WHEN, WHY AND HOW DO ATTENTIONAL CONTROL SETTINGS INFLUENCE REFLEXIVE CAPTURE?

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ABSTRACT

Cassie Barasch Ford: When, why and how do attentional control settings influence reflexive capture?
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Most models of selective attention acknowledge the role of both goal-driven and saliency-driven factors (Itti & Koch, 2001). An important ongoing debate asks when and to what extent top-down task settings prevent distraction by salient but irrelevant stimuli. Some studies suggest that reflexive orienting of spatial attention occurs <u>only</u> when distractors are congruent with task-relevant properties of the ***target*** (Folk, Remington, & Johnston, 1992); while others argue that the initial capture of attention is entirely stimulus-driven (Theeuwes, 1991). The present study tested whether attentional control settings always mediate capture, whether capture changes over time, and whether individual differences predict attentional capture. The first set of experiments tested whether a non-predictive and non-congruent cue captures attention when subjects are required to make a "target-absent" button-press response on catch trials. Results indicated reflexive spatial attentional capture to the distractor's location, even when the stimulus shared no critical features with the target, but *only* when a behavioral response to catch trials was required. These findings provide new evidence that the ability of a stimulus to capture attention goes beyond the contingency of congruency between cue and target, and demonstrate that top-down set mediates capture through suppression, which is disabled when participants must attend to the temporal order of events. A second set of experiments extended these results with evidence that the novel capture found in the first experiment diminished over time as a function of experience with the task; whereas capture in the classic contingent case remained present throughout the experiment, suggesting that capture was initially stimulus-driven in both cases, followed by top-down suppression of irrelevant stimuli. Results from a third experiment demonstrated capture to a congruent cue despite its low validity (16%), supporting the contingent capture hypothesis. However, we also found evidence that experience with the cue's probability may have induced more efficient disengagement over time, suggesting another way in which attentional control settings may be disabled. Overall these studies contribute to our understanding of the complex influences of internal and external factors on attentional capture, as well as the ways in which we can study them both experimentally and analytically.

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CHAPTER 1: INTRODUCTION

As we navigate the external world we are bombarded with constant sensory information, not all of which is relevant to our immediate goals. Selective attention enables both the processing of relevant items as well as the reduction of interference by irrelevant items by biasing our limited processing resources (Desimone & Duncan, 1995). Within theories of attention, the saliency of an object typically refers to its physical distinctiveness (Fecteau & Munoz, 2006; Itti & Koch, 2001). Our ability to both attend to and suppress salient items is adaptive, allowing us to quickly avert danger ("watch out for that a falling tree branch") or stay on task ("don't click that banner ad!"). The extent to which physically salient, but task irrelevant visual stimuli capture attention has been hotly debated by cognitive scholars for quite some time and remains unresolved (Eimer & Kiss, 2008; Fellrath, Manuel, & Ptak, 2014; Folk, Remington, & Johnston, 1992; Gibson & Kelsey, 1998; Theeuwes, 1991, 2004; Zehetleitner, Koch, Goschy, & Mu, 2013). Understanding when, why and how visual attention is directed to distracting objects has multiple implications for applied scientists as well, including those building models of salient object detection for artificial intelligence (Ramik, Sabourin, Moreno, & Madani, 2014), and those creating effective and specific interventions for attentional disorders in which attention is erroneously and detrimentally captured (Greenaway & Plaisted, 2005).

Two types of spatial attentional orienting have been identified, each with distinct behavioral and electrophysiological effects: endogenous and exogenous (Muller & Rabbitt, 1989; Posner & Cohen, 1984; Theeuwes, 1991). Endogenous attentional orienting refers to voluntary, effortful, relatively slow, and conscious shifts that arise from goal-related factors and is typically induced experimentally by incentivizing people to use directional cues by making them spatial predictive

(Posner, 1980) or attaching a reward to such shifts (Anderson & Folk, 2010). In contrast, exogenous attentional orienting refers to involuntary or reflexive, effortless, relatively fast, and (potentially) unconscious shifts of attention that may or not be behaviorally beneficial and are associated with distraction (Hopfinger & Mangun, 1998; Posner & Cohen, 1984). Experimentally, exogenous attentional shifts are associated with orienting to distracting stimuli that may or may not share characteristics with a target, and are often taken as evidence of attentional capture, or distraction (Theeuwes, 1991).

