1 all other stimuli must wait. This deferment of access to the central stage of processing is thought to be the cause of delayed response times to S2. Therefore, past research has shown that the CBT is a powerful explanation of the common dual-task limitations, such as the PRP effect (Shin, Cho, Lien, & Proctor, 2007).

However, studies on decision-making and motor programming (e.g., Gold & Shadlen, 2000, 2001, 2003) bring to light the possibility that the basic assumption of serial, discrete-stage theories, which portray the cognitive system as an assembly line, cannot wholly account for how the underlying neural substrate operates. For example, Gold and Shadlen (2000) demonstrate that decisions are based on continuously accumulating information, potentially all the way into premotor regions dedicated to enacting a decision (see also Spivey, 2007 for a review of diverse evidence of this). Thus, accounts of information processing should incorporate the notion that the cognitive system is built upon an interconnected network of subsystems that perform their individual duties under the influence of uninterrupted updates from the constituent parts of the whole system.

One such approach is coordination dynamics (Kelso, 1984). Viewed from this perspective, processing limitations seen in dual-tasking situations occur from a number of dynamic interactions across the cognitive system. It may not be the case that a single iron gate stands between perceptual processing and central (i.e., decisional/response-selection) stages of processing, where stimuli line up in a single-file line waiting for their turn to pass in a first-come, first-served fashion, presumably forming the infamous cognitive bottleneck. Moreover, processing a perceptual event and responding to it is a complex task that entails many subtasks, which includes but is not limited to: a) integration of the object's features, b) perceptual categorization, c) establishing an episodic memory trace of the object,

d) identification of the object, e) retrieving possible relevant information about the object from long-term memory, f) integrating bottom-up and top-down components, g) calling upon the relevant task/goal information, h) mapping the object to an appropriate response, i) developing the intention to act, j) planning the movement, k) initiating the response, and l) controlling the act of responding. The mechanisms responsible for each subtask of the process do not exist in their own discrete stage *per se*, instead moving from one component to another is a graded process. The underlying mechanisms responsible for each aspect in the sequence of events that results in information processing are continuously receiving information from and influencing each other. In this way, information processing is an autonomous self-organizing and highly flexible phenomenon. Furthermore, although each individual mechanism has capacity limitations, not all mechanisms reach maximum capacity on a predetermined timescale or at a single step in the process. Therefore, at any moment in time a variable number of these mechanisms can perform in parallel while others, which may have reached their capacity limits, operate in a more serial manner.

Importantly, taking a coordination dynamics approach provides an explanation for why authors have found conflicting evidence for the number and loci of information processing bottlenecks. Sigman and Deheane (2006) are just one example of the many researchers whose results support a single bottleneck at the response-selection stage of processing, while Johnston and McCann's (2006) findings indicated a bottleneck closer to the perceptual processing stage. DeJong

(1993) suggested multiple bottlenecks including a response initiation bottleneck and a response-selection bottleneck that could also be congested by perceptual categorization. It may be that they are all correct. The coordination dynamics perspective suggests that information processing flexibly conforms to aspects of the task at hand by altering the way in which the cognitive system controls how processing resources are divided and shared. For example, if a student is answering a quantitative question on a test (e.g., GRE, ACT), the cognitive system may construct an information processing structure that tends to operate in a more serial manner, focusing most of its resources on a single task at a time. On the other hand, when driving, the cognitive system allows the driver to handle the complex task(s) of driving as well as talking on a cell phone, while still monitoring the environment for unexpected events, such as a child running out into the street.

Broadly speaking, the purpose of the current work is to investigate cognitive control in an experimental dual-task paradigm. Specifically, how attention changes the way it processes information within varying perceptual contexts by surveying the *process* of dynamic, coordinated cognitive control as it unfolds over time. In what follows, a few pertinent models that provide theoretical links between the classic structural bottleneck theory and coordination dynamics are reviewed. Then, action dynamics and an introduction to the novel methodology presently employed for collecting real-time, dual-task cognitive control are briefly described. Finally, two exploratory experiments are presented.

Competition for Processing Resources

Neural dynamic approaches to vision and attention, such as Desimone and Duncan's (1995) biased-competition model of visual attention posit a dynamic, active process, which opposes the long-standing theoretical construct of the attentional spotlight (Treisman, 1982). Instead of a central executive directing attention around the visual field, their biased-competition model purports that attention is an end result of settling competition within the cognitive system. 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 the neurons (i.e., "processing resources") become responsible for processing larger areas of the visual field, those areas must compete with each other for the processing resources. This competition is resolved by means of a biasing attentional template (i.e., working memory) that monitors task-relevant information. Whichever stimulus wins the competition for the limited processing resources is the stimulus that can be consciously reported and responded to.

Potter, Straub, and O'Connor (2002) have proposed a discrete-stage theory of information processing in dual-task situations, which incorporates the cognitive competition seen in Desimone and Duncan's (1995) model, that sought to explain dual-task limitations in the attentional blink (AB) paradigm. Their model, termed the two-stage competition model, suggests that there are two levels of central processing. In the first, all presented stimuli are processed on a preliminary basis. This initial processing "scans" the stimuli for characteristics that match a stored representation of task-relevant information. If the "scan" reveals that a stimulus does have these features, that stimulus will begin to attract processing resources to itself. Once a certain threshold is met, the stimulus then enters the second level, which is a limited capacity stage that is responsible for classic central processing tasks (i.e., stimulus-response mapping). It may be reasonable to postulate that Potter et al.'s theory is similar to Treisman's (1982) attenuation model. However, the attenuation model only deals with processing information in the order that it is received, as does the classic bottleneck theory. In Potter et al.'s model, the order in which a stimulus enters a limited capacity stage of processing is active and dynamic. For example, if S2 is presented before S1 enters the second level of central processing and the initial "scan" of S2 finds task-relevant features, the two stimuli will compete for the limited processing resources. The stimulus that enters the second level first does so because it has attracted sufficient resources first. The notion that a subsequently presented stimulus can "pull" processing resources away from a previously presented stimulus will serve as a principle theoretical question in the present studies.

Integration of Perception and Action

As previously mentioned, coordination dynamics proposes that cognition arises from how information in the form of raw sensations percolate through the brain. Individual neurons begin to process that information by activating networks that begin to autonomously organize by coupling or decoupling until a unique structure materializes for each perceptual experience. The interaction of these nested subsystems continuously flows into each other. The graded process is not limited to perception and cognition but also flows into action (e.g., Balota & Abrams 1995; see Song & Nakayama, 2009; Spivey & Dale, 2006, for a review). Even as early as 1908, Pillsbury noted, "There is no act of attention that in unaccompanied by some motor process" (p.12). Moreover, Hommel, Musseler, Aschersleben, and Prinz (2001) propose that perception and action planning are "indistinguishable". More recently, Caroso-Leite and Gorea (2009) suggested that both perception and action planning have their genesis within a single processing network and even go as far as to posit that motor movements are a more sensitive measure than conscious perceptual identification. In fact, the decreased level of perceptual sensitivity is well documented in attentional blink literature in that even if a subject cannot report the identity of a secondary target presented within a stream of distractors, it is processed enough to cause priming effects (Vachon & Tremblay, 2006).

Therefore, in the tradition of Tipper, Howard, and Jackson (1997), action dynamics explores the variability of response movements as they unfold in order to elucidate the cognitive processes that enabled the movement. Within the novel action dynamics methodology that we employ, participants respond to stimuli that are presented within a continuous dual-task paradigm by pointing with a Nintendo

Wii remote instead of arbitrary key presses to indicate responses, as is usually done in typical dual-task experiments. This methodology provides a rich source of arm-movement data that provides insights into the dynamics of cognitive processing itself (Dale, Kehoe, & Spivey, 2007; Farmer, Cargill, Hindy, Dale, & Spivey, 2007; Freeman, Ambady, Rule, & Johnson, 2008; Spivey, Grosjean, & Knoblich, 2005).

The Present Study

The purpose of the present experiments is to "uncork" the bottleneck in order to peer inside at the inner workings of the autonomously coordinated cognitive processes that yield the behavioral regularities commonly referred to as the bottleneck. The principle measures employed in typical investigations into dual-task limitations (e.g., PRP) are reaction time and error rates, which only provide data on the end result of information processing. For both of the studies in this work, focus will be shifted to exploring the process itself by modifying the typical PRP paradigm to produce a continuous dual-task experiment. The paradigm is referred to as "continuous" because it continually records data as the responses unfold, not just when the response is selected, reflecting the *progression* of information processing and the competition experienced by the cognitive system.

In the following, purely exploratory experiments, the primary question being asked is centered on whether attention/cognitive control is best characterized in terms of its structural limitations (i.e., bottleneck) or its flexible, dynamic properties. It is hypothesized that if information processing is a passive first-come, first-served phenomenon, as the classic structural bottleneck theory proposes, participants should always respond to the stimuli in the order they were presented and the response trajectories should reveal direct movement to the correct response option in a serial manner. However, if information processing is an active process within which stimuli compete for processing resources as proposed by coordination dynamics and Potter et al. (2002), the response movements should reflect this by displaying deviations in the trajectories modulated by the presentation of the second stimulus. In other words, the second stimulus will “pull” on the responses as their progression is tracked, lending support to an active, dynamic interaction among stimuli during processing.

A secondary point of interest radiates from a central coordination/action dynamics prediction. That is, that the emerging systematic patterns within the response trajectories may be indicative of particular structure(s) that the cognitive system produces in order to process the information based on the unique combination of experimental parameters. The patterns will be stable as long as the experimental context remains uniform. Manipulating the experimental parameters (e.g., stimuli salience, presentation duration, temporal proximity, etc.) would require the cognitive system to construct different processing structures resulting in differing response trajectory patterns. Furthermore, because information processing is situated within ever-changing environmental contexts (e.g., one cannot step into the same river twice), the response trajectory patterns should adjust, and perhaps even *adapt*, to the experimental contexts. In other words, the systematic trajectory patterns should be consistent for each of the experiments (e.g., responses to trails that consist of the shortest SOA should be approximately tantamount in each experiment, providing that memory, perceptual load, etc. remains the same). However, the time course of these patterns may flexibly adjust to the individual experimental contexts. For example, SOAs in one experiment could be 150, 500, and 999 ms and in a second experiment the SOAs could be 30, 100, and 200 ms. Trajectories of trials that include the shortest SOAs of each experiment (150 ms and 30 ms) should be similar even though the time course may differ.

CHAPTER 2

EXPERIMENT 1

The first experiment investigates whether a subsequently presented stimulus is capable of pulling processing resources away from a previously presented one, as predicted by the Potter et al. (2002) model, while using SOAs that are commonly used in PRP experiments.

Methods

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 is projected onto the wall at the end of the room creating a display approximately 1.4 m in width (29.1° visual angle). Participants interacted with the experimental program by using the Nintendo Wii remote. Standing behind the table, participants held the Wii remote in their right hand that was approximately lined up with the projector's lens. The Wii remote interfaces with the Apple mini computer via a Bluetooth transfer protocol called DarwiinRemote (2006, Hiroaki Kimura). A Nyko infrared emitter at the base of the projected screen provides the remote with a frame of reference so that arm movements are mapped isomorphically onto x,y pixel-coordinate movements (see Figure 1). MATLAB Psychophysics Toolbox (Brainard, 1997) was used to develop the experimental program, produce the tone stimuli, and sample the Wii remote-controlled cursor movements as streaming x-y coordinates at approximately 80-90 Hz.

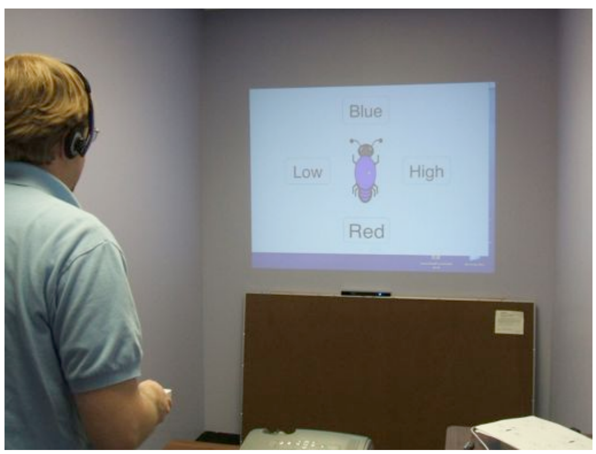

Figure 1. Experimental environment and interface. Participants stood in a darkened room (not shown) and placed on a headset. They interacted with the interface via a Nintendo Wii remote while their response trajectories were being recorded.

Procedure

Stimuli. In the continuous dual-task paradigm, participants performed a visual discrimination task (T1) and an auditory discrimination task (T2). 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.

Previously, 35 (30 females, mean age 19.8) University of Memphis undergraduates who reported normal or corrected to normal vision participated in a color norming task. Each bug stimulus was presented 6 times in random order on a computer screen and the participants were asked to respond by determining whether the bug was red or blue by typing response keys on the keyboard. Once normed, the bug stimuli were used as S1 in the current study.

At varying SOAs (150, 500, 999 ms) after S1 is displayed, a tone (S2) was played via headphones. There were four levels of tone pitch that varied between low and high (300, 500, 700, 900Hz). T2 was to categorize the pitch of the tone as high or low. The levels of saliency in the visual and auditory discrimination tasks were manipulated in order to produce varying amounts of cognitive competition. The task difficulty increases when ambiguous stimuli are presented, therefore it is predicted that these trials will induce more competition within the cognitive system. Whereas, categorizing the salient stimuli is expected to reduce cognitive competition.

Task. 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 replaced the fixation point and then was followed by S2.

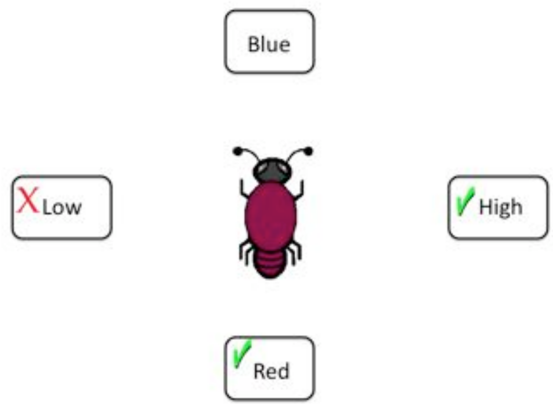

Figure 2. Feedback and the experimental interface. Response order was not set. Participants could respond to either S1 or S2 first. (However, only trials when S1 was selected first were used in the analyses.) Accuracy feedback was displayed in the form of a red “X” to indicate incorrect selections and green check marks indicated correct responses. (No trials that included any incorrect response were used in the analyses.)

In previous PRP studies, participants respond to each stimulus with different hands (e.g., Jentzsch et al., 2007; Johnston & McCann, 2006; Ruthruff & Pashler, 2001; see Pashler & Johnston, 1998, for a review). In the current experiment, responses to both stimuli are conducted through the participants’ right hand only. Requiring participants to respond to both stimuli through a single response medium was expected to increase competition within the cognitive system for that medium. Participants were instructed to respond by moving the

Wii remote-controlled cursor and clicking on the appropriate response boxes that correspond to S1 and S2 as quickly and as accurately as possible. Participants were not instructed to respond in the order the stimuli were presented but to respond in the order of their perceptual decisions. Feedback within the experimental interface 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 correct responses to both stimuli were 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 then 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.

Measures

The Wii remote is not fixed on a surface (as in computer-mouse studies, Dale et al., 2007; Spivey et al., 2005). This causes constant subtle fluctuation in the held-out hand. Therefore a pixel radius to define an "escape" region was used. Previously, Dale, Roche, Snyder, McCall (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 and it was thus determined that a 50-pixel escape region would be more appropriate.

Basic Measures. Analyses for each experiment presented in this work are separated and displayed in two tables. The first of which displays *basic response time measures*. These measures include T1 latency, T1 reaction time, and T2 reaction time. A latency period for T1 was calculated in milliseconds from the time the trial began until participant's response movements exit the 50-pixel escape region, producing *T1 latency.* How long it took for a response to unfold over time serves as a second measure. *T1 response time* 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. *T2 Response time* was measured from the T1 response selection (or presentation of S2, whichever came first) to the selection of a correct T2 response. To analyze these dependent measures, a 3 (SOA) x 2 (bug: salient vs. ambiguous) x 2 (tone: salient vs. ambiguous) linear mixed-effects model for each of the measures was conducted (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 are not significant.

Dynamic Measures. The second set of analyses that were conducted for each experiment presented here analyzed the unfolding of the responses and are grouped in tables titled *x-axis deviation results*. These analyses focused on measuring how variables such as SOA, bug color and tone pitch affected how much the participant's T1 response movements deviate along the x-axis. Since T1 responses required only vertical movements, deviations along the x-axis serve 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 the response movements captured cognitive competition, then any x-coordinate deviation present in the evolving trajectories should reflect the direction of the correct S2 response. To analyze these dependent measures, we employed the use of 3 (SOA) x 2 (sound type: high vs. low) linear mixed-effects models for each 50 ms interval, from 50 ms until 400 ms after S2 was presented (using MIXED procedure in SPSS, with subjects as a random factor).

CHAPTER 3

EXPERIMENT 1 RESULTS

Basic Response Time Measures

T1 latency was significantly reduced for saliently colored bugs by approximately 37 ms. Similarly, RT1 and RT2 were significantly increased by ambiguous stimuli by approximately 15 and 71 ms respectively. Also, lower SOAs induced faster reaction times for both tasks by approximately 87 ms for T1 and 167 ms for T2. These findings are displayed in Table 1.

Table 1

Results of Basic Response Time Measures

DV	T1 Latency	T1 RT	T2 RT
	M (ms), F	M (ms), F	M (ms), F
Ambig.	512, 32.2***	1,312, 82***	705, 48.5***
Salient	475	1297	634
150ms		1,271, 15.9***	608, 107.9***
500ms		1284	625
999ms		1358	775

*** $p < .001$.

Dynamic Measures

There was a significant main effect of sound type (i.e., whether S2 was a high or low pitch tone) on the x-axis deviations in the T1 response trajectories from 50 ms to 400 ms after S2 was presented, $F(1, 8{,}180.4) = 4.0$, $p < .05$. This effect was stronger when the trials were divided by bug color and analyzed separately. An additional outcome when analyzing the bug color subsets was that there was a significant interaction between sound type and SOA. The significant findings are listed in Table 2. Although not statistically significant when pooling the bug color subsets, this interaction is plotted at 50 and 250 ms into the T1 response trajectory in Figure 3.

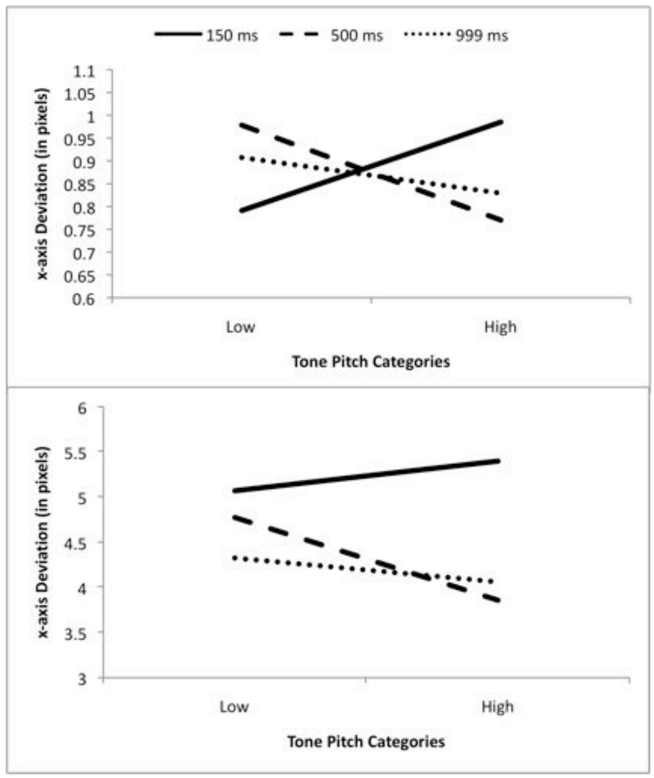

Figure 3. Mean x-axis deviation at 50 ms (top) and 250 ms (bottom) into T1 response trajectory for Experiment 1. Higher x-axis deviation reflects more rightward movements (movements towards high-tone responses). Lower x-axis deviations indicate more leftward trajectories (drifting toward the low-tone responses).

Table 2

X-axis Deviation Results

	Blue S1 Trials			Red S1 Trials			All Trials		
Time into T1 response (ms)	Sound Type (F)	SOA (F)	Sound Type x SOA (F)	Sound Type (F)	SOA (F)	Sound Type x SOA (F)	Sound Type (F)	SOA (F)	Sound Type x SOA (F)
50-400	22.0***	253.9***	37.3***	55.3***	24.0***	34.0***	4.0*	200.7***	
50		5.9**	5.5**		10.9***				
100		13.2**	3.9*		12.3***				
150		28.7***	4.0*		6.3**				
200	8.0**	49.4***						19.4***	
250	6.4**	51.5***		5.1*		5.4*		33.7***	
300	7.9**	47.0***	3.7*	16.0***	10.0***	5.4*		47.1***	
350	4.4*	34.3***	4.5*	22.5***	17.3***	8.7**	3.7*	47.3***	
400		30.8***	14.7***	15.3***	26.2***	8.0**	5.4*	54.2***	

* $p < .05$. ** $p < .01$. *** $p < .001$.

CHAPTER 4

EXPERIMENT 1 DISCUSSION

The data from the current study are in line with previous investigations showing 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. Furthermore, this result is likely unique to this experiment because T1 and T2 responses were collapsed into a single medium, as opposed to responding to each task with separate hands as is typically the case in classic PRP studies. Moreover, programming a single response in the left hand and then another in the right hand may require more time than programming two responses for one hand.

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. These results suggest that S2 is being processed very early into the T1 response, and competing with it, resulting in a drift 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; see also Tipper et al., 1997, for manual trajectories) has shown that saccade trajectories also show a similar pattern of deviation toward a distractor when the saccade latency is less than 200 ms but the eyes moved in the opposite direction when the latency is more than 200 ms, indicating active inhibition.

CHAPTER 5

EXPERIMENT 2

The results of Experiment 1 seem to lend support to the notion that a secondary stimulus can pull processing resources away from a previously presented one, as the Potter et al. (2002) model proposed. This finding in turn begins to suggest that perhaps cognitive control is better characterized by its flexible, dynamic properties than its structural limitations. We conduct a second experiment in order to investigate this possibility further. The data resulting from the first experiment fall in line exactly with McSorley et al.'s (2006) findings. However, it leaves the door open to more questions. Is the 200 ms mark, separating attracted versus repulsed trajectories, particularly special? Is cognitive control always subject to this seemingly structural time course? Or, does it adjust to the experimental context? Experiment 2 uses SOAs that were reduced by magnitude of 5 from Experiment 1, which more closely resembled those used by Potter et al. (2002). If the 200 ms mark is in fact an innate structural limitation then all of the T1 response trajectories should exhibit a pull toward the correct S2 response. However, If cognitive control dynamically adjusts, as coordination dynamics proposes, then the pattern of the T1 response trajectories should mirror those of Experiment 1, in that trajectories of the shortest SOA trials should be attracted while trajectories of the two longer SOA trials should be repulsed even thought they are all 200 ms or less.

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, 100, 200 ms. Measures and analyses were also the same as Experiment 1.

CHAPTER 6

EXPERIMENT 2 RESULTS

Basic Response Time Measures

T1 latency was significantly reduced for saliently colored bugs by approximately 16 ms. Similarly, RT1 and RT2 were significantly increased by ambiguous stimuli by approximately 162 and 48 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 Response Time Measures

DV	T1 Latency	T1 RT	T2 RT
	M (ms), F	M (ms), F	M (ms), F
Ambig.	529, 4.5*	1,401, 83.7***	667, 11.4***
Salient	513	1239	619

* $p < .05$. *** $p < .001$.

Dynamic Measures

As in the first experiment, there was a significant main effect of sound type (i.e., whether S2 was a high or low pitch tone) on the x-axis deviations in the T1 response trajectories from 50 ms to 400 ms after S2 was presented, $F(1, 9{,}166.7) = 31.7$, $p < .001$. However, unlike Experiment 1, there was also a significant interaction between sound type and SOA even before the trials were divided by bug color type. The significant findings are listed in Table 4 and the interaction is plotted at 50 and 250 ms into the T1 response trajectory in Figure 4.

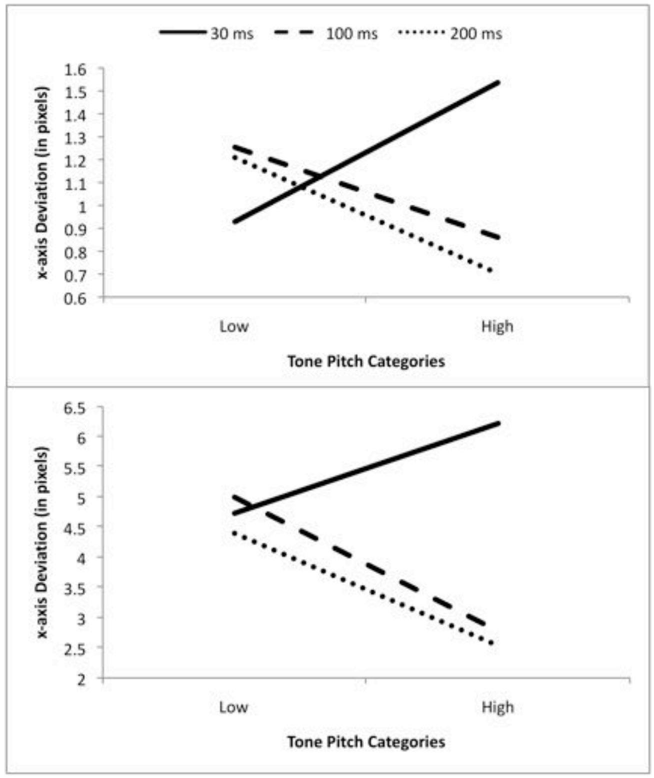

Figure 4. Mean x-axis deviation at 50 ms (top) and 250 ms (bottom) into T1 response trajectory for Experiment 2.

Table 4

X-axis Deviation Results

	Blue S1 Trials			Red S1 Trials			All Trials		
Time into T1 response (ms)	Sound Type (F)	SOA (F)	Sound Type x SOA (F)	Sound Type (F)	SOA (F)	Sound Type x SOA (F)	Sound Type (F)	SOA (F)	Sound Type x SOA (F)
50-400	23.3***	251.4***		14.4***	264.0***	10.2***	31.7***	513.1***	7.7**
50		97.4***	17.3***		69.5***			166.7***	15.6***
100		77.1***	11.1**		37.9***			110.6***	6.8**
150		75.7***	9.4**		50.9***			124.8***	5.6**
200		61.0***			51.7***			113.0***	
250		43.0***			52.1***			96.0***	
300	7.1**	33.6***			36.5***		6.5**	70.2***	
350	8.4**	21.8***		3.6*	40.2***		11.1***	59.9***	
400	10.2**	23.5***		11.9***	26.0***		21.3***	48.5***	

* $p < .05$. ** $p < .01$. *** $p < .001$.

CHAPTER 7

EXPERIMENT 2 DISCUSSION

The effects of SOA in the response 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 did not allow participants the luxury of extra processing, or cognitive slack, time.

In Experiment 1, inhibition was not evident in trials with the 150 ms SOA. Interestingly, in Experiment 2 inhibition of the T2 response was observed in trials 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. This pattern provides more evidence supporting the coordination dynamics approach to cognitive control.

CHAPTER 8

GENERAL DISCUSSION

The primary question of this work was: Is attention/cognitive control best characterized in terms of its structural limitations (i.e., bottleneck) or its flexible, dynamic properties? The subject is considered from the viewpoint that perception, cognitive operations, and bodily movement are all part of a complex dynamical system. Additionally, this perspective is used to facilitate a more in-depth peek into the “black box” during dual-task information processing. By analyzing the action-dynamics data provided in both experiments, scrutinizing how the response unfolds in real-time provided evidence that the cognitive system does actively adjust to changing experimental contexts. This finding falls in line with neurophysiological evidence that processing limitations may not be due to a strict, structural bottleneck that occurs at a predetermined point in information processing. Instead, even if a common underlying neural substrate is responsible for information-processing bottleneck(s), an “adaptive coding mechanism” is responsible for aligning task-specific, stimulus-response mappings yielding flexible limitations that could occur in perceptual and/or response stages of processing (Ivanoff, Branning, & Marois, 2009).

Context and Cognitive Control

The secondary question addressed in this work was: Are there any emerging patterns in the response trajectories that may be indicative of the cognitive system adjusting to conform to the unique combination of experimental parameters. Results from both experiments lent support to the notion that characterizing the cognitive system in terms of its dynamic flexibility is perhaps doing it more justice than focusing on its limitations, because a specific time course required for inhibition to emerge was not seen. Moreover, changing the SOAs within the experimental contexts modulated when the cognitive system experienced competition and inhibition. This finding demonstrated that the cognitive system takes into consideration the relative speed of stimulus presentation and flexibly adapts so that it is able to temporarily inhibit subsequently presented stimuli while a previous stimulus is being tended to. That is, instead of there being an inherent structure by which attention is directed resulting in fixed amounts of processing time based on task difficulty, attention adapts to the trial context by adjusting the way information is processed by creating new "structures" for each experience. Essentially, coming to a decision reflects a nonlinear process by which instability of the components within the cognitive system is temporarily stabilized by the coming together of those components (Johnson, Spencer, & Schöner 2008). Therefore, an attractive explanation of the findings of Experiments 1 and 2 is that when presented with the specific combination of context, current goal, and working memory load the cognitive system adapts in a consistent fashion. This allows T1 response movements in the shortest SOA trials in both experiments to be pulled toward the correct S2 response while the trajectories of trials with longer SOAs demonstrate inhibition. Evaluating cognitive control for processing rapidly presented information is essential for understanding how attention adapts to context. Crucially, "rapidness" within the cognitive system is relative to trial context. In other words, the length of time it takes for the assorted networks within the cognitive system to organize themselves into an appropriate processing structure is not set in stone.

Conclusion

The experiments presented here are not without limitations. It is possible that the extent to which the stimuli compete with each other may be reduced because in both experiments S1 will be a constant stimulus but S2 is presented only briefly. While this is characteristic of most dual-task experimental designs, adjusting the presentation duration of S1 to reflect that of S2 may enhance competition among the stimuli in future studies. This adjustment may change the trajectory patterns because working memory will be taxed, which may cause a delay in the inhibition of the S2 response. Another limitation is that participants might have been able to make ballistic-like responses because target regions may have been large enough to accommodate speed over placement accuracy. In future studies, reducing the size of the response boxes may provide more fine-grained action dynamics data.

Despite the limitations, these exploratory studies have lent support to the position that the behavioral regularities, which have historically been attributed to the cognitive bottleneck, are less structural limitations and more an emergent quality of the cognitive system. As with most things in nature, interactions among the smallest of particles (i.e., molecules, atoms) initiate chain reactions, which yield the bewildering complexity of intelligent life (Kelso, 2002). In the same way, the cognitive system organizes itself to process information as efficiently as possible based on the current context. It is important to note that we propose that a serial, discrete-stage-like structure does not define the cognitive system but is self-imposed as the result of various factors being coordinated within a certain context. The structure may dissolve at anytime if certain factors change, causing the cognitive system to re-organize itself to better fit the new situation (Van Orden et al., 2003). Moreover, talk of supporting one theory over another may be a scientific oversimplification, when another conceptual strategy is quite possible: serial, discrete-stage theories and coordination dynamics may be integrated by identifying the contexts within which each holds, granting a pluralistic approach to executive control (cf. Dale, 2008; Navon & Miller, 2002). This work is a first step towards unveiling the basic processes that may give way to a bottleneck from a perspective that is often seen as precluding it.

These exploratory studies investigated general issues of how the cognitive system is best “characterized”, which spawn more explicit questions regarding the “nuts and bolts” of the system. The task instructions did not specify response order, rather participants where encouraged to respond in the order of their perceptual decisions. Although, only correct trials in which participants responded to S1 first and S2 second were analyzed, there were trials that demonstrated the reverse response order. Future studies should explore what factors contribute to how the cognitive system determines the order in which information is processed? What strategies are used to decide the most efficient way to process incoming stimuli? Under what conditions are these strategies most efficient?

Finally, driving is an oft-used example in dual-tasking literature, but usually it demonstrates limitations. I would like to shine a different light on the comparison. In essence, the cognitive system can be compared to your car on the interstate. Typically, the speed limit is approximately 65 mph and so the most efficient way to drive in normal conditions is to set your speed control to 65. However, if the road conditions change, if the car in front of you speeds up a bit or slows down, you can tap the accelerate or coast buttons in order to adjust the momentum. It may be that the human cognitive system behaves in such a way. If driving on an unfamiliar road, you may drive slower; if following directions to a place you've never been before, then you deal with each street sign as it comes (e.g., operate in a more serial, discrete manner). On the other hand, if the traffic around you is going faster than usual and you are moderately familiar with the route then you speed up, adjusting to the speed of traffic; if you are driving an extremely familiar route then you can rather successfully multi-task. It all depends on the context within which you are operating.

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Appendix A

THE UNIVERSITY OF
MEMPHIS

CONSENT FORM
CIA Laboratory
Principal Investigator(s): Kristy Snyder-Tapp & Rick Dale, Ph.D.

Investigator's Statement

PURPOSE AND BENEFITS

This research project investigates speeded responses to visual stimuli. Your participation, including the resulting data, represents a valuable contribution toward our understanding of action and cognition. Upon completion of the experiment, you will be informed about the purpose of the experiment so that you can learn more about this area of behavioral research.

PROCEDURE

Before the experiment, you will be asked whether or not you have experienced problems with your vision. Because this task crucially involves responses to visual stimuli, individuals with vision problems, including color blindness are not eligible to participate in this particular study. Prior to the experiment, you will be given specific instructions about what is required, including the exact duration of the experiment; we expect the session to be completed within .5 hour. You will be asked to perform the experimental task, in which you will provide speeded responses to stimuli that vary in color on a continuum from red to blue. Your task is to "whack" the bug(s) that are more blue than they are red.. A computer will control the experiment trials, so you will be using the Wii-remote to move on to the next stimulus trial.

RISKS, STRESS, OR DISCOMFORT

Since many observations are required for a reliable measure of performance, fatigue occasionally occurs during participation. There will be opportunities for rest breaks, which will be of sufficient time to offset any momentary fatigue. There are no other known risks to your participation; please feel free to ask questions before, during, or after the session.

OTHER INFORMATION

You will receive .5 credit toward fulfillment of course requirements for each hour of experimental participation. You may refuse to participate and withdraw at any time during the session with no penalty other than forsaking the credit that you would have received from the remaining portion of the experiment. If you wish to stop, simply tell the researcher. Your identity as a participant will remain confidential. Only investigators working within the laboratory will have access to the data, which will not be saved with reference to your name. Any records that do refer directly to you will be accessible only by the investigator, and will be destroyed once all analyses related to the project have been complete. We expect the findings of this study will be published in a scientific journal; no information that identifies you by name will be released.

____
Investigators' Name (Printed) Date

____
Investigators' Name (Signed) Date

Subject's Statement

The study described above has been explained to me. I voluntarily consent to participate in this activity. I have had an opportunity to ask questions. I understand that immediate questions I may have about the research or about my rights as a participant will be answered by one of the investigators. Any remaining questions can be directed to the principal investigator [via e-mail at radale@memphis.edu (901-678-4938) or [illegible]@memphis.edu (901-218-2898)]. The investigator provided me with a copy of this form. I certify that I am at least 18 years of age.

____
Subject's Name (Printed) Date

____
Subject's Name (Signed) Date

OPTIONAL SUBJECT INFORMATION: Federal guidelines require participants in research experiments to be representative of the general population of this region. In order to achieve this goal, it would be helpful to know the following information.
GENDER: Female____ Male____
ETHNIC/RACIAL ORIGIN: African-American____ Asian/Pacific Islander____ Caucasian____
Hispanic____ Native American____ Mixed Race____
Any questions about your right as a participant in this study may be forwarded to the Chair of the Institutional Review Board for the Protection of Human Subjects at (901) 678-2533