

Unexpected 'all-or-none' processing utilized by executive systems when working
memory and inhibitory control requirements increased

by

Jeff Mason Frazer
B.Sc., Queen's University, 2005

A Thesis Submitted in Partial Fulfillment of the
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ABSTRACT

The “All-or-None Hypothesis (ANH)” (Diamond, 2005; 2006) was examined, positing that executive systems process information and respond to the environment using global heuristics, versus a more piecemeal approach. 104 adults were tested on two novel paradigms designed to uniquely test the ANH. Working Memory (WM) and Inhibitory Control (IC) demands were manipulated, to test the impact of these task demands. Performance measured by reaction times and accuracy on both paradigms provided some support for the ANH. However, this effect was greatest when participants required ‘executive-type’ inhibition, versus ‘motor-type’ inhibition to suppress a response. Further, increasing the WM load increased the ANH trend, while varying the IC requirements had little effect. To our knowledge this is the first direct test of Diamond’s ANH, and extended its specificity in terms of task demands.

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Unexpected All-or-None Processing Utilized by Executive Systems when Working Memory and Inhibitory Control Requirements Increased

A Dynamic environment: Cognitive Control and Cognitive Flexibility

Whenever humans interact with their complex environments, their executive control systems are taxed in many ways. If responding efficiently is desirable within an environment, control over behaviours is necessary to carry out responses that are quick and appropriate. An ‘executive system’ can be thought of as a system that assesses the context of a situation, draws upon previous experiences with similar contexts, and then selects the best response given the current goal. In any particular situation it is helpful to organize our mental representations for behaviours. Such organization makes responding to an ever changing environment more efficient, because environmental cues are translated into action faster and more accurately. Organization increases when one *learns* that they should behave a certain way in a particular situation (or in the face of a familiar cue in the environment) to achieve the most effective results. These stimulus-response associations are facilitated by practice, allowing behaviours to become more ‘automatic’, and can lead to habitual responses to environmental cues.

In a dynamic environment, however, behaviours must continually be adjusted to meet the current demands of the immediate context. In order to act appropriately, one must attend to current environmental cues and modify their behaviours accordingly. If the requirements of the current context dictate that a new behavior is better suited to the goal, it may be necessary to inhibit responses that are no longer appropriate. Cognitive control, a function of the executive system, allows one to proceed with different courses of action, and overcome the tendency to respond to environmental cues in only one

particular fashion. For example, consider driving a car. Typically, driving is learned via practice ‘behind the wheel’, and driving can become somewhat ‘automatic’. For example, on a boring stretch of highway that an individual becomes accustomed to, commuting to work daily for years, the entire driving experience (the ‘environment’) will elicit a practiced, automatic set of behaviours. Consider that on a particular day, the practiced route has been altered by some event (e.g. a detour due to construction, an accident, a flood, etc.). The individual must change the way they drive and alter their typical course of action to achieve the goal of getting to work. Although the road, the vehicle, the time of day, and their relative driving skill are all the same, their response to this practiced situation must change (perhaps resulting in driving more slowly or cautiously) – as they must exert cognitive control to change the practiced driving behaviour.

Now consider what would happen if the context was changed further (i.e. the driver had to swerve out of the way of an obstacle). In this situation, the context becomes dynamic and not only requires a different response, but the ‘response demands’ keep changing. Also consider the driver in a different city, or a different country, with different traffic rules (e.g. driving on the left side of the street), and a different climate - the driving conditions are new. Though the individual may be a practiced driver, and the task relatively automatic, all of these factors could change the driving in order to adapt to the situation. When context changes such as these occur, cognitive control allows one to switch between actions quickly and flexibly; efficiently adapting to appropriately match the requirements of the new environment. ‘Cognitive flexibility’ is the ability to exert cognitive control, but pertains to situations where the context is dynamic.

Cognitive ‘Monitoring’ and ‘Top-Down Biasing’

In conjunction with a cognitive control system that guides actions dynamically, a *monitoring* system is also necessary to evaluate the effects of such control. Much work has been done to suggest that monitoring processes are necessary following behaviour, to provide on-going feedback regarding the effectiveness of the behavior (i.e. when is control needed most). Botvinick, Carter, Braver, Barch, and Cohen (2001) argue specifically that the degree to which control processes are engaged is linked to the amount of ‘conflict’ that occurs during information processing, and suggest a central goal of cognitive control is to prevent conflict. Cohen, Dunbar, and McClelland (1990) and others have suggested that the detrimental effects of conflict on performance occur because of ‘crosstalk interference’ – that is two concurrent and parallel processes are activated simultaneously by a single stimulus, and compete for activation, though they may be incompatible responses (which interfere with one another).

The anterior cingulate cortex (ACC) has widely been accepted as playing a role in cognitive control (e.g., D’Esposito et al., 1995), and in many theories, the ACC has been implicated in processes related to cognitive monitoring. Botvinick et al. (2001) summarized many ACC activation studies, and suggested that the ACC may be involved in three types of tasks: 1) where one must override a prepotent but task-irrelevant process, 2) choosing between equally permissible responses, and 3) tasks where an error has been made. Given the connections between these tasks and cognitive monitoring, Botvinick et al. (2001) aptly suggest that the ACC’s function may be described as *monitoring conflict* – be it detecting interference caused by a prepotent response (task-irrelevant process), monitoring conflict between multiple incompatible responses, or

monitoring errors. Therefore, the ACC is thought to serve as the neural substrate for cognitive monitoring, and responding selectively to conflict detection.

Botvinick et al. (2001) also suggest that the monitoring system “exerts an influence” on the executive control system in response to conflict. This system not only *monitors*, but also acts to *engage control systems* to heighten their influence on behaviour when increases in conflict are detected. As an example, Gratton, Coles, and Donchin (1992) found using an Eriksen flanker task that participants displayed less interference effects following incompatible trials, versus compatible trials – suggesting that control is enhanced when the monitoring system detects an incompatible (conflict-laden) trial. Likewise, research with the Stroop task, it has demonstrated that there are fewer interference effects when the frequency of incongruent trials (e.g. the word RED printed in blue ink) is increased (for example, see Logan, 1980). This suggests enhanced control implementation (presumably to counter the effects of interference), when the ratio of incongruent to congruent trials increases. As a final example, it has been shown that when participants engage in a forced-choice task, they tend to adopt more conservative strategies following the commission of errors (for example, see Laming, 1968). This suggests that upon making an error, a monitoring system detects this and signals for heightened control to minimize errors thereafter.

In summary, a conflict monitoring system may serve to inform the executive control system when more control is required for a given task - and detection of high conflict would result in increased cognitive control. For example, when a stimulus appears that elicits multiple responses (e.g. a prepotent response as well as a learned, less automatic response), the monitoring system would then signal for heightened control on

the next trial. This control implementation system (executive system) then processes the next stimulus in a top-down fashion to make responding easier. Thus, ‘conflict’ indicates insufficient control, and leads to a processing bias that facilitates more efficient responding.

According to a model put forth by Miller and Cohen (2001), the implementation of control is systematic once the monitoring system detects conflict. Their model specifies that when a cue (‘C1’) is presented that elicits two responses (‘R1’ and ‘R2’), the response that is carried out depends on the current context – which is signaled by another cue (e.g. ‘C2’ or ‘C3’). Normally, one would respond to C1 in a prepotent fashion (R1). However, if another cue is present (e.g. C2), a different (less ‘automatic’) response may be more appropriate (R2). In this case, prefrontal cortex (PFC) is required (according to the model) to exert adequate executive control, and guide the appropriate course of action (R2). This occurs via an “excitatory *bias* signal” that re-directs activation from C1 to R2 (rather than R1). Thus with effort (required to bias activation), PFC can trigger for prepotent responses to be withheld, though likely at a cost – unless this pairing or mapping of C1 to R2 occurs repeatedly (with practice). When conflict occurs and is detected (signaling for heightened control allocation), this top-down bias signal implemented by the PFC enhances future responses by increasing cognitive control over the motor response.

Cognitive Flexibility requires Working Memory (WM) and Inhibitory Control (IC)

In addition to the presence of conflict, a dynamic context also taxes the executive control system more heavily, and recruits several abilities. Contextual cues must first be

assessed to activate and maintain in mind the possible set of appropriate actions for the new context. Moreover, it is sometimes necessary to alter behaviours to adapt them to the new situation, and shift the relative preference of each option in accordance with the goal. Thus, it seems from these examples that cognitive control (and flexibility in the case of a dynamic environment) depends on working memory (WM) abilities to an extent (as a resource) – to hold information in mind about how to act and to update this information as the context changes.

Simultaneously, as the context changes it is sometimes necessary to overcome the tendency to respond in previously-practiced ways, to perform different or novel behaviours. That is, sometimes ‘habitual actions’ need to be inhibited if they have been associated with the current context. Occasionally, one must also inhibit the response that preceded the current situation, as the task demands change or if the behaviour is no longer correct to meet the goal. In addition to working memory then, inhibitory control (IC) is also required. In order to exhibit cognitive flexibility, one must stop acting in certain ways if and when the new or changed context demands it for achieving the desired response (goal).

This helps to clarify the ‘biasing signal’ implied by Miller and Cohen’s model of the PFC. When a cue (“C2”) appears that represents a new context, it signals a need for a new behaviour (“R2” and not “R1”). Enhanced control allocation entails increasing the relative activation of the new response (“R2”), while de-activating (inhibiting) as much as possible the habitual response (“R1”). This is why the monitoring system is important, according to Botvinick et al. (2001) - it detects when conflict occurs between multiple actions and correspondingly stimulates an increase in control allocation over actions.

Heightened control allows one to inhibit more easily. Therefore, cognitive flexibility relies on both working memory and inhibitory control as crucial to being able to respond to rapidly changing contexts.

The Task-Switching Paradigm, Task Sets, and Set-Shifting

Cognitive psychologists have devised a set of experimental paradigms to study many of the aforementioned abilities, as individuals switch between different responses according to pre-specified cues or contexts. These ‘task-switching paradigms’ require participants to quickly respond to one stimulus (or set of stimuli) in one way (either all of the time or when cued to do so), and to respond to another stimulus (or set of stimuli) in a different way (again, either all of the time or when cued to do so). Participants create associations between the different stimuli and their required responses, a process sometimes referred to as ‘stimulus-response mapping’ (for example, see Crone et al., 2004a). This cognitive mapping of responses to specific stimuli is also referred to as developing ‘task sets’. Rogers and Monsell (1995) suggest that adopting a task set is to “select, link, and configure the elements of a chain of processes that will accomplish a task” (Rogers and Monsell, 1995, p.208). Experience or practice with particular stimuli leads to these cognitive mappings. An individual gradually learns the sequencing of events that occurs from the time that the stimuli appeared, until a final response is made (including intervening steps such as: stimulus identification, response selection, etc.). The purpose of this mapping and task set establishment is to increase one’s efficiency for future exposures the same stimuli, and tasks. Thus, our executive control system again utilizes organization to reduce mental effort.

Task-switching paradigms require cognitive control, in order to switch between the task sets that have been created for each stimulus set (see Rogers et al., 1998). Many experimenters have shown that when a switch is required (when participants are required to stop performing one task and start a different task), people are generally slower than when they repeat the same behaviour (Mayr & Keele, 2000; Meiran, 1996; Rogers & Monsell, 1995; Allport, Styles, & Hsieh, 1994). It is believed that switching between task sets (set shifting) is what makes task-switching paradigms so difficult. Meiran (2000) suggests that costs in performance when switching tasks is either due to the need to reconfigure the stimulus set (activate the relevant stimuli associated with the new task), or the response set (activate the now-relevant response repertoire) associated with each task. Similarly, Mayr and Kliegl (2000) have supported the notion that *activating* the currently required task set – i.e. retrieving it from memory - is an important component of task-switching.

Other studies have looked at differences between task-switching paradigms that utilize univalent stimuli (which only have one potential response) and paradigms that implement bivalent stimuli (which have two potential responses)(Meiran, 2000; Monsell, 2003). In such tasks, the participant might be situated in front of a computer screen with 2 differently colored response buttons placed in front of them.(red to the right and blue to the left) They are then shown stimuli on the screen, a red circle presented on the left side of the computer screen.and told to chose a response to match the stimulus. One possible response would be to push the button to their left (as the stimulus was presented to the left), or they might instead push the red button to their right hand (as the color of the button matches the stimuli). This stimulus is *bivalent* – in that it has two separable

properties: colour and location and can be matched in 2 separate ways. If instead all the circles were white; there would no longer be two different stimulus properties, and it would be clearer that proper response would likely be to the stimulus location alone. It is not surprising that studies have found that switching is more difficult in tasks that use bivalent versus univalent stimuli. The authors of these studies (and others) have suggested that costs incurred from switching might not merely be due to the effort associated with *activating* new task sets (either stimulus or response), but may be secondary to the need to *reconfigure* previous stimulus-response mappings, termed task-set reconfiguration (Meiran, 1996). This supports the idea that the executive control processes involved in task-switching may be multifaceted, and require both working memory (to activate and maintain new task sets) as well as inhibitory control (to prevent previous task sets or inappropriate responses from impeding performance).

Switch Costs

Early ‘task-switching’ research (Jersild, 1927) compared the time required to perform non-switch trial blocks with that on trial blocks consisting of alternating tasks. Observed differences between these two types of trial blocks, measured by reaction times and accuracy, were used to calculate a *switch cost* (or “shift loss” in Jersild’s terms). Jersild attributed these switch costs to the “extra difficulty associated with reconfiguring task-set” (Rogers and Monsell, 1995). Since Jersild, many experimenters have varied this basic task-switching paradigm (for example, see Spector & Biederman, 1976; Allport et al., 1994). For example, “global switch costs” (see Davidson, Amso, Anderson, and Diamond, 2006), or “mixing costs” (Los, 1996; Meiran & Gotler, 2001), refer to an difference in overall performance between non-switch blocks (where participants respond

in only one fashion on each trial), and blocks that require shifting (switching) between tasks from trial to trial. These studies have documented switch costs, seen as a decrement in performance in terms of reaction times or accuracy, even when participants are merely aware that a switch *could occur* on a future trial. This differs from “local switch costs” or simply “switch costs,” which refer to the immediate change in performance from one trial to the next, when a switch is required. Braver et al. (2003) suggested that perhaps ‘mixing costs’ assess “sustained components of cognitive control, such as the increased active maintenance demands associated with keeping multiple task sets at a relatively high level of activation or with engaging attentional monitoring processes to increase sensitivity to environmental cues that signal task changes.” In contrast (local) switch costs reflect “more transient control processes associated with task switching, such as the internal reconfiguration or updating of goals or the linking of task cues to their appropriate stimulus-response mappings.”

Importantly, switch costs may provide information about the executive control processes at work during these paradigms. According to Botvinick et al. (2001) for example, differences in switch costs represent the degree to which our monitoring system (possibly involving the ACC) is able to detect conflict (elicited by competing stimulus properties), and subsequently signal a need for more or less control on the next trial. Conflict detection should provoke heightened control, and in turn lead to lower switch costs. If we can further our understanding of switch costs, perhaps we can better understand the specific processes (and their mechanisms) necessary for cognitive control, cognitive flexibility, and conflict monitoring.

For example, Davidson et al. (2006) illustrated ‘asymmetric switch costs’, incurred when switching from one type of task to another (e.g., switching from an easier task to a more difficult task) are not always equivalent to the reverse switch cost (e.g. switching from a harder task to an easier task). Other investigators have found that switch costs can be reduced when participants are given the opportunity to prepare for the switch (Mayr & Kliegl, 2001; Meiran, 1996; Rogers & Monsell, 1995). This suggests that executive control allows for strategic processes which increase performance efficiency. This may also involve strategies when the task preparation interval is *minimized*, as is normally the case when cognitive flexibility is taxed most heavily. In particular, the executive system may have some sort of ‘default’ strategy, which is utilized to increase efficient processing in cases where the demand for cognitive flexibility is high.

The “All-or-none Hypothesis”

Diamond has argued that besides predictable switch costs, human behavior also seems to act in accordance with another principle, which she has labeled the “All-or-None” principal (Diamond, 2005; 2006). Diamond hypothesizes that this principal extends beyond task-switching paradigms and encapsulates a more general set of phenomena, related to cognitive (executive) control systems. Essentially, Diamond’s “All-or-None Hypothesis” (ANH) could help provide heuristics for cognitive control in general, especially when ‘cognitive flexibility’ is required.

Specifically, Diamond suggests that the brain operates in an organized and global fashion, preferring to “work on a grosser level of functioning; and only with effort, or more optimal functioning ... in a more selective manner”. Thus it might be easier for the

executive system to utilize global or overall cognitive schemes, versus more selective or specific processes, when changes in behaviour are required by a task. Such global schemes potentially include heuristics such as ‘reverse everything’, ‘repeat’, ‘inhibit’, or even ‘encode all properties’. Importantly, these heuristics have a critical impact on responses when demands are changed as required by dynamic sets of stimuli.

Diamond also suggests that this tendency to implement “global commands” may be the developmental ‘default; such that the brain initially works at a gross level and only with “fine-tuning” (through experience over development) acts in a more differentiated manner. Thus, these ‘global rules’ or heuristics maybe implemented by default because they are “hardwired in” the neural system. If it is the default strategy to process environmental information and respond to it with gross-level processing, this may become a dominant tendency even into adulthood (if ‘fine-tuning’ *for specific processes* is never developed). Interestingly, if ‘all-or-none’ processing is a dominant tendency across contexts, it should be difficult to inhibit using this ‘default’ and significant IC may be required to overcome this tendency.

Diamond’s ANH was derived from observations of individuals’ performance on several task-switching paradigms, though she suggests that the implications of her hypothesis extend beyond this type of task. Diamond (2005) originally put forth three specific tenets to the ANH; 1) that it is easier for individuals to switch *everything* (that is the rules for a response and the actual response), or nothing (rules or actual response), than to switch one thing (rule or response) but not the other, and 2) that it is easier to take into account all salient aspects of a stimulus versus only some, and 3) that it is easier to inhibit a dominant response all of the time versus only some of the time.

As such, Diamond's theory suggests that similar to the formation of stimulus-response mappings and task sets, our executive system uses an 'all-or-none' principle as a response strategy or 'cognitive heuristic,' to process information efficiently and reduce mental effort. As such, a decrement in performance incurred after a 'switch' in task demands could be driven by this response strategy of organizing our motor responses to reduce the need to exert mental effort, and may simply be a product of normal neural organization.

Support for the ANH comes from some of Diamond's work (e.g., Davidson et al., 2006), as well as from other studies investigating task-switching. For example, it has been observed that when the same task is repeated over successive trials (i.e. no task-switch occurs), reaction time and error rates are reduced as participants execute the *same response* as on the previous trial (e.g., Bertelson, 1965; Pashler & Baylis, 1991; Rabbit, 1968). In addition, Rogers and Monsell (1995) found that when participants were required to switch tasks from one trial to the next but executed the *same motor response*, there was no reduction in reaction time or error rate (consistent with ANH). They even found performance decrements in some cases, illustrating 'repetition costs' (or 'reversed repetition effects') (see Hsieh, 1994; Rogers and Monsell, 1995). Several authors have offered theories to explain repetition costs in task-switching paradigms. For example, Rogers and Monsell (1995) suggest that it may be due to a 'transient suppression of active responses'; a mechanism that functions to prevent response perseveration; or a product of associative strength increments (via previous exposures) that facilitate familiar 'links' and inhibit unfamiliar links.

This finding of repetition costs is actually predictable from Diamond's ANH in situations where the task repeats but the responses change, as the ANH states that it is easier to switch 'everything or nothing, than it is to switch only one thing or another' (e.g. the rule or the actual response). Evidence for this tenet of the ANH was also provided in a recent developmental study (Davidson et al., 2006) that implemented a modified *Directional Stroop* paradigm (also see Seymour, 1973; 1974). The stimuli used in the modified Directional Stroop paradigm (Davidson et al, 2006) were small circles (either white or dark in colour), presented on either side of a computer screen. If a white circle was presented, participants were required to press a response button on the same side as the stimulus; while a dark stimulus required participants to press the button on the opposite side to the stimulus. Each stimulus therefore had two intrinsic properties relevant to responding (colour and location). Specifically, Davidson et al. found on this paradigm that participants' responses were slower when either just the response site changed or just the rule changed from one trial to the next, versus when both or neither changed.

Interestingly, the current theories of conflict put forth by Botvinick et al. (2001) as well as that suggested by Miller and Cohen (2001) fail to explain the findings of the Directional Stroop, as they only address conflict at the level of the stimulus. Specifically, conflict theory would predict that following presentation of a 'dark circle,' heightened 'conflict' would be detected on the basis of colour (as the stimulus location and the correct response site would be incongruent) and would signal a need for greater cognitive control thereafter. This could explain slower responses to trials in which the 'rule' must be changed. However, this theory would not explain slowing on trials in which only the location for the 'response' must be changed, or faster reaction times on trials where

‘both’ the rule and response change. It would seem that upon detection of conflict by a monitoring system, a heightened ability to ‘do the opposite’ (via enhanced control or a ‘bias signal’) will not be as efficient if only the response site changes. ‘Conflict’ theory then, is only a viable explanation for these “all-or-none” phenomena if one performs the exact same motor response, following the enhancement of cognitive control (after conflict occurs). In contrast, the ANH suggests a processing heuristic for *perceptual conflict sensors* as well as *motor output units*. Thus, all-or-none processing could be an overarching principle that guides both perceptual processing and motor output.

Consequently, the ANH may provide a more general theory regarding cognitive control, and a process intrinsic to our executive control system that extends beyond the realm of task-switching. While Diamond has also provided some evidence in support of the second and third tenet of the ANH, for the purposes of the current study, the first tenet is of most interest, as it competes not only with intuition regarding the relative difficulty of different types of ‘switches’ (switching *one thing* is harder than switching *everything*), but also provides a challenge to the existing ‘conflict’ account of task switching that predicts switch costs from perceptual conflict alone.

At this time there are no published studies by either Diamond or others which have explicitly tested the first tenet of the ANH. Rather, support has been suggested following observations from studies with a different focus. Given the potentially ‘unifying’ implications of Diamond’s hypothesis with regard to executive system processing heuristics, it is important that this theory be tested explicitly.

The Current Study

The primary aim of the current study is to test if the first tenet of Diamond's ANH. To examine this, two new task-switching paradigms aimed explicitly at testing this tenet will be utilized. The study also aims to investigate limitations to the ANH. As all of the studies that provide support for the ANH have implemented a similar design, it may be that the ANH only holds true in paradigms that implement two response rules. As such, the current paradigms will investigate the impact of more than two response rules. Additionally, the current study also addresses the impact of changes in WM and IC requirements on task performance. For example, the ANH may only be supported when the WM load is great enough to be taxing, and subsequently the executive system defaults to a heuristic such as 'all-or-none' for efficiency. However, it is possible that the ANH might not hold true in situations where WM demands exceeds some critical level, beyond which an all-or-none strategy is no longer the most efficient. Alternatively, all or none processing may be observed when IC needs are low, but not when the tasks requires higher levels of IC.

This study aims to determine if the all or none heuristic is observed across varying levels of WM and IC demands (altered simultaneously). It is hypothesized that with increasing WM and IC demands, an all-or-none response pattern as suggested by the ANH will not be supported in analysis of either reaction time or error rates. This is hypothesized mainly in response to Diamond's statement that this 'all-or-none' response pattern is a *developmental default*, which may become more 'fine-tuned' or 'differentiated' over the course of developmental (via experience). A 'developmental default' suggests a condition that provides basic guidelines for behaviour initially, prior

to exposure with the environment in which the strategy will be implemented (in the absence of experience). While such a default might be programmed ‘innately’ to allow for efficient responses, as the complexity of the environment increases, it is hypothesized that a control system would also be able to develop or ‘fine-tune’ with experience. Therefore, it is hypothesized that at some level of WM and IC demands, participants’ performance will not evidence the all-or-none phenomena, because the ‘all-or-none’ strategy appears to be a ‘simpler’ default strategy - that may not be best suited for more complex environments.

Methods

Participants

104 ‘PSYC 100’ students were recruited for this study from the University of Victoria (mean age = 20.28, $SD = 2.24$) Psychology Subject Pool. Participants did not receive monetary compensation for their participation, but received ‘credit’ toward their final grade in PSYC 100. Participants arrived at the lab and informed consent was obtained. All participants completed all tasks.

The Tasks and Stimuli

Participants completed a computerized task in which they were first asked to respond in one of two ways to an arrow presented in the center of the computer screen. Responses were either made by pressing a button situated on the left or right side of a response bar located centrally in front of the participant. In total, participants were taught and required to remember four ‘response rules’ throughout this task, dictating which of the two buttons to press in response to each of 6 distinct stimuli (arrows). These four rules were as follows: a) When you see a **large white arrow**, press the button in the

direction that the arrow points, b) When you see a **large black arrow**, press the button that is in the *opposite direction* to where the arrow points, (e.g. if a black arrow points to the left – press the right button), c) When there is a **single vertical stripe** embedded within the body of either arrow type (either black or white), respond *opposite* to how you would normally based on the first 2 rules (e.g. for a black arrow with a single stripe one would now press the button in the *same direction* that the arrow points), and d) When you see **two vertical stripes** embedded within the body of any arrow, press whichever button you would normally based on the first 2 rules (for either a large black arrow or a large white arrow). In combination, there were six distinct arrow ‘stimulus types’ (see Figure 1), two arrow types that did not have any stripes on the body of the arrow (one black, one white), two arrow types that had a single vertical stripe, and two arrow types that contained two vertical stripes. Each arrow type, when presented in our task, could thus be differentiated in terms of three different properties: the direction of the arrow (pointing either left or right), the colour of the arrow (black or white), and the number of stripes contained within each arrow (no stripe, one stripe, or two stripes). Each stimulus ‘type’ suggests a distinct ‘rule’ for responding, and as such changes in stimulus types will be referred to as ‘rule changes’.

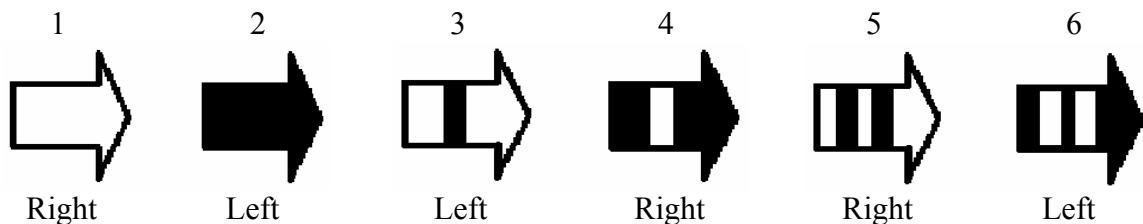


Figure 1: The six different arrow ‘types’, where Right or Left indicates the correct response side.

Importantly, each of the six different arrow types required varying degrees of both WM and IC. For example, in the case of the two ‘simple’ arrows (no stripes), very little WM or IC is required in order for participants to deduce the correct response site. They must simply respond in the direction of the arrow for a white arrow, and must recruit minimal IC ability to respond opposite to the arrow direction when they see a black arrow.

With the addition of stripes embedded within the arrows, both WM and IC requirements changed. For example, arrows containing a single stripe required participants to hold an additional rule in mind while responding. When participants who previously responded to the simple arrows were presented with arrows containing a single stripe, they also needed to recruit additional IC ability. For example, a white arrow with one stripe would require IC to *not respond in the direction of the arrow* (similar to the IC required by a black arrow with no stripes), as well as IC to *inhibit the previous rule associated with white arrows*. When arrows with two stripes were introduced (within task blocks containing arrows with no stripes, arrows with single stripes, and arrows with two stripes), WM demands were increased further - participants needed to maintain an additional rule pertaining to the stripes in WM. The IC demands were also *altered*; however, it is important to note that IC level was not defined *across* WM levels – that is the introduction of additional striping rules did not dictate the IC level. Rather, IC level was defined *within* each level of WM. In particular, the relative frequency of ‘inhibition trials’ was manipulated *within each of the three WM levels* (blocks 1-3; blocks 4-6; and blocks 7-9 respectively), resulting in *three levels of IC per WM level*; one block contained 25% ‘IC trials’, the second contained 50% ‘IC trials’, and the final block contained 75%

‘IC trials’. For the purposes of data analyses, ‘IC trials’ were defined as those where participants responded in the opposite direction to where the arrow pointed (i.e. black, un-striped arrows; white, single-striped arrows; or black, double-striped arrows). By varying the relative ‘frequency of IC trials’ in this way, it allowed for IC requirements to be stratified, to clarify the role of IC in all or none processing.

To assess the effects of increasing the WM demands, three different WM levels were defined. Specifically, the WM load was increased as the *number* of different arrow types appearing in each block increased - as new rules were introduced. For example, blocks 1-3 included only white and black arrows with no stripes (2 arrow types); blocks 4-6 included these same arrow types *in addition to* arrows with one stripe (4 arrow types), and blocks 7-9 included all 6 arrow types.

Participants also completed a similar task (as with the arrows) in which they were asked to respond in one of two ways to *two arbitrary shapes* presented *on either side* of the computer screen. This second set of stimuli allowed for investigation of the impact of inhibitory control over the prepotent *Simon* effect. Specifically, it was anticipated that the shapes tasks would differ from the simple (non-striped) arrows task in terms of its IC requirements. For example, the shapes task required participants to inhibit their tendency to respond on the same side as a stimulus, a salient prepotent motor response (Simon effect). On the other hand, the arrows task required participants to inhibit their *learned response* to arrows (an arbitrary shape) - that is, to orient in the direction of an arrow head.

For the shapes task, participants learned that for one of the shapes they were to press the left button, while they should press the right response button when they saw the

second shape. In addition, when either of the two shapes were **striped**, participants were informed to respond opposite to how they would normally (e.g. for the shape that dictates pressing the right button - with additional stripes - one would now press the left button). There were therefore four distinct ‘shapes’ (see Figure 2): the two original shapes, and these same two shapes with striping embedded within them. WM and IC requirements were again varied by introducing the ‘stripe’. For example, at first participants were required to remember two rules: a) when shape ‘A’ appears, press the right button, and b) when shape ‘B’ appears, press the left button. When the striped shapes were included in a task block (shapes A’ and B’ respectively), WM demands were effectively increased, since participants now needed to hold in mind three rules: the same two as before, but also that c) when a striped shape appears (either A’ or B’) respond opposite to how you would normally for that shape.

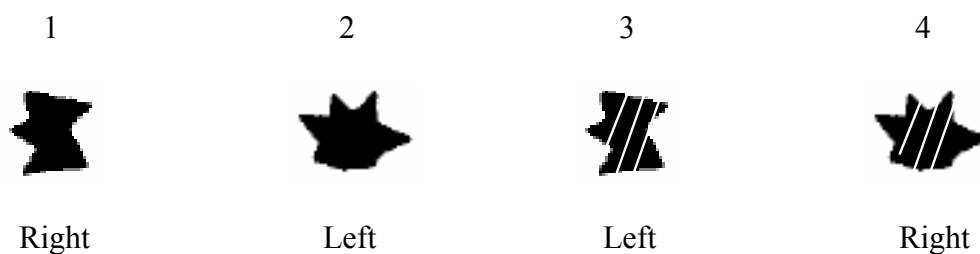


Figure 2: The 4 different shapes, where Right or Left indicates the correct response site.

Displaying the shapes on either side of the screen provided manipulation of IC similar to the Simon effect. Hence, ‘inhibition trials’ were those where the stimulus location and the shape ‘rule’ conflicted – i.e. when shape 1 was presented on the left, when shape 2 was presented on the right, when shape 3 was presented on the right, or when shape 4 was presented on the left.

To assess the impact of WM and IC demands on the shapes task, six distinct task blocks were implemented. Similar to the arrows task, WM and IC demands were altered by using different shapes within each block. WM was again increased by increasing the *number* of different shapes presented in each block. For example, blocks 1-3 (WM level 1) contained only the two original shapes; while blocks 4-6 (WM level 2) contained all four shapes. The relative frequency of ‘IC trials’ was manipulated in the shapes task across trial blocks. Specifically, WM levels 1 and 2 each contained three blocks; one block involved 25% ‘IC trials’, another involved 50% ‘IC trials,’ and a final block involved 75% ‘IC trials’.

Procedure

Participants were seated in front of a PC computer screen at eye height and approximately 16” from the participant. Responses were made on a ‘button bar’ approximately 12” x 3”, with two large buttons either left of right of the center of the board by approximately 2”. The button bar was placed on the table in front of participants, who were told to use their dominant hand to press either button for an appropriate response. All computer tasks were programmed in Borland’s C (version 3.1). Participants were first provided with on-screen instructions for the upcoming task, followed by one practice trial per stimulus type (6 arrow types for the arrow task; then 4 shapes for the shape task) where errors were explained, and finally participants were given the opportunity to ask any questions if they wished to clarify the rules of either task. Participants were then allowed to proceed with the tasks – the arrows task was always administered first followed by the shapes task. *Within each task* participants were

not cued as to when additional arrow types or shapes would appear in new trial block – i.e. they were required to hold in mind all of the rules for the arrows task (associated with each arrow type) as well as the rules of the shapes task *throughout both tasks*. Of note, participants were given a brief ‘break’ from responding after each trial block (for both tasks), and participants were cued after the arrows task that the shapes task would begin.. The interstimulus interval for all trials was 800 ms. In total, both tasks took approximately 30 minutes to complete.

Data Analysis

Reaction times (ms) and accuracy per trial (scored either 1 or 0), generated by the computer tasks, were used to calculate the dependent variables of interest. These measures were compared *across trials*, as a function of the switch type (4 for the arrows task; 3 for the shapes task), WM load (3 levels for the arrows task; 2 levels for the shapes task), and IC requirements (3 levels for both tasks). Accuracy per trial became ‘percent correct’ per ST, WM load, or IC requirement; while reaction times were simply averaged for each level of our independent variables. The switch type (ST) main effect was our primary measure for investigation of all or none processing advantages. STs were assigned per trial, as a function of the previous trial – i.e. either: a) the arrow type (1 to 6) or the shape (1 to 4) changed but the correct response required pressing the same button (an ‘arrow type’ or ‘shape’ ST); b) only the response button changed (e.g., a type 1 arrow pointing left followed by a type 1 arrow pointing right) (a ‘response’ ST); c) both the arrow type (or shape) and the response button were switched (an ‘all’ ST), or d) when neither the arrow type (or shape) nor the response button were changed (a ‘none’ ST). The first trial of every task block was excluded from analysis as it is not possible to

calculate a ST for these trials. Reaction times and accuracy on trials were indicative of the relative difficulty of a particular ST - STs that led to greater 'costs' in performance were *compared with the other STs*. Therefore, 'switch costs' were not actually calculated as a difference score, but rather calculated as average reaction times and accuracy. For example, if one particular ST was more difficult (on average) than another ST higher reaction times or lower accuracy would be observed.

Two factorial repeated-measures ANOVAs were used to compare average reaction times and accuracy (percent correct) as a function of three within-subjects factors: Switch Type, WM Demands, and IC requirements. These analyses were completed separately for both the arrows and shape conditions. RM-ANOVA provided information on main effects of switch type and task demands (WM and IC), and their interactions. Planned contrasts were also conducted to compare between switch types.

Hypotheses and Predictions

The first tenet of the ANH was tested using the arrows task and the arbitrary shapes task. In accordance with the ANH, it was anticipated that participants would perform faster and more accurately when both the arrow type/shape *and* the response changed ('all' ST) or when neither changed from the previous trial ('none' ST), versus when *only* the 'arrow type/shape changed ('arrow type' ST or 'shape' ST) or *only* the correct response changed ('response' ST). Hence better scores should be observed when participants had to switch everything (both the arrow type/shape *and* the response button) or nothing (neither) than when switching only the arrow type/shape or the response. It was additionally hypothesized that as WM and IC demands increased that the all-or-none advantage would not be observed.

Results

Prior to any analysis, the data were examined at the trial level and outliers were omitted such that all data points more than 2 standard deviations from the mean were excluded from the analyses. This resulted in less than 2% of the data points being removed. The data was then analyzed using repeated measures ANOVA. Of note, later analyses of the original data set (including outliers) revealed that this outlier-removal procedure did not affect the pattern of significant findings for any of the analyses.

Inhibitory Control Requirements

First, the relative difficulty of each task (arrows vs. shapes) was examined in terms of their respective IC requirements. This was accomplished by comparing participants' performance between the 2 basic stimulus types for each task; one requiring no IC and the other requiring IC. Therefore, for the arrows task we compared performance on white, non-stripped arrow trials against performance on black, non-stripped arrow trials; and compared congruent trials with incongruent trials from the first 3 blocks of the shapes task. These analyses revealed that for the arrows task, the 'IC effect' for RTs was small, $t(22688.81) = 8.19, p < .01, d = .11$; but was small-medium in size for accuracy, $t(32479.49) = 24.45, p < .01, d = .27$. For the shapes task the IC effect was smaller, for RTs, $t(9837.88) = 1.47, p = .14, d = .03$, as well as for accuracy, $t(9376.50) = 8.16, p < .01, d = .17$. This suggests, as we expected, that there were differences between the two tasks in terms of their IC demands. In particular, the arrows task was more difficult in terms of its basic IC requirements.

Arrows Task

Participants' performance was assessed across trials as a function of the switch type (4), working memory load (3), and inhibitory control requirement (3); first using reaction time (RT), and then percentage of correct responses made (accuracy) as measures of performance. Planned contrasts were completed to test primary hypotheses for differences between switch types, and post hoc analyses were run to explore significant main effects for WM or IC. Simple main effects were analyzed for any significant interactions. The assumption of homogeneity of covariance was not met for any of the analyses, as assessed via Mauchly's test of sphericity. As such, Greenhouse-Geiser corrections were reported for analyses. For all pairwise comparisons, Bonferroni correction was used to adjust for multiple comparisons.

Switch Type

Repeated measures analyses revealed a significant main effect for switch type (ST) on RTs, $F(2.18, 211.58) = 442.90$, $p < .001$, $\eta^2 = .82$, as well as accuracy, $F(1.59, 154.10) = 58.05$, $p < .001$, $\eta^2 = .37$. Planned contrasts revealed that average RTs for 'all' and 'none' STs combined were significantly lower (faster) than the average RTs for 'arrow type' and 'response' STs (e.g., one or the other), $F(1, 103) = 292.07$, $p < .001$, $\eta^2 = .74$ (see Figure 3). Table 1 (below) displays the results of each planned contrast run between the STs for RTs.

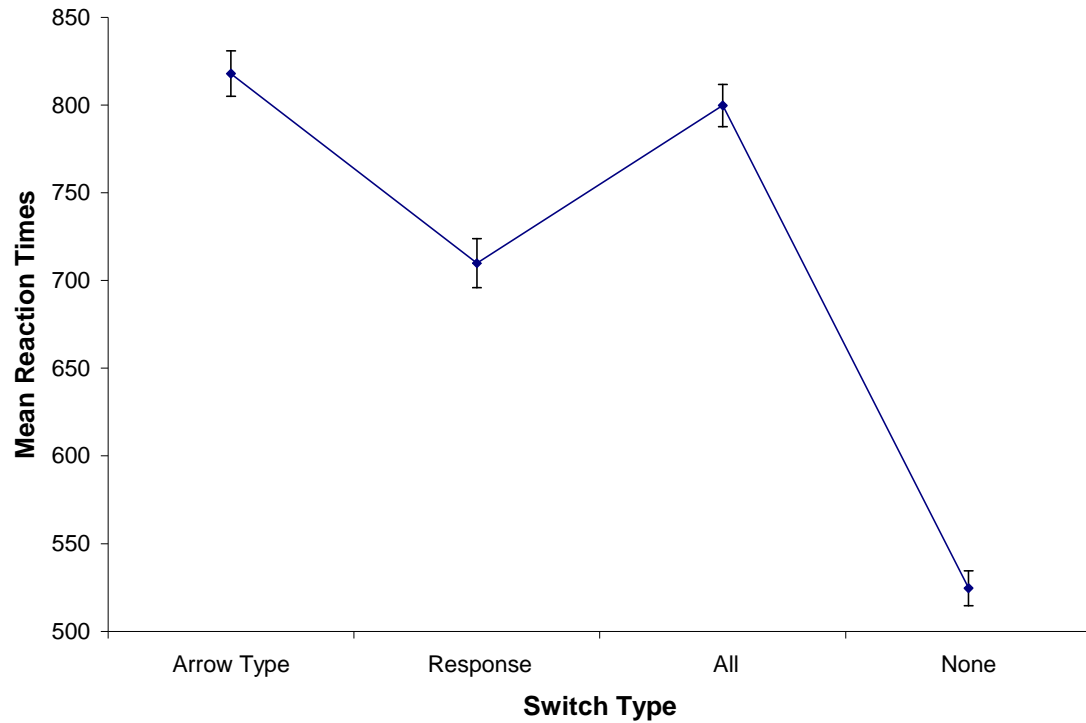


Figure 3. Mean reaction times (ms) as a function of Switch Type (ST).

Table 1. Planned contrast results comparing RTs between STs

Contrast (STs)	F Value	Sig.	Partial eta squared
Arrow vs. All	$F(1,103) = 22.89$	$p < .001$	$\eta^2 = .18$
All vs. Response	$F(1,103) = 84.30$	$p < .001$	$\eta^2 = .45$
Arrow vs. None	$F(1,103) = 1002.01$	$p < .001$	$\eta^2 = .91$
Response vs. None	$F(1,103) = 309.51$	$p < .001$	$\eta^2 = .75$

These results suggest that, when combined, the ‘all’ or ‘none’ STs were easier for participants (they responded faster), than the switch ‘one thing’ or ‘another’ STs (arrow and response STs), supporting the ANH. More specifically, the ‘arrow type’ ST was

found to be more difficult for participants than either the ‘all’ or ‘none’ STs, as participants took longer to respond. However, support for the ANH was not found with the ‘response only’ ST, which was easier for participants than the ‘all’ ST – in terms of RTs.

Similarly, planned contrasts revealed that average accuracy for ‘all’ and ‘none’ STs (combined) was significantly higher (more accurate) than combined accuracy for the ‘arrow type’ and ‘response’ STs, $F(1,103) = 83.53$, $p < .001$, $\eta^2 = .45$ (see Figure 4). Table 2 (below) displays the results of each planned contrast run between the STs, in terms of accuracy.

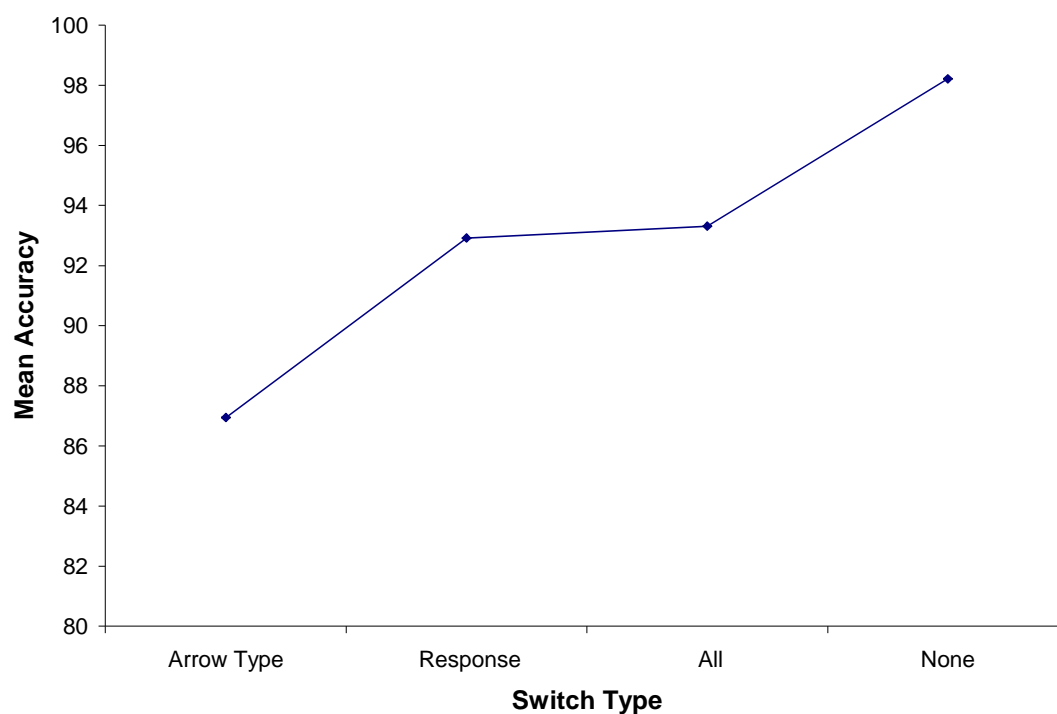


Figure 4. Mean accuracy (percent correct) as a function of Switch Type (ST).

Table 2. Planned contrast results comparing accuracy between STs

Contrast (STs)	F Value	Sig.	Partial eta squared
Arrow vs. All	$F(1,103) = 233.66$	$p < .001$	$\eta^2 = .69$
All vs. Response	$F(1,103) = .16$	$p = .692$	$\eta^2 = .00$
Arrow vs. None	$F(1,103) = 301.39$	$p < .001$	$\eta^2 = .75$
Response vs. None	$F(1,103) = 22.92$	$p < .001$	$\eta^2 = .18$

Once again, the results show that the ‘arrow type’ ST was more difficult than either the ‘all’ or ‘none’ STs, however; the ‘response’ ST was only *significantly* more difficult than the ‘none’ ST and did not differ from the ‘all’ condition.

Working Memory

Repeated measures analyses also revealed a significant main effect for working memory (WM) load on participants’ RTs, $F(1.81, 175.40) = 304.08, p < .001, \eta^2 = .76$, as well as accuracy, $F(1.52, 147.40) = 8.37, p < .001, \eta^2 = .08$ (see Figures 3 and 4).

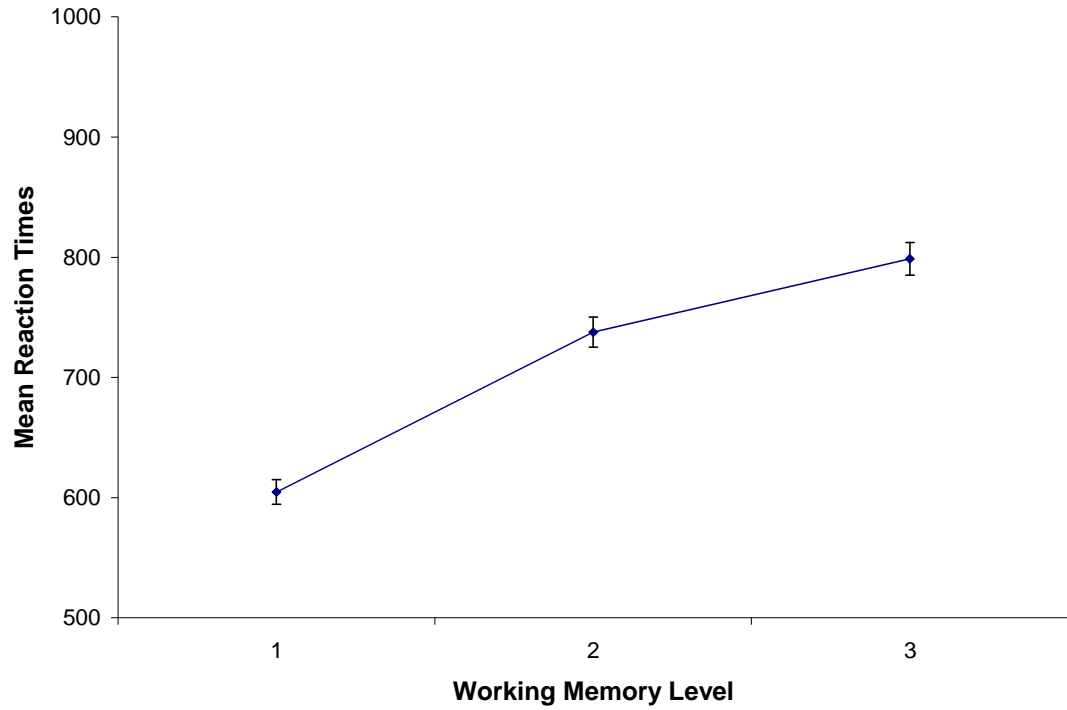


Figure 5. Mean reaction times (ms) as a function of Working Memory (WM).

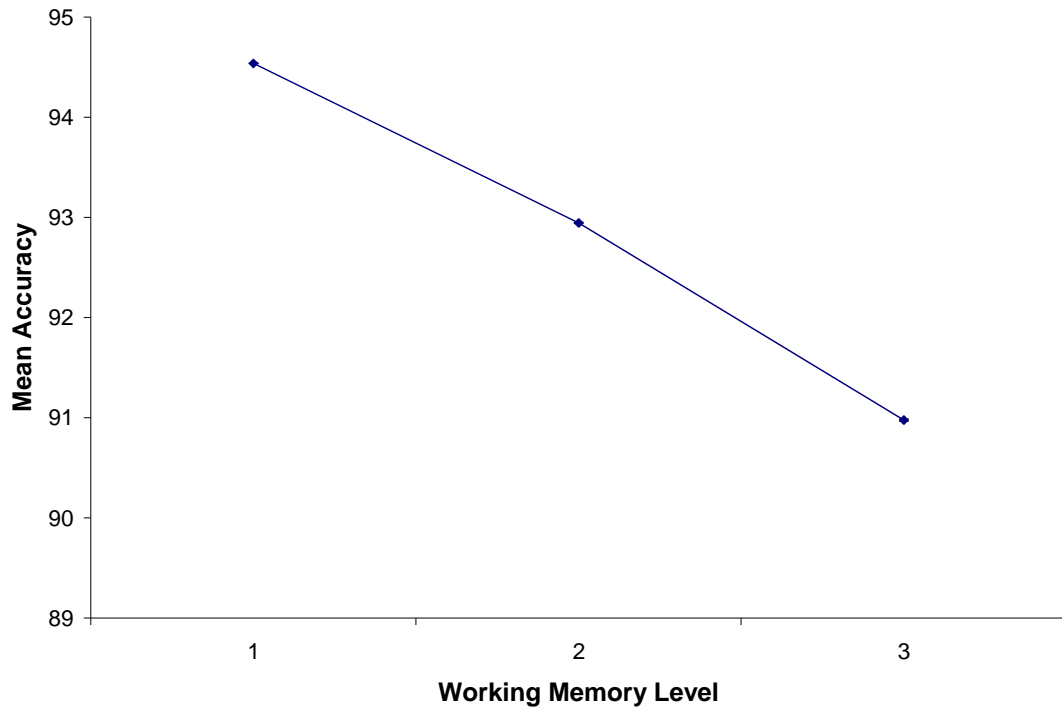


Figure 6. Mean accuracy (percent correct) as a function of Working Memory (WM).

Post hoc analyses were run using RTs and accuracy to compare between each level of WM, and the pairwise comparisons are displayed in Tables 3 and 4 (below).

Table 3. Paired samples *t*-test results between WM levels using RTs

Pair	T statistic	Sig.	r²
WM 1 – WM 2	$t(103) = -19.12$	$p < .001$	.69
WM 1 – WM 3	$t(103) = -21.92$	$p < .001$	.57
WM 2 – WM 3	$t(103) = -8.58$	$p < .001$	.73

Table 4. Paired samples *t*-test results between WM levels using accuracy

Pair	T statistic	Sig.	r²
WM 1 – WM 2	$t(103) = 2.79$	$p < .01$	.06
WM 1 – WM 3	$t(103) = 3.57$	$p < .01$	.03
WM 2 – WM 3	$t(103) = 2.33$	$p < .05$	.28

These results reveal a clear linear (positive) relationship between WM level and task difficulty – in that WM level 3 was the most difficult condition, both in terms of participants' RTs and accuracy.

Repeated measures analyses also revealed a significant interaction between WM level and ST on RTs, $F(2.15, 208.98) = 37.14$, $p < .001$, $\eta^2 = .28$, as well as accuracy, $F(1.55, 150.46) = 3.66$, $p < .05$, $\eta^2 = .04$. Simple effects analyses for RT data revealed that when WM was increased to level 3, the impact of the ST differed – and there was no

longer a significant difference between the ‘arrow type only’ and ‘all’ STs, $t(103) = -.33$, n.s. (see Figure 7).

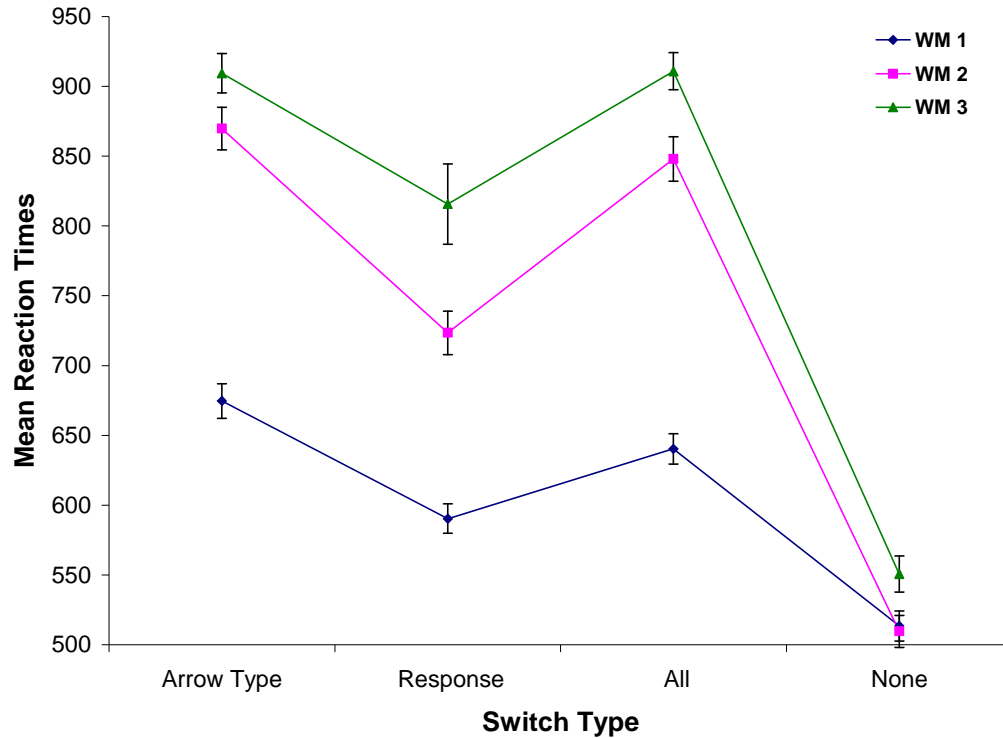


Figure 7. Mean reaction times (ms) as a function of Switch Type (ST), plotted for each of the three Working Memory (WM) levels.

Simple effects analyses for percentage correct revealed an even greater effect of WM on the pattern of results for ST. In particular, several non-significant pairwise comparisons emerged between switch types, for each level of WM. For the first WM level, the difference between ‘all’ and ‘response only’ switch types was non-significant, $t(103) = -1.63$, n.s.; as was the difference between ‘response only’ and ‘none’ switch types, $t(103) = -.99$, n.s. However these analyses may be affected by ceiling effects – as all participants’ approached perfect scores on these conditions. For the second WM level,

the difference between the ‘all’ and ‘response only’ switch types was non-significant, $t(103) = .20$, n.s., in contrast to the switch type main effect. Finally, for WM level 3 there were two non-significant differences, pairwise comparisons revealed non-significant differences between the ‘arrow type’ and ‘response’ switch types, $t(103) = -.76$, n.s., as well as between the ‘all’ and ‘response only’ switch types, $t(103) = .85$, n.s. Although the ‘all’ versus ‘response’ comparison was non-significant for WM level 3, plotting the data reveals a trend. As can be seen in Figure 8, as WM level increases, the data become more supportive of the ANH – with accuracy for ‘arrow type’ and ‘response’ STs (switch one thing) both being lower than either ‘all’ or ‘none’ STs.

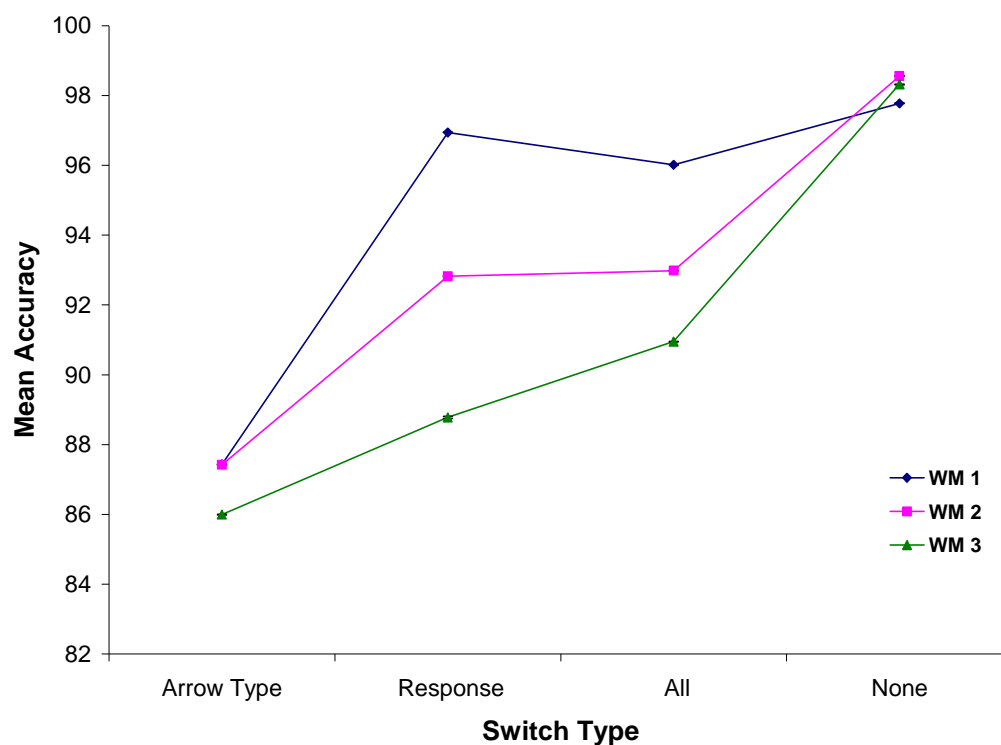


Figure 8. Mean accuracy (percent correct) as a function of Switch Type (ST), plotted for each of the three Working Memory (WM) levels.

Inhibitory Control

Repeated measures analyses revealed a significant main effect for the level of inhibitory control (IC) on participants' RTs, $F(1.83, 177.03) = 36.17$, $p < .001$, $\eta^2 = .27$, as well as accuracy, $F(2, 194) = 3.50$, $p < .05$, $\eta^2 = .04$ (see Figures 9 and 10).

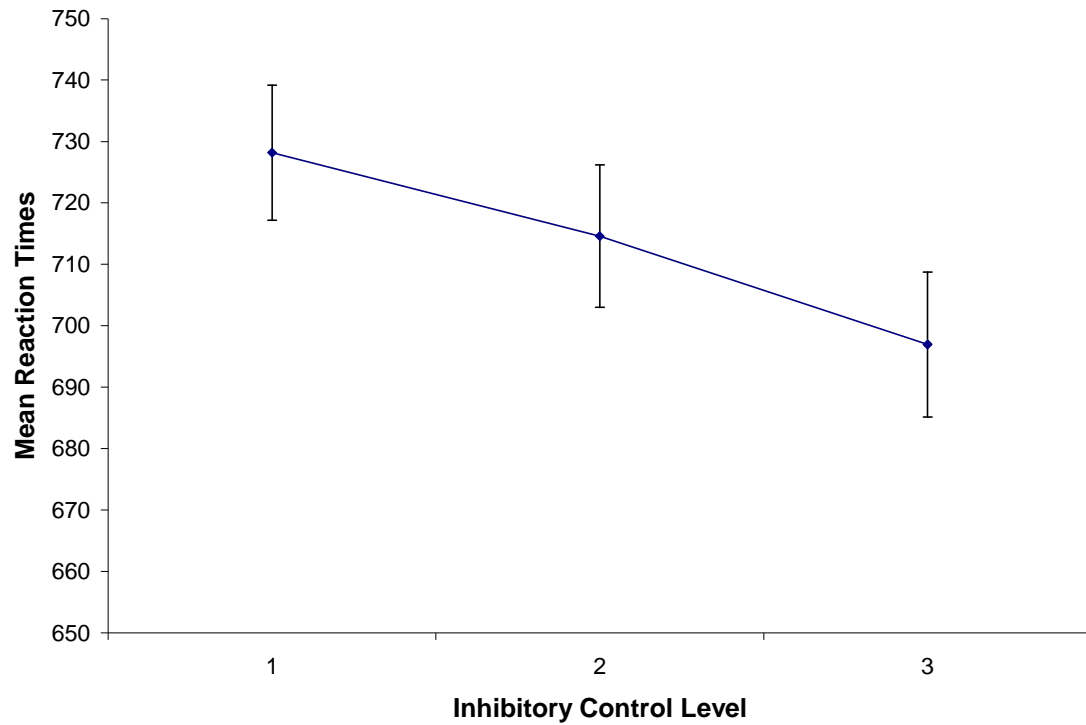


Figure 9. Mean reaction times (ms) as a function of Inhibitory Control (IC).

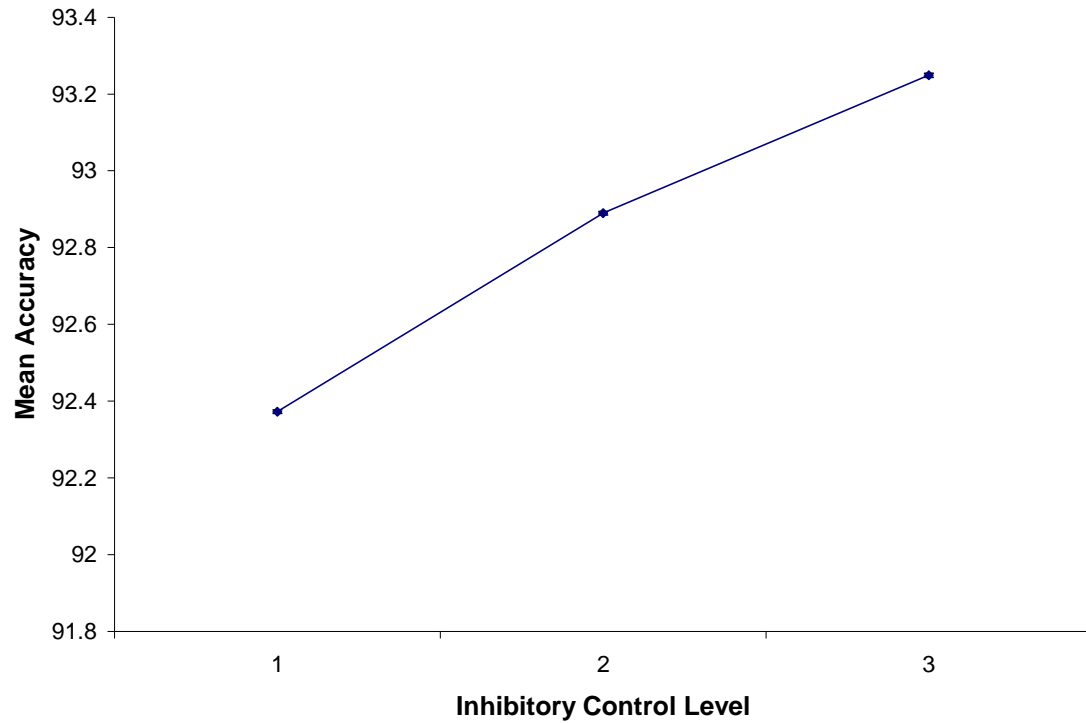


Figure 10. Mean accuracy (percent correct) as a function of Inhibitory Control (IC).

Post hoc analyses were run using RTs and accuracy to compare between each level of IC, and the results of pairwise comparisons are presented in Tables 5 and 6 (below).

Table 5. Paired samples *t*-test results between IC levels using RTs

Pair	T statistic	Sig.	r^2
IC 1 – IC 2	$t(103) = 3.98$	$p < .001$	.91
IC 1 – IC 3	$t(103) = 7.02$	$p < .001$	.86
IC 2 – IC 3	$t(103) = 4.12$	$p < .001$	.87

Table 6. Paired samples *t*-test results between IC levels using accuracy

Pair	T statistic	Sig.	r²
IC 1 – IC 2	$t(103) = -1.67$	$p = .099$	.67
IC 1 – IC 3	$t(103) = -2.75$	$p < .01$	.67
IC 2 – IC 3	$t(103) = -1.16$	$p = .250$	.68

Post hoc analyses revealed a negative linear relationship between IC level and task difficulty, in terms of participants' RTs - IC level 3 was the least difficult condition. Using accuracy data (percent correct), post hoc analyses revealed that only IC level 1 and IC level 3 were significantly different, though there was a linear trend between IC level and task difficulty. This indicates that IC requirements had a significant impact on RT data, but accuracy to a lesser degree.

RM-ANOVA also revealed a significant interaction between IC level and ST on RTs, $F(4.67, 452.79) = 49.28, p < .001, \eta^2 = .34$, as well as percentage correct, $F(4.34, 420.69) = 11.41, p < .001, \eta^2 = .11$. Simple effects analyses for RTs revealed that only in IC level 1 did the pattern of results across the ST's vary (see Figure 11).

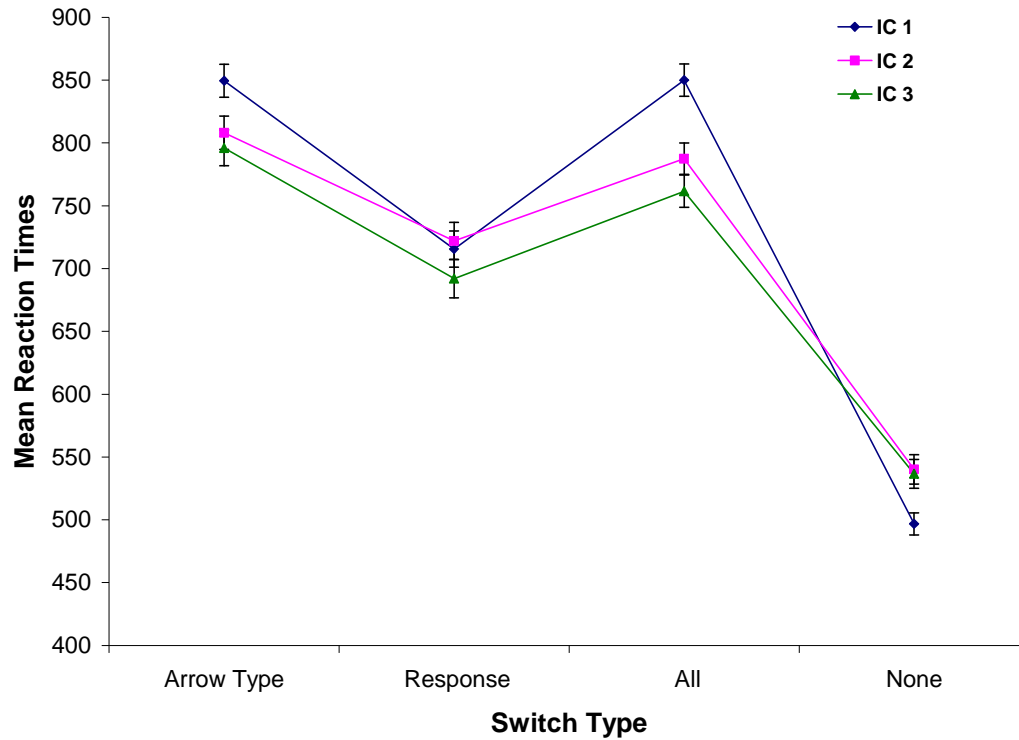


Figure 11. Mean reaction times (ms) as a function of Switch Type (ST), plotted for each of the three Inhibitory Control (IC) levels.

With respect to accuracy, across all levels of IC, the pattern of results on ST was similar to that reported in the main effect. For all levels of IC, the difference between the ‘all’ and ‘response only’ STs were minimal, while all other pairwise comparisons were significant. From Figure 12 it can be seen that the ‘arrow type only’ switch was particularly more difficult in the 25% IC trial block.

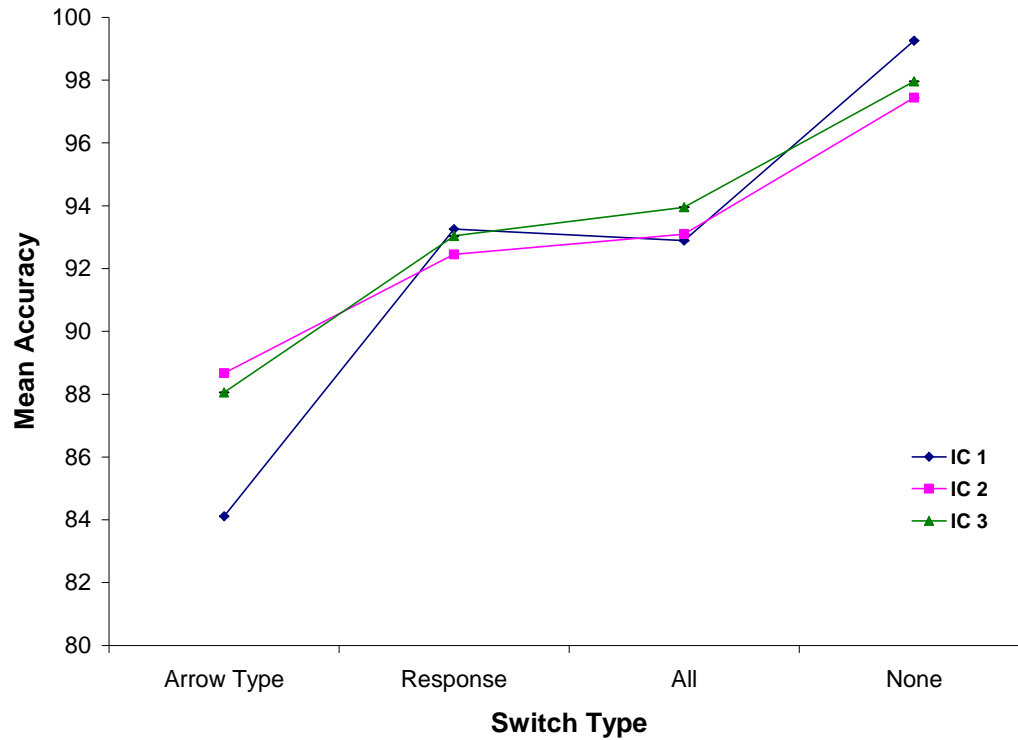


Figure 12. Mean accuracy (percent correct) as a function of Switch Type (ST), plotted for each of the three Inhibitory Control (IC) levels.

Finally, a significant interaction was found between WM level and IC level using RTs, $F(3.16, 306.65) = 14.11$, $p < .001$, $\eta^2 = .13$, as well as accuracy, $F(3.38, 328.11) = 3.15$, $p < .05$, $\eta^2 = .03$ (see Figures 13 and 14).

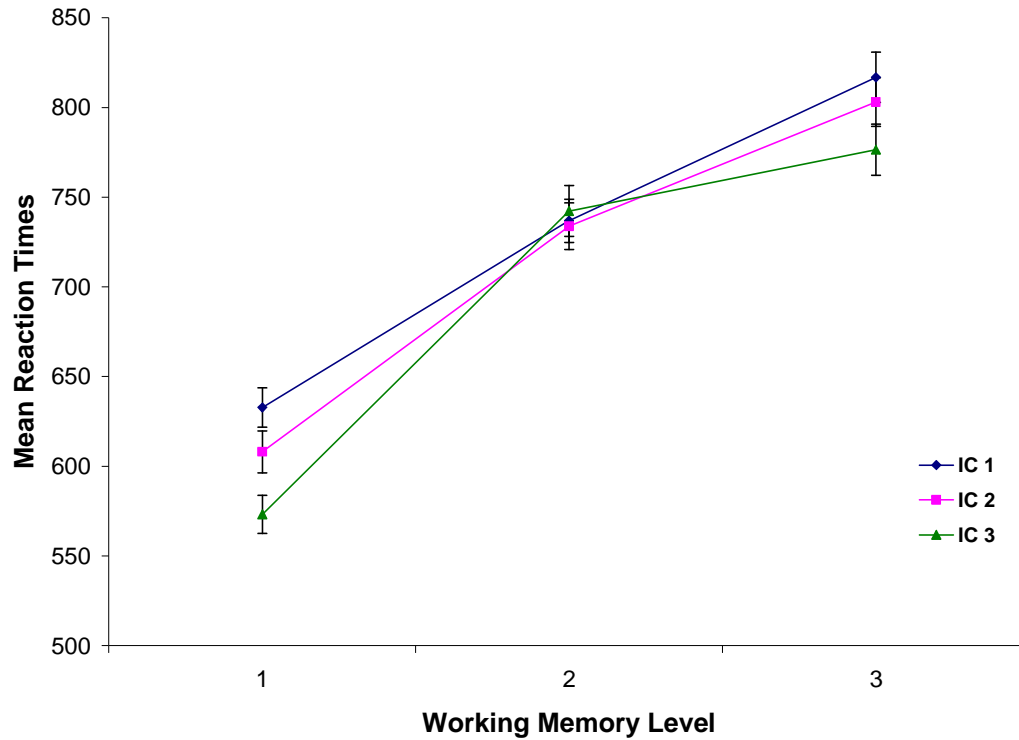


Figure 13. Mean reaction times (ms) as a function of Working Memory load (WM), plotted for each of the three Inhibitory Control (IC) levels.

Simple effects analyses of accuracy revealed that there were no significant differences between any of the levels of IC, for either the first or second WM level. However, for WM level 3, there was a significant difference between IC levels 1 and 2, $t(103) = -3.50$, $p < .01$, and also between IC levels 1 and 3, $t(103) = -5.49$, $p < .001$ (see Figure 14).

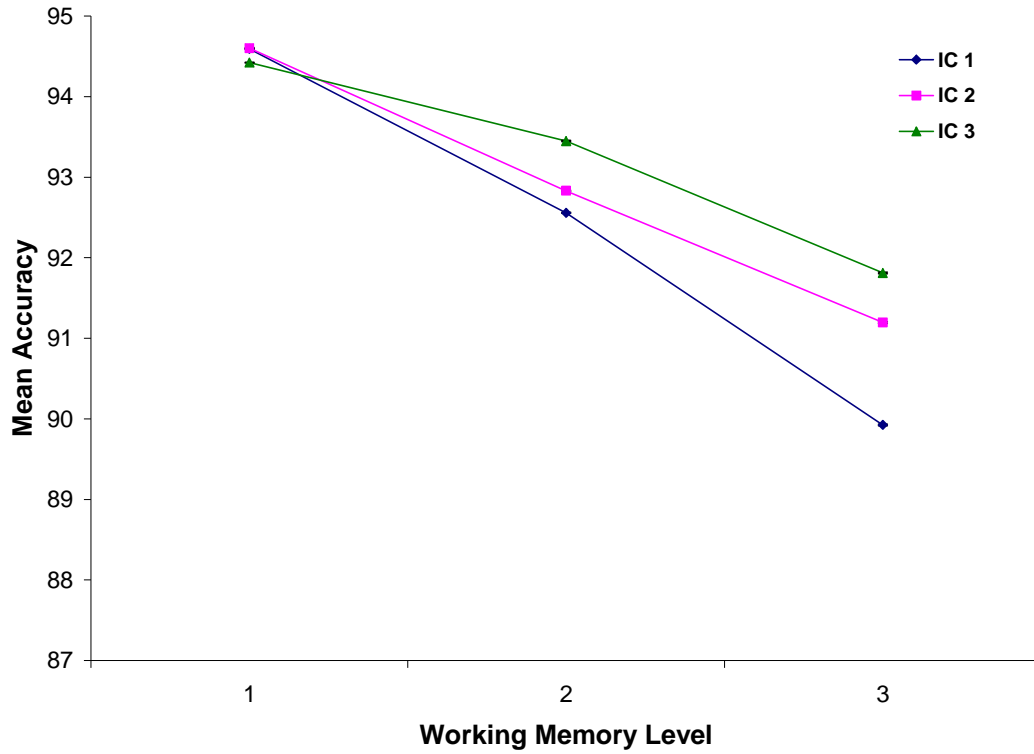


Figure 14. Mean accuracy (percent correct) as a function of Working Memory load (WM), plotted for each of the three Inhibitory Control (IC) levels.

Shapes Task

Similar to the arrows task, data at the trial level for the shapes task were trimmed for outliers beyond 2 standard deviations from the mean – again resulting in less than 2% of the trials being removed. As in the previous task, no change in the pattern of significant findings were observed when data were analyzed using these additional trials.. Again, repeated measures ANOVA was used to assess switch type (4), working memory load (2), and inhibitory control requirement (3); first on reaction time (RT), and then percentage of correct responses made (accuracy) as measures of performance. Planned post hoc analyses were run for all significant main effects found, as well as to test for simple main effects for all significant interactions. Greenhouse-Geiser corrections were used when appropriate; and a Bonferroni correction was used for all pairwise comparisons to adjust for multiple comparisons.

Simon Effect

To assess for a ‘Simon Effect’ in the data we compared participants’ performance on the shapes task between congruent and incongruent trials. Analyses of RT data, using paired samples *t*-test did not reveal any differences in performance between congruent and incongruent trial conditions, $t(103) = 1.51$, n.s. In contrast, analysis of accuracy revealed significantly higher accuracy on congruent trials, versus incongruent trials, $t(103) = 4.31$, $p < .001$. Thus, participants’ responses on this paradigm did display the anticipated ‘Simon Effect’ for accuracy.

Switch Type

Repeated measures analyses revealed a significant main effect for switch type (ST) on RTs, $F(1.12, 57.05) = 528.96$, $p < .001$, $\eta^2 = .91$, as well as accuracy, $F(1.42, 72.46) = 13.40$, $p < .001$, $\eta^2 = .21$. As would be predicted by the ANH, planned contrasts revealed that average RTs for ‘all’ and ‘none’ STs combined were significantly lower (faster) than the average RTs for the ‘shape type’ ST, $F(1,103) = 623.03$, $p < .001$, $\eta^2 = .86$ (see Figure 15). Table 7 (below) displays these results.

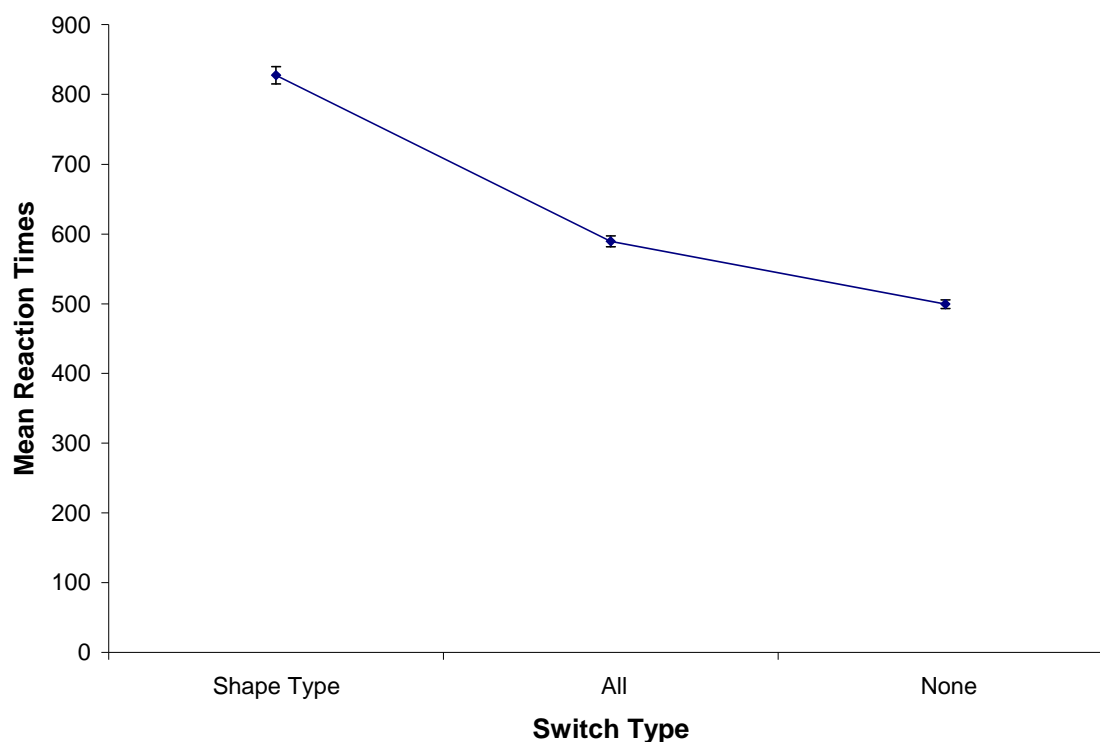


Figure 15. Mean reaction times (ms) as a function of Switch Type (ST).

Table 7. Planned contrast results comparing RTs between STs

Contrast (STs)	F Value	Sig.	Partial eta squared
Shape vs. All	$F(1,103) = 433.10$	$p < .001$	$\eta^2 = .81$
Shape vs. None	$F(1,103) = 799.59$	$p < .001$	$\eta^2 = .89$

These results suggest that the ‘all’ or ‘none’ STs were easier for participants (they responded *faster*), than the switch ‘one thing’ ST (the ‘shape type’ ST), supporting the ANH.

Similarly, planned contrasts revealed that average accuracy for ‘all’ and ‘none’ STs (combined) were significantly higher (more accurate) than accuracy for the ‘shape type’ ST, $F(1,103) = 35.07$, $p < .001$, $\eta^2 = .25$ (see Figure 16). Table 8 (below) displays the results of each planned contrast.

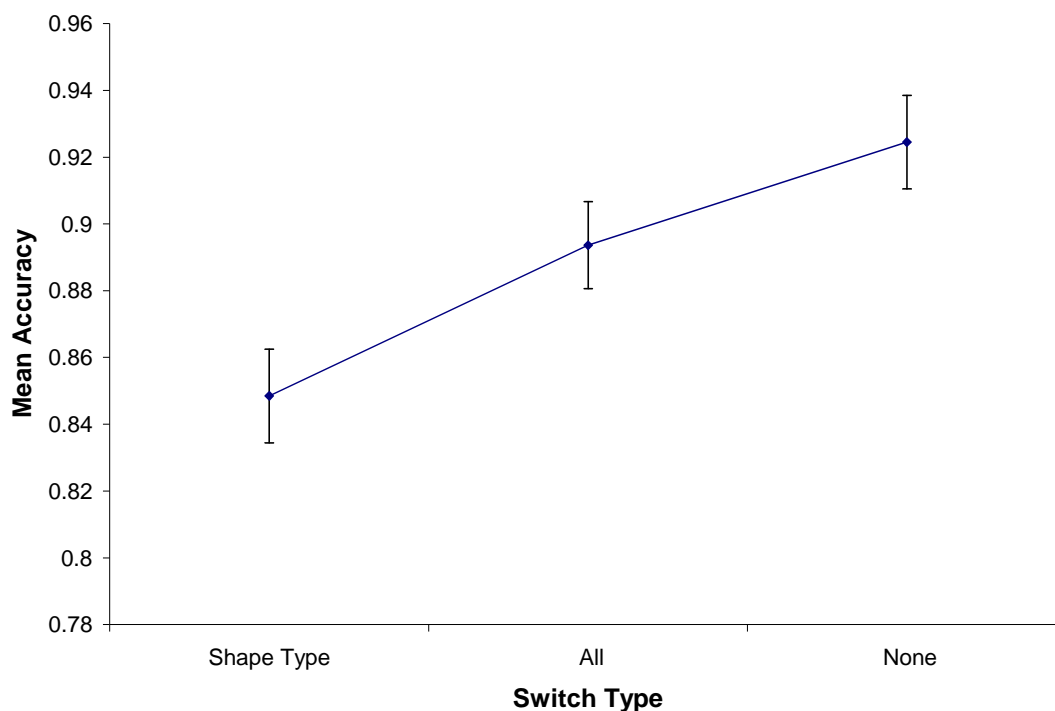


Figure 16. Mean accuracy (percent correct) as a function of Switch Type (ST).

Table 8. Planned contrast results comparing accuracy between STs

Contrast (STs)	F Value	Sig.	Partial eta squared
Shape vs. All	$F(1,103) = 17.56$	$p < .001$	$\eta^2 = .15$
Shape vs. None	$F(1,103) = 55.21$	$p < .001$	$\eta^2 = .35$

Once again, these results suggest that the ‘all’ or ‘none’ STs were easier for participants (they responded *more accurately*), than the switch ‘one thing’ ST (the ‘shape type’ ST), again providing support the ANH.

Working Memory

The repeated measures analyses did not reveal a significant main effect for working memory (WM) level on participants’ RTs, $F(1, 51) = .19$, n.s.(see. Figure 17). Though there was no significant difference, RT on WM level 1 does appear somewhat quicker than in level2. There was a significant main effect for WM on accuracy, $F(1, 51) = 69.30$, $p < .001$, $\eta^2 = .58$, (see Figures 18). Overall, increasing the WM load led to worse performance, in terms of both speed as well as accuracy.

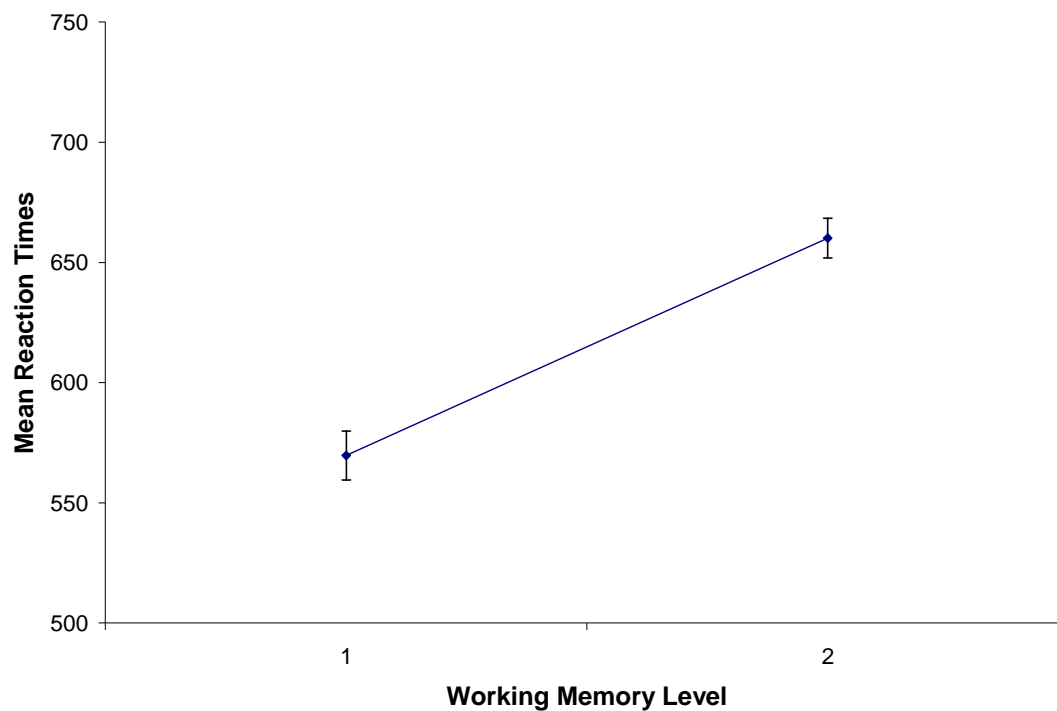


Figure 17. Mean reaction times (ms) as a function of Working Memory (WM).

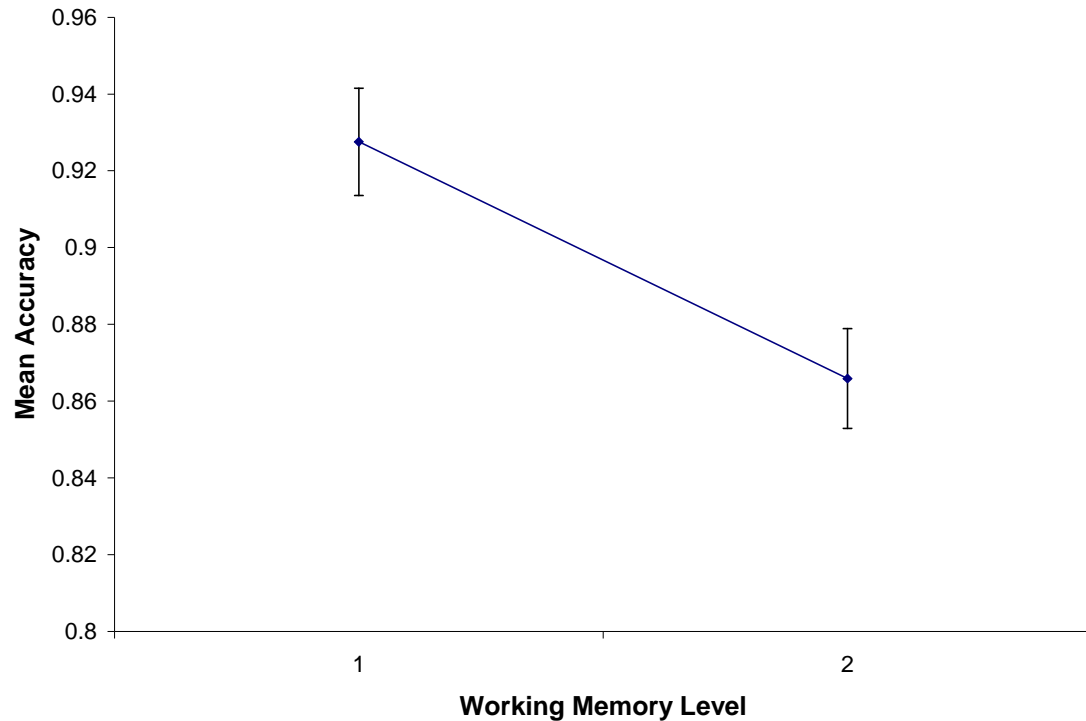


Figure 18. Mean accuracy (percent correct) as a function of Working Memory (WM).

The RM-ANOVA also revealed a significant interaction between WM level and ST on RTs, $F(1.09, 55.35) = 188.60$, $p < .001$, $\eta^2 = .79$, as well as accuracy, $F(1.39, 70.62) = 42.85$, $p < .001$, $\eta^2 = .46$. In terms of RTs, simple effects analyses revealed that all pairwise comparisons were significant, with the ‘shape type’ being the most difficult ST for both WM levels (compared with ‘all’ and ‘none’ STs) – supporting the ANH. From Figure 19, it is clear that the significant interaction was caused by a much greater difference between the ‘shape type’ and ‘all’ switch types for the first level of WM, compared with the second WM level.

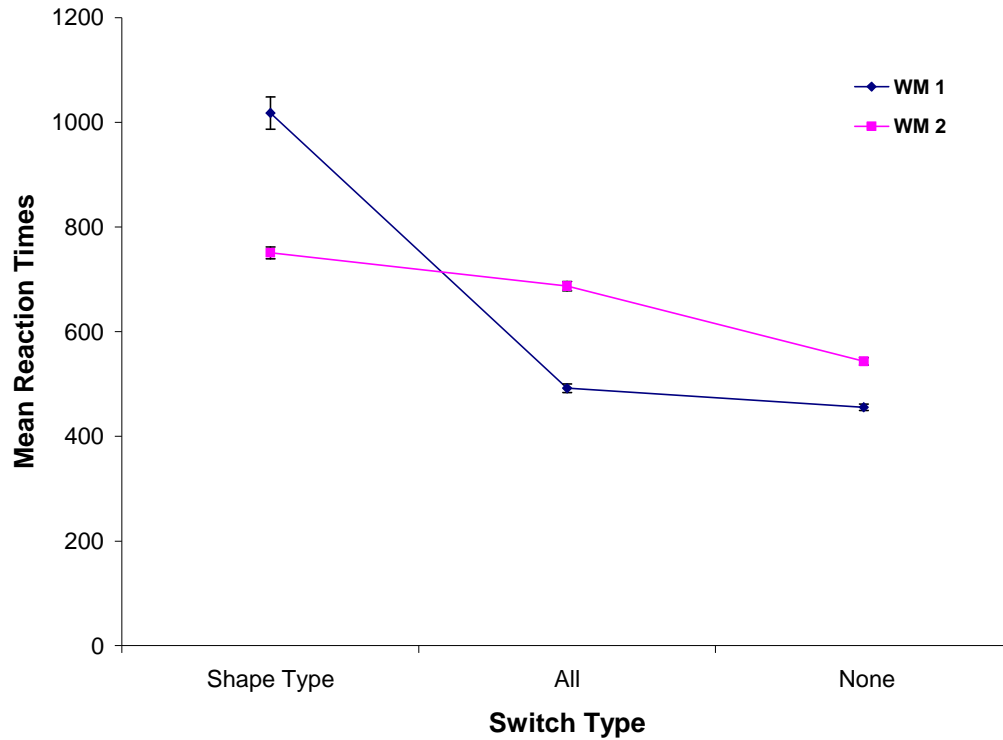


Figure 19. Mean reaction times (ms) as a function of Switch Type (ST), plotted for both levels of Working Memory (WM).

For accuracy, simple effects analyses again revealed that all pairwise comparisons were significant; except for one comparison – between the ‘shape type’ and ‘none’ STs for WM level 1, $t(51) = 1.90$, n.s. However, the accuracy data revealed an interesting pattern across the two levels of WM. In particular, (see Figure 20) for the first WM level, the ‘shape type’ switch was easier than either the ‘all’ or ‘none’ STs; whereas the ‘shape type’ switch was the most difficult ST in the second WM level.

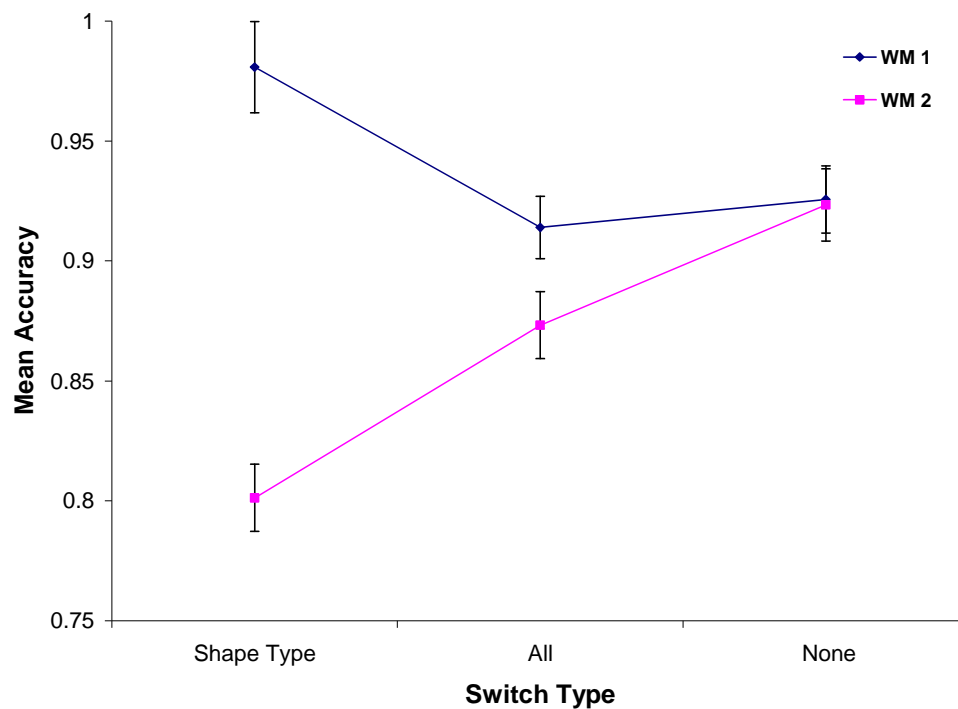


Figure 20. Mean accuracy (percent correct) as a function of Switch Type (ST), plotted for both levels of Working Memory (WM).

Inhibitory Control

Repeated measures analyses revealed a significant main effect for the inhibitory control requirement (IC) on participants' RTs, $F(2, 102) = 7.59, p < .01, \eta^2 = .13$, but not accuracy, $F(1.76, 89.71) = .25, n.s$ (see Figures 21 and 22).

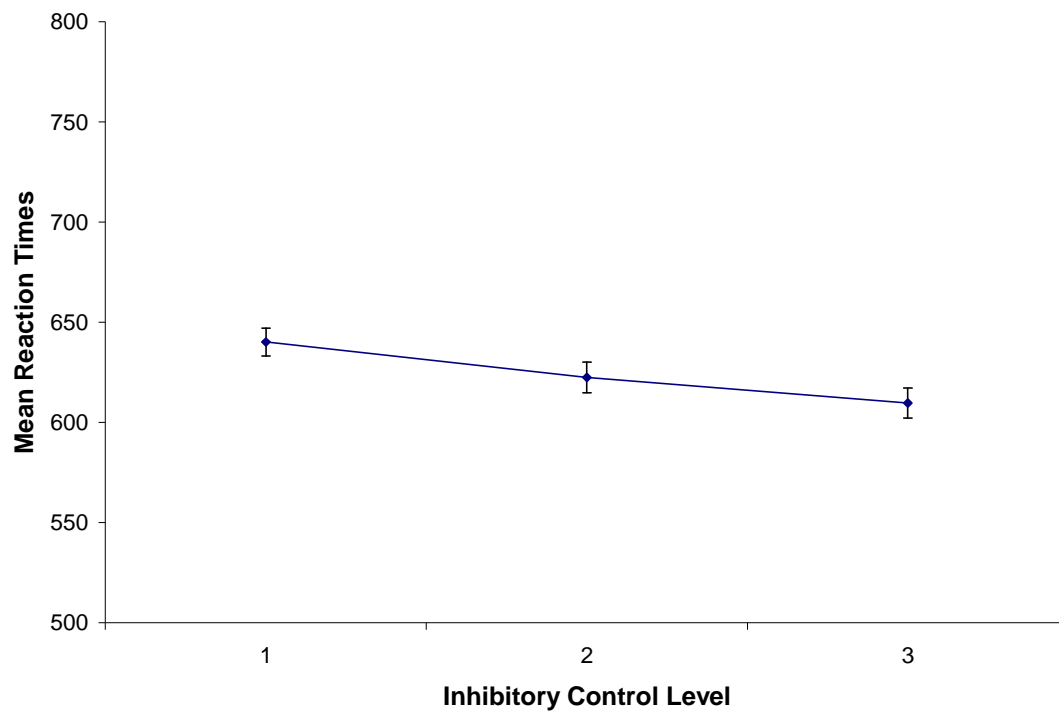


Figure 21. Mean reaction times (ms) as a function of Inhibitory Control (IC).

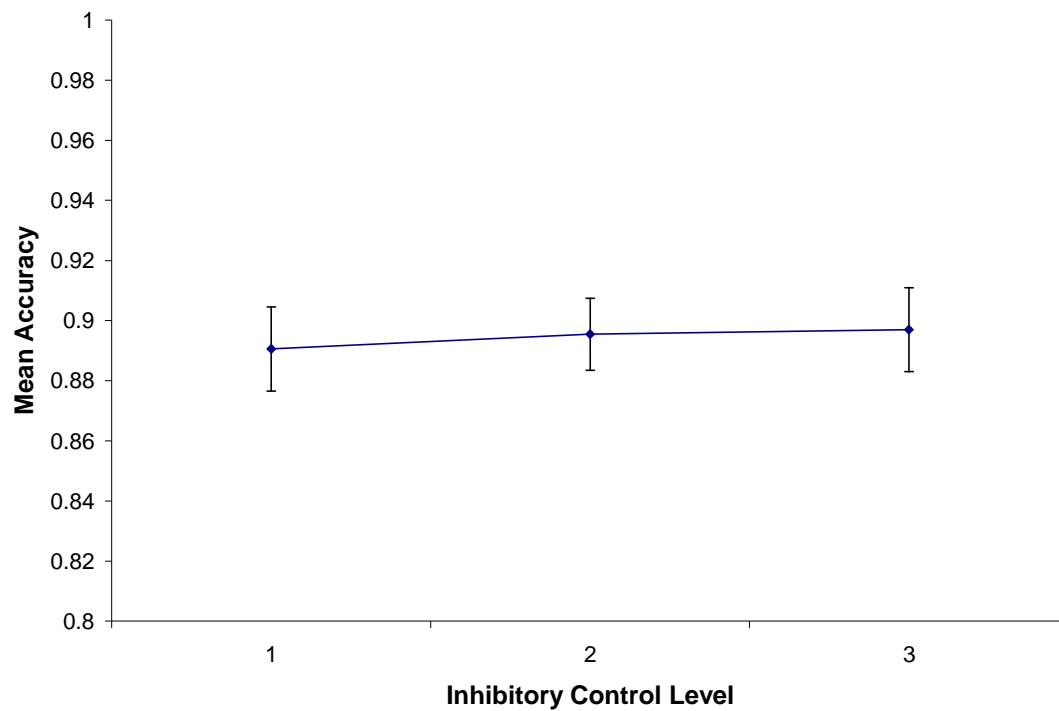


Figure 22. Mean accuracy (percent correct) as a function of Inhibitory Control (IC).

Post hoc analyses were run using RTs to compare between each level of IC, and the pairwise comparisons are displayed in Table 9 (below).

Table 9. Paired samples *t*-test results between IC levels using RTs

Pair	T statistic	Sig.	r²
IC 1 – IC 2	$t(103) = 4.37$	$p < .001$	.72
IC 1 – IC 3	$t(103) = 6.75$	$p < .001$	.65
IC 2 – IC 3	$t(103) = 3.29$	$p < .01$	.75

These results suggest a clear linear (negative) relationship between IC level and task difficulty in terms of RTs. The non-significant results found for the accuracy data may suggest that for the shapes task, IC impacted RT alone (and not accuracy).

The repeated measures analysis also revealed a significant interaction between IC level and ST on RTs, $F(4, 204) = 3.93$, $p < .01$, $\eta^2 = .07$, as well as on accuracy, $F(4, 204) = 2.76$, $p < .05$, $\eta^2 = .05$. In terms of RTs the interaction is subtle, but seems to be driven by a *greater* decrease in RT in the third IC level (compared with IC level 1 or 2); from the ‘shape type’ switch to the ‘all’ and ‘none’ switch types (see Figure 23).

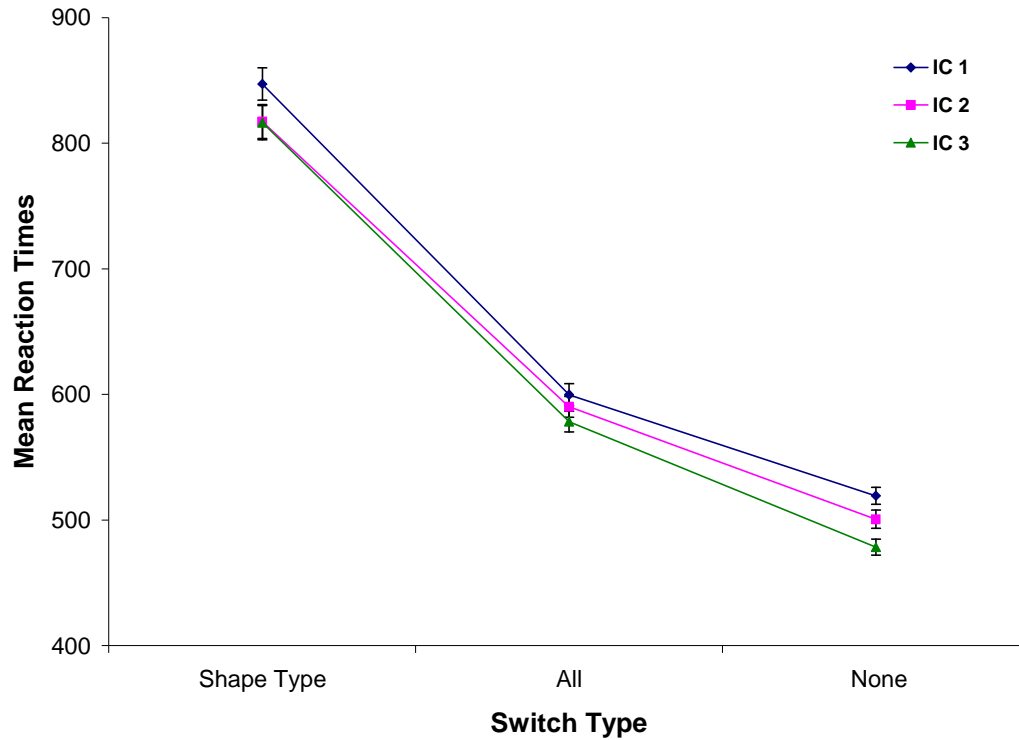


Figure 23. Mean reaction times (ms) as a function of Switch Type (ST), plotted for each of the three Inhibitory Control (IC) levels.

In terms of accuracy, simple effects analyses revealed that for all levels of IC, differences in accuracy between the ‘shape type’ ST and the ‘all’ ST, as well as between the ‘shape type’ ST and the ‘none’ ST were significant (see Figure 24). Thus, an All-or-None trend is apparent at all levels of IC, and is statistically significant on accuracy.

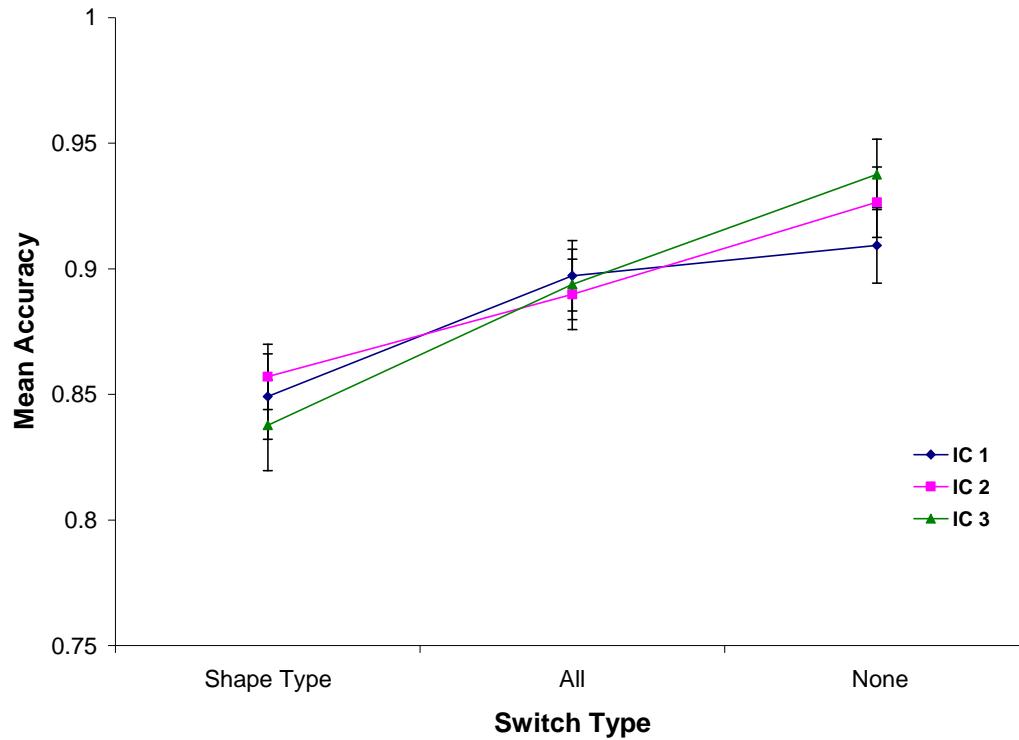


Figure 24. Mean accuracy (percent correct) as a function of Switch Type (ST), plotted for each of the three Inhibitory Control (IC) levels.

No significant interaction was found between WM level and IC level using RTs or accuracy.

Discussion

In general, the results from both paradigms introduced in this study revealed similar findings, and provided conditional support for the ANH. In particular, our data supported the ANH when comparing ‘stimulus type’ switches (i.e. when either the arrow type or shape switched) with ‘all’ or ‘none’ switches, but did not support the ANH for ‘response’ switches. However, the data did suggest that the task demands, WM

requirements in particular, had a meaningful influence on ‘all-or-none’ processing. Each paradigm will be discussed, followed by discussion of integrated findings. Finally, the implications of these findings will be discussed in terms of utility for future research and impact on our knowledge of executive control functioning.

The Arrows Task

On the arrows task, a significant main effect was found for ST. In particular, when combined the ‘all or none’ STs were easier than ‘one thing’ STs in terms of both RTs as well as accuracy – supporting the first hypothesis of the current study. When separated, the ‘arrow’ ST was found to be more difficult than either the ‘all’ or ‘none’ STs. The ‘response’ ST, however, was only more difficult than the ‘none’ ST. Indeed, the ‘all’ ST was significantly more difficult than the ‘response’ ST. This finding reflects an important caveat to the ANH. Our findings suggest that the ‘arrow type’ ST was more difficult for participants than the ‘response’ ST, but may also suggest that the ANH only holds true when executive IC is involved. This may be due to a difference in terms of each ST’s unique IC requirement. In accordance with Nigg’s recent taxonomy for different types of inhibition (Nigg, 2000; 2001), these two STs require distinct ‘types’ of IC – ‘executive cognitive’ inhibition (suppression of a thought; henceforth termed ‘executive IC’) versus ‘executive motor’ inhibition (suppression of a primary or reflex response; henceforth termed ‘motor IC’), respectively. For example, an ‘arrow type’ ST requires participants to inhibit the previous ‘rule’ for responding (i.e. the previous arrow type), while activating the new ‘rule’ associated with the arrow type for the current trial. Since the correct response does not change, no inhibition is required to stop from

pressing the previously appropriate button response. Thus, no ‘motor’ inhibition would be required. On the other hand, a ‘response’ ST would require just this - motor inhibition to overcome the tendency to respond as one did on the previous trial. No ‘executive’ inhibition would be required; the participant would use the same rule as the previous trial (the arrow type would remain constant). Therefore, motor inhibition may be easier to overcome than executive inhibition; that is, it may not tax an executive system to the same degree that executive inhibition might. If this is true, our results perhaps suggest that overcoming motor inhibition does not require (at least not to the same degree) the use of an ‘all-or-none’ heuristic to respond efficiently.

The accuracy data also revealed the same ST effect – the ‘arrow type’ ST was more difficult for participants than either the ‘all’ or ‘none’ STs (again supporting the ANH). However, unlike the results revealed by the RT data, the ‘all’ and ‘response’ STs were not significantly different. This suggests that challenges to motor inhibition may negatively impact accuracy, more so than speed of responding.

As hypothesized, the results also revealed a significant main effect for WM; participants responded slower and less accurately when WM demands increased. A significant interaction was also found between ST and WM. The ST main effect remained fairly consistent across all 3 WM levels *in terms of RT data*; although there was no significant difference between the ‘arrow’ and ‘all’ STs for the third WM level. More interesting was the significant interaction found between ST and WM *for accuracy* (percent correct). In particular, participants reliably responded less accurately for the ‘arrow type’ ST, compared with the ‘all’ or ‘none’ STs (supporting the ANH), but they *also began to respond less accurately for the ‘response’ ST* than either the ‘all’ or ‘none’

STs with increasing WM demands. This suggests that when WM demands are increased adequately, the motor inhibition necessitated by a ‘response’ ST may become too difficult to overcome simultaneously. Therefore, sufficiently increasing WM demands appears to result in all-or-none processing even when motor inhibition is involved. This makes sense, as WM and IC are both ‘executive functions’ that act as ‘resources’ for executive control systems, characterized as having a limited capacity (e.g. Miller and Cohen, 2001). Some authors suggest that this capacity is limited because this system is only able to actively maintain and keep separate a limited number of distinct representations at once (e.g. Usher and Cohen, 1999). Thus, the maintenance of several representations simultaneously within WM (holding in mind the rules corresponding with each of the arrow types), would place a heavy strain on the limited capacity of an executive system. However, further taxation would occur with heightened IC demands, as additional control allocation would be required. This WM x ST interaction may therefore be evidence that when a limited capacity executive control system is taxed sufficiently (with heightened WM demands, ample executive-type IC requirements, or even motor-type IC demands in combination with sufficient WM demands), all-or-none processing is engaged. This directly contradicts our hypothesis that when task demands are increased enough, an ‘all-or-none heuristic’ may no longer be observed.

A significant main effect for IC level was observed; revealing a *negative* linear relationship between IC level and task difficulty – as the number of inhibitory trials (IC level) increased, participants responded faster, and more accurately. Thus participants appeared to ‘inhibit’ more readily in blocks with a higher number of stimuli requiring inhibition. This is similar to findings in the literature related to the Stroop task; where

fewer interference (inhibitory) effects have been found when the frequency of incongruent (inhibitory) trials is increased (e.g. Logan, 1980; Lindsay and Jacoby, 1994). Indeed this finding is aptly explained by conflict monitoring theories mentioned earlier (Botvinick et al., 2001; Miller and Cohen, 2001) given a top-down ‘biasing signal’ to enhance control implementation and prepare it to exert executive control on the after the detection of conflict.

An interaction was found between ST and IC level, however it was minimal and in general IC level alone had very little impact on the pattern of findings across the ST’s. This suggest that the the ‘all-or-none’ response pattern is not simply a reflection of global enhancement of executive control seen with increasing conflict. If this were the case, we should have found greater effects, depending on the level of ‘conflict-laden’ stimuli. Finally, a significant interaction was found between WM and IC demands. Of note, a higher IC level (likely reflective of lower inhibitory demand as noted previously) was related to increased accuracy when WM demands were at their greatest.

The Shapes Task

The shapes task was implemented in addition to the arrows task to ensure that our results would not be confounded by task difficulty. Further, this allowed us to test the ANH using two distinct paradigms. The shapes task also allowed for investigation of importance of inhibitory control needed to overcome the Simon Effect (for overview see Lu and Proctor, 1995) – in which participants had only two response rules and 2 WM levels. This resulted in only three STs, since it was not possible to have a ‘response only’ ST – each shape always dictated the same response, regardless of which side of the

screen it was presented on. A significant Simon effect was found on accuracy only, with lower performance accuracy on trials requiring IC, versus those that did not require IC.

Overall RM-ANOVA again revealed a significant main effect for ST. In terms of both RTs and accuracy, the ‘shape type’ ST was more difficult for participants than either the ‘all’ or ‘none’ STs, which provides support for ANH.

A significant main effect was also found for WM; as the WM load increased, the task became more difficult (accuracy), though RTs were not significantly affected.

With respect to IC level (i.e. 25%, 50%, or 75% IC trials), participants performed significantly faster (and slightly more accurately) when the frequency of IC trials increased. However, once again the IC level had little impact on the ‘all or none’ pattern of performance.

Combined Results

In summary, both the arrows task and the shapes task provided some evidence in favor of more accurate or faster responding when participants had to switch either both their motor response and the stimulus type (rule) they were responding to, or switched neither or them, versus when they had to only switch one. That said, this effect seemed most consistent on trials that required switches in the stimulus (rule) type. For the arrows task, the ‘arrow type’ ST was more difficult than either the ‘all’ or ‘none’ STs in terms of speed and accuracy. Similarly, the ‘shape type’ ST (in the second task) was more difficult than either the ‘all’ or ‘none’ STs. This finding is surprising, because one would not anticipate that an ‘all’ switch would be easier than a stimulus (rule) type switch. For example, for an ‘all’ ST participants must switch their response (i.e. inhibit the previous

response while activating a new response) *as well as* switch the rule for responding (i.e. inhibit the previous rule while activating the new rule). On the other hand, they only need to switch the rule (inhibit the previous rule while activating the new rule) for ‘stimulus type’ STs. One might anticipate that the mental effort required to carry out the combination of two different types of inhibition *simultaneously* should be additive - and therefore the ‘all’ ST should be more difficult. Nonetheless, this was not supported by our data. Interestingly, Nassauer and Halperin (2003) suggest that *perceptual* and *motor* inhibition require distinct cognitive resources, and also hypothesized that they would have additive effects, but indeed found that they did not. Similarly, the implementation of executive control did seem to follow an ‘all-or-none’ heuristic when the stimulus type (rule) was changed. This study supports the idea that *sometimes* it is easier to execute a ‘switch everything’ command, versus switch only one thing – i.e. when trying to switch only the ‘rule’ component of a response. However, our results did not provide convincing support that this same finding applies to needing to change only the motor response (e.g., the response side in these paradigms).

As the ‘response’ ST did not prove to be more difficult for participants on the arrows task than the ‘all’ ST, it highlights a possible distinction between executive and motor inhibition requirements, or perhaps the ‘level’ of the conflict (e.g., perceptual/rule versus motor response). Our data seem to support the notion that an all-or-none ‘processing heuristic’ might only be temporarily implemented when an executive system is sufficiently taxed. However, as WM demands increased, so did the tendency toward an ‘all-or-none’ pattern of response in accuracy –even the ‘response only’ ST became more difficult than either the ‘all’ or ‘none’ switches. Once again, this may suggest that

increased WM demands play a crucial role in taxing the executive system, and enhances the all-or-none ST effect. This could be due to the dual-nature of WM function, as described by Baddeley (1986) as involving both a storage component as well as an executive control component (the ability to perform operations on temporarily stored information). Therefore, increasing the WM load may reduce the ‘spared’ control ability of a limited capacity executive control system – intrinsically linked with WM ability.

Contrary to initial hypotheses, the data support that increasing the task demands *increased* the ‘all-or-none’ findings. It was suggested *a priori* that the all or none heuristic would no longer hold true at some critical level of task demands. However, this was not supported. In fact, as demands increased, participants’ responses exemplified the ‘all-or-none’ responding *to a greater degree* – perhaps supporting the notion (Diamond, 2005; 2006) that this may be a developmental ‘default’ in terms of strategy. This particular heuristic may therefore be the most efficient tactic for responding to complex and taxing task demands.

Taken together, it seems that Diamond’s ANH does help to explain how individuals exert cognitive control, especially with increasing demands on aspects of executive control. However, we can now clarify that the nature of the ‘challenge’ for an executive system is quite different, depending on which executive functions are taxed. Specifically, our data suggest that the ANH appears to be particularly exacerbated by increasing WM demands, and also in situations where executive IC is required (versus situations involving motor IC).

Limitations of the study

There are a number of limitations of this study which may have impacted the results. Of note, various types of inhibitory control was required *throughout* our tasks - executive-type IC based on perceptual/rule characteristics, as well as prepotent response tendencies (motor IC). Therefore, it might have been very difficult to simultaneously overcome (via IC) an overarching heuristic to respond in an all-or-none fashion, especially if this is a ‘developmental default’. Perhaps if a task was implemented that only increased WM requirements, and required minimal or no IC involvement, it would be possible to test if ‘spared’ IC ability would allow someone to overcome their all-or-none strategy. Furthermore, because IC was required throughout both tasks it is difficult to assess whether it is necessary to tax an executive system by increased WM *and* IC demands (to produce the ‘all-or-none’ effect), or if sufficient WM demands alone are adequate. Therefore, future studies could address these questions by further manipulation of IC requirements – including situations where very little IC ability would be needed.

In addition, participants’ ‘efficiency trade-off’ was difficult to assess; i.e. when or how they chose to respond accurately versus quickly. This would be an interesting method for analyzing our data, especially given our assumption that a central goal of the executive system is to be efficient – likely motivating all-or-none processing. Also, given the potential ‘practice effects’ witnessed in our data, replication of this study would likely benefit from increased counterbalancing techniques. Especially pertinent to IC contributions, it would be interesting to test if reducing participants’ ability to predict more frequent IC requirement would make the task more difficult, or consequently alter the witnessed impact of IC on the ST effect.

The implementation of increasing WM demands could also be seen as somewhat problematic in this study. First, all ‘rules’ for the various stimuli types (arrow conditions) were presented at the beginning of the study, versus immediately preceding the conditions in which the subjects were required to use these new ‘rules’. As such, some might argue that the WM load actually remained consistent across the various blocks of the task, as participants were required to ‘remember’ all the potential stimuli types, regardless of if they ‘encountered’ them within a block. It could also be reasonably argued that these rules would not be ‘activated’ in WM until participants were shown a stimulus that required recall of the rules (e.g., they wouldn’t be holding in mind the rule for a stimulus with one or two stripes, until they ‘saw’ one to respond to). Regrettably, given the way the WM conditions were implemented it is impossible to know whether subjects did keep ‘practicing’ or ‘active’ the various rules that they might encounter or not over the entire experiment, reducing the face validity of this manipulation..

In addition, there is the possibility that as the WM demands increased ‘across’ the tasks, for all subjects, so did the actual length of time they were engaged in the task. As such, the WM effect could in part be due to a ‘time on task’ or fatigue effect. This stated, it is important to note that fatigue effects could potentially be balanced by a corresponding practice effect across task blocks. It seems reasonable to assume that the overall WM effect found is at least in part attributable to the manipulation of WM demands. Of note that participants were highly accurate across levels of WM. Accuracy approached 95% in WM level 1, and only decreased to 91% for the most demanding WM level and it is unlikely that the effects obtained simply reflect the task being too difficult.

Finally, it is possible that the task manipulations did not increase the task demands enough (WM and IC), to effect a change in strategy implementation as was hypothesized. Potential evidence for this assertion is seen in the accuracy data as participants consistently responded quite accurately. Although the task seemed relatively difficult, especially at WM level 3, given the subjects were college students it is possible the executive demands were not taxing enough. Future studies should address all these issues, perhaps including tasks that are more demanding in terms of working memory, but not directly tied to the ongoing task. It is also interesting to hypothesis what would result by placing even greater demands on the executive system.

Implications of Findings

In spite of these limitations, our data provided support for some aspects of the ANH. Once again, evidence in favor of an all or none processing heuristic from the current study challenges, to an extent, the existing ‘conflict monitoring’ account of task switching mentioned previously. This account predicts that differential switch costs will result from the amount of conflict detected by a cognitive monitoring system in response to ‘conflict’ in three distinct situations: instances involving ‘response override’ (where automatic but task irrelevant responses must be overcome); when choosing between equally permissible responses; and following the commission of response errors. In the current study, only situations involving response override (exerting IC to overcome a prepotent response) and error commission are applicable. If we predicted switch costs based on conflict caused by ‘response override’ situations, for example, we would

analyze post-IC trials (on average occurring 50% of the time). Thus, this account would only predict performance for half of the trials in our tasks.

Moreover, these theories only predict performance when conflict is the only stimulus dimension. Specifically, these accounts can only predict performance following a conflict trial – and even in these cases the account would be incomplete according to Diamond’s predictions. Diamond’s observation that the switch costs are impacted by response would be accounted for. Thus other theories do not explain differential switch costs incurred after a non-conflict trial and not explain differential switch costs incurred after moving from a conflict trial to a non-conflict trial (either ‘arrow type’ or ‘all’ ST) – other than to suggest that heightened control would not reduce switch costs, as such control would not be useful (there would be no subsequent conflict). Therefore, Diamond’s all-or-none phenomena are not better accounted for by these ‘conflict’ theories, which are based on conflict alone.

To conclude; although “the ability to act flexibly in light of changing circumstances, rather than by simple habits, is an important foundation of higher intelligence” (Morton and Munakata, 2002); we may nonetheless be hardwired to act in ‘less flexible’ ways when we are taxed by heavy demands, due to the potential for such a strategy to be the most efficient way to handle complex demands.

For the Future of Executive Control Research

Due to the novelty the tasks used in the current study, replication is necessary; re-implementing these same tasks, but also using new paradigms to substantiate our results. For the future, it might also be interesting to examine the ANH in unique populations, particularly those displaying altered executive functioning ability. For example, it might

be informative to examine how a group of individuals with reduced ability to exert IC would perform on our tasks; e.g. individuals diagnosed with ADHD. These individuals might implement a different strategy altogether (in order to respond efficiently), or they might even reveal *heightened* all-or-none processing – as it is plausible that these individuals ‘default’ to using a heuristic earlier on along the task demand continuum. In any case, the executive control and monitoring abilities taxed in the current study are precisely the neural systems of interest with this disorder. As such, it could potentially be helpful to understand how these ‘impaired’ systems would function when taxed by dynamic, complex task demands. If we could gain a better understanding of *how* these systems might ‘break down’, secondary to our basic understanding of these systems, such an understanding could lead to more effective treatment strategies for those impacted by disorders of executive control.

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