The focus of the present study is how attention is directed reflexively, and when internal goal-related factors influence this type of orienting. There are two prominent and competing positions about when in the information processing stream goal-related factors begin to influence attentional capture. Those adopting a preattentive viewpoint take the position that top-down factors (such as internal goals) influence the earliest stages of sensory processing, resulting in reflexive attentional shifts only to behaviorally relevant items (Muller & Krummenacher, 2006). Preattentive processing refers to cognitive and sensory processes that are performed automatically, in parallel, and without attentional resources (Folk et al., 1992). The result of these processes is that some sensory information is tagged for further attentional and higher order cognitive processing while other information is ignored. In a series of studies from the 1990's which have since been replicated and extended, Folk et al. (1992) demonstrated that a distracting visual object will only capture attention when it shares critical physical features with the target. These findings along with subsequent extensions support the theory that a top-down attentional settings act at preattentive stages of sensory processing (Eimer & Kiss, 2008; Folk & Remington, 1998). The mechanism underlying this mediation is thought to involve *suppression* (Zehetleitner, Goschy, & Müller, 2012) in which the top-down set acts to prevent processing of irrelevant features.

On the other side of the debate are those that argue that all physically salient, and therefore potentially behaviorally relevant, stimuli capture attention reflexively, and top-down factors impact attention post-attentively, resulting in further processing or rapid disengagement (Fellrath et al., 2014; Theeuwes, 2004, 2010; van der Stigchel et al., 2009; Zehetleitner et al., 2013). Researchers who argue in favor of the postattentive viewpoint argue that the mechanism underlying capture to only relevant items is one of disengagement from irrelevant items after some degree of processing takes place (Belopolsky, Schreij, & Theeuwes, 2010). This argument suggests that capture still takes place by salient distractors at the earliest stages of attentional processing but attention is quickly disengaged (potentially through suppression and inhibition) due to top-down attentional control settings acting at later stages of processing (Theeuwes, 2010). When and why and how top-down attentional control settings mediate capture by salient physical distractors is the focus of the present study. A series of experiments tested: (a) whether top-down settings can be disrupted by additional task demands (b) the time course and flexibility of top-down attentional settings and (c) the role of individual differences in how top-down settings both develop over time and influence involuntary capture.

Top-down biasing of saliency-driven reflexive capture

The first goal of this study is to test the degree to which top-down attentional control settings mediate saliency driven capture. Most models of selective attention acknowledge the role of both goal-driven and saliency-driven factors (Desimone & Duncan, 1995; Fecteau & Munoz, 2006; Itti & Koch, 2001; Lamy & Kristjánsson, 2013; Muller & Rabbitt, 1989). In their review of the behavioral and neural evidence supporting a saliency map supporting attentional selection, Fecteau & Munoz (2006) conclude that selection reflects a priority map, which combines both saliency and relevance as a result of both feedback and feedforward processes. Despite general agreement that both of these factors play critical roles in how attention is directed, it is still unknown (and hotly debated) when each factor begins to exert control (Lamy & Kristjánsson, 2013; Theeuwes, 2010). More specifically, it is still unclear at what stage of information processing top-down or feedback processes either support or suppress saliency-driven attentional capture. The following section will review a selection of the large body of research investigating the relative influence and timing of both goal-related factors and saliency-related factors on reflexive attentional capture in order to highlight the questions that still remain.

Some of the earliest modern studies of reflexive attentional capture demonstrated that a non-predictive cue (Posner & Cohen, 1984) or irrelevant distractor (Yantis & Jonides, 1984) resulted in a shift of spatial attention when there was any degree of spatial uncertainty about the target (Theeuwes, 1991). In particular, abrupt onsets or changes in luminance appeared to uniquely capture attention even under conditions in which other salient singletons did not (Yantis & Jonides, 1984). In these early studies, and many since, evidence of attentional capture comes from reaction times (RT) measured in cueing tasks (Posner, 1980). To test reflexive orienting, a spatially non-predictive, and therefore task-irrelevant, visual object is presented at one of several possible target locations (Figure 1). The target is then presented either at the same spatial location (valid target), or at one of the other locations (invalid target). The cue is non-predictive because it carries no spatial information about the upcoming target, which is equally likely to appear at any one of the preset potential target locations (e.g. if 2 possible locations, the cue precedes the target 50% of the time; if 4 possible locations, the cue precedes the target 25% of the time). Attentional capture to the cue is <u>inferred</u> when reaction times to targets are faster for cued-location target as compared with uncued-location targets. Based on both behavioral and electrophysiological evidence, it is believed that reflexive attentional orienting to a spatial location results in early biasing of sensory processing (Hopfinger & Mangun, 1998).

Attentional capture (i.e. reflexive shifts of attention to the location of the cue) is hypothesized as being automatic, due to the time course of the attentional effects (Hickey, van Zoest, & Theeuwes, 2010; Hopfinger & Mangun, 1998; Muller & Rabbitt, 1989), and to the fact that shifting to the cue location will not help performance when the cue is non-predictive. In a two-location cueing paradigm, Lambert, Spencer, & Mohindra (1987) found that even when the target was more likely to be invalid, participants sill responded faster to valid targets, further supporting an interpretation of capture as being automatic. Importantly, this occurred only when participants were unaware that the cue was anti-predictive. When subjects were made aware of the nature of the cue's predictability, they were no longer faster at valid locations. They were not, however, faster at invalid locations, indicating that either the cue was causing reflexive orienting to its location from which people quickly disengaged, but did not reorient to the other potential target location, or that the cue did not reflexively capture attention at all.

In addition to cueing paradigms, bottom-up attentional capture has been found using the additional singleton paradigm, a modified version of visual search (e.g. Theeuwes, 1991, Figure 2). In this task, participants are typically asked discriminate a target in a two-choice task (e.g. discrimination of a line: vertical or horizontal). The target is further identified by a specific feature (e.g. green circle) and is surrounded by a uniform set of distractor objects (e.g. green squares). Evidence of capture is found when responses to the target are slower in the presence of a salient but irrelevant distractor object presented simultaneously in the target array. Evidence from both behavioral and ERP studies utilizing the additional singleton paradigm have supported the post-attentive view of top-down control of attentional capture by indicating that attention is reflexively captured to the most salient visual object, but is quickly disengaged when this item is not the target (Hickey, Di Lollo, & McDonald, 2009; Hickey, McDonald, & Theeuwes, 2006).

Despite the early research suggesting that reflexive capture is driven by saliency factors alone (or at least initially), a line of research, beginning around the same time, found that capture to salient visual stimuli could be suppressed by top-down factors. In their seminal study proposing a contingent attentional capture hypothesis, Folk et al. (1992) argued that attention will only be reflexively captured to a stimulus that shares critical properties with the to-be-identified target and is therefore contingent upon top-down settings. Folk et al. (1992) distinguish between two distinct categories of stimulus properties: dynamic discontinuities such as abrupt onsets, and static discontinuities such as a color or shape singleton. In a series of four experiments, they demonstrated that when searching for a target belonging to one category, attention was only captured to a cue belonging to the same category.

The contingent capture work arose out of experiments that demonstrated capture always and only to dynamic changes, specifically abrupt onsets (Remington, Johnston, & Yantis, 1992). In a series of five experiments, Remington et al. (1992) found slower reaction times when a bright flash cue was presented either at an invalid location, at all 4 potential target locations, or at the center of the display (i.e. fixation). Interestingly, they did not find evidence that the flash facilitated target processing, but only that it exclusively interfered with processing when it was spatially incongruous. However, more recent studies have also found facilitation of target processing by onset cues in both behavioral and ERP measures (Cosman & Vecera, 2014; Hopfinger & Mangun, 1998; Hopfinger & Ries, 2005). The early evidence that onsets captured attention, even when participants were explicitly told that the target would not appear at the location of the flash for the entire block of trials were interpreted as saliency-driven capture that is free from top-down control (Lambert, Spencer, & Mohindra, 1987; Remington et al., 1992). In response, Bacon & Egeth (1994) argued that any time a task involves responding to a pop-out target (i.e. a visual object that can be distinguished from its neighbors along a single feature dimension, such as shape) participants adopt a singleton search mode. The adoption of this search mode may result in capture by any singleton, such as a single onset or singleton defined along a non-target dimension (e.g. color).

Strong evidence that irrelevant distractors capture attention comes from studies that have used the additional singleton paradigm (Hickey et al., 2006; Theeuwes, 1991, 2004). When a salient singleton is presented in the same array as a less salient target, behavioral and ERP evidence suggests capture to the salient distractor first, followed by processing of the target following hypothesized disengagement from the cue (Hickey et al., 2009, 2006). These results are interpreted as reflecting a top-down search mode for singletons (Lamy, Carmel, Egeth, & Leber, 2006; Leber & Egeth, 2006). However, such an interpretation cannot reconcile other evidence that changes to luminance (Atchley, Kramer, & Hillstrom, 2000; Franconeri, Hollingworth, & Simons, 2005), or motion (Abrams & Christ, 2003) also cause attentional capture. These examples seem to suggest that under certain conditions top-down set is unable to mediate capture by salient distraction. Alternatively, it may be the case that attention is always capture to salient distractors, but when the items are not sufficiently salient, or do not match top-down settings, attention is quickly disengaged from the spatial location of the distractors and therefore does not bias processing of subsequent stimuli. (Theeuwes, 2010).

Event-related potentials (ERPs) evidence of top-down and bottom-up attentional capture

At the heart of the debate about top-down versus bottom-up capture is the question of not *whether* top-down factors influence capture, but rather *when* (Fellrath et al., 2014). However, behavioral evidence of capture to a cue or simultaneous distractor are observed anywhere from 400 to 1500ms *after* the capture is thought to have occurred. As a result attentional capture is inferred rather than directly observed. Due to their high temporal resolution, a number of reliably evoked ERPs have been used to answer questions about how attention affects perception, and what factors influence attentional selection and its component operations. ERP components are generally defined as a scalp-recorded voltage change that reflects a specific neural or psychological process (Kappenman & Luck, 2012). ERPs have been particularly useful in clarifying how and when attention affects cognitive processing of visual information. Early sensory-related ERP components, such as the P1 and N1, named for being the first positive and negative deflection, respectively, reliably reflect modulations of attention on sensory processing, with attended stimuli receiving higher levels of processing indexed by larger amplitudes (Mangun, 1995; Mangun & Hillyard, 1991). Later components such as the P300, observed at latencies longer than 300ms following a stimulus onset are primarily driven by higher order processes related to attention, such as the violation of expectancies, or memory updating (Mangun & Hillyard, 1991; Rugg & Coles, 1995). Critically, between these early effects on sensory processing and later effects on other cognitive functions, is a time window (~200-300 msec post stimulus onset) during which neural activity seems to reflect some critical process or processes related to the focusing of spatial attentional on relevant or task-related stimuli. A widely studied component, the N2pc, occurs during this time period. It is elicited following a bilateral visual array, which contains a target or target-like item as well as non-target items that require suppression. Unlike early sensory components (P1, N1) the N2pc is not simply triggered by physically salient visual events, but rather, is elicited by items that are related to the task at hand (Luck & Hillyard, 1994; Seiss, Kiss, & Eimer, 2009).

A number of studies have looked at modulations by attention on the early sensory components for evidence of attentional to tease apart top-down and bottom-up influences on attentional capture. Fellrath et al. (2014) measured early sensory ERPs (P1, N1) elicited by non-predictive cues to determine if and when top-down factors (i.e. task relevance) and bottom-up factors (i.e. stimulus salience) resulted in attentional biasing of sensory information processing. Stimulus saliency (luminance) and task relevance (cue-target color match) were manipulated independently in a 2 x 2 design (bright versus dim; match versus mismatch) so that researchers could model the effect of each factor and a possible interaction on both behavior and on ERP components of interest. Unlike most cueing paradigms, spatial congruency was not manipulated as cues were presented peripherally, either to the right or left of fixation; whereas targets were presented centrally. Relevance but not salience affected participant's behavior, such that participants were significantly faster to respond only to targets that were preceded by a color-matching cue (e.g. red cue followed by red target). However, they did find that saliency, but not relevance modulated the amplitudes of the early sensory components, with larger P1 and N1 amplitudes elicited by high relative to low saliency targets. Relevance only began to modulate the ERP at a later stage of processing, beginning around 200 - 250 ms after the targets stimulus onset, which was classified as an effect on the P2 by the authors. The differential timing of the effects of the conditions of salience and relevance on the evoked brain potentials are critical. Most studies that have tried to tease apart if and when saliency-driven capture occurs without top-down mediation look only at the N2pc (and later components such as the sustained posterior contralateral negativity, SPCN), and by design, are unable to detect effects of attention on the early sensory components, due to a visually balanced stimulus display (Ansorge, Kiss, Worschech, & Eimer, 2011; Eimer & Kiss, 2008; Hickey et al., 2009, 2006). Selective modulation of the N2pc by task-relevant cues as compared with task-irrelevant cues has been interpreted by many as strong evidence that the initial stage of visual selection is under the control of top-down settings (Ansorge et al., 2011; Eimer & Kiss, 2008; Kiss, Jolicøeur, Dell'Acqua, & Eimer, 2008; Lien, Ruthruff, & Cornett, 2010; Lien, Ruthruff, Goodin, & Remington, 2008). However, the results found by Fellrath et al (2014) suggest that attention may be captured by salient stimuli, but when irrelevant, the effects of capture are short-lived and replaced by goal-driven processes, in line with the disengagement hypothesis (Theeuwes, 2010).

Similar to Fellrath et al. (2014), Hopfinger & Ries (2005) found no behavioral capture for an onset cue followed by a color-singleton target with only 2 locations however, they did find ERP evidence suggesting that some degree of capture took place. Specifically, they found that the target-elicited P1 amplitude was greater for valid relative to invalid targets, for both congruent (color cue - color target) and incongruent targets (onset cue - color target). Although the amplitude of the P1 was not modulated by congruency, the duration of the effect was different across conditions, with a sustained valid - invalid difference that persisted into the N1 latency for congruent targets only. Additionally, the topography of the P1 was equivalent across congruency conditions, further supporting the interpretation that a similar processing bias resulted from the cue. It's possible that capture for onset cues may be more sensitive to specific design features and task peculiarities than other cues given the strength of the signal generate by a single object presented without competing visual information. The contradiction between behavior and ERP evidence found by Fellrath et al. (2014) and Hopfinger & Ries (2005) may indicate why, in several studies that measured only behavior, onset cues have resulted in contradictory findings that don't definitely support a bottom-up or a top-down account of attentional capture. Onset cues followed by color-singleton targets have resulted in both a behavioral cueing effect (Cosman & Vecera, 2014; Ford & Hopfinger, 2013), and a lack of behavioral cueing effect (Eimer & Kiss, 2008; Hopfinger & Ries, 2005). Critically, ERP evidence has shown that onset cues not resulting in behavioral cueing effects may none-the-less act to bias attentional processing.

Most of the research utilizing ERPs to determine the stage at which top-down factors influence saliency-driven capture focus on the N2pc component which occurs ~200-300 msec post stimulus onset, during which neural activity seems to reflect some critical process or processes related to the focusing of spatial attentional on relevant or task-related stimuli. It is elicited following a bilateral visual array, which contains a target or target-like item as well as non-target items that require suppression. Unlike early sensory components (P1, N1) the N2pc is not simply triggered by physically salient visual events, but rather, is elicited by items that are related to the task at hand (Luck & Hillyard, 1994; Seiss et al., 2009). Multiple studies have shown that the N2pc is selectively elicited by a non-predictive singleton-cue only when it matches a critical feature of the to-be identified target (Ansorge et al., 2011; Eimer & Kiss, 2008; Kiss et al., 2008). However, as previously mentioned, it may be the case that even at 250 following the target, the effects of reflexive capture by a salient but irrelevant cue are no longer present (Theeuwes, 2010).

In summary, there is compelling evidence to suggest that top-down mediation of saliency-driven capture may occur pre-attentively (Ansorge et al., 2011; Eimer & Kiss, 2008; Folk & Remington, 1998; Folk et al., 1992; Gibson & Kelsey, 1998; Lien et al., 2008) but that this suppression can be disrupted by abrupt onsets (Liao & Yeh, 2013; Schreij, Owens, & Theeuwes, 2008; Yantis & Jonides, 1984), changes to saliency or luminance (Atchley et al., 2000; Franconeri et al., 2005; Theeuwes, 2004), motion (Abrams & Christ, 2003) or differing task demands (Lien, Ruthruff, & Naylor, 2014). **Therefore, the first aim of the present study is to test assertions that top-down attentional control settings for features mediation attentional capture by a salient but task irrelevant distractor.**

<u>Development of an attentional set</u>

The concept of an attentional set is central to the argument that attention will only be captured by items with features or properties associated with the task (Folk & Remington, 1998; Folk et al., 1992; Lamy et al., 2006; Lien et al., 2010). The attentional set is broadly defined as items and/or features of items related to the task-at hand; and many theories of attention include a critical relationship between working memory and attentional selection in which the contents of visual working memory (VWM) influence attentional selection (Bundesen, 1990). In cueing tasks, for example, an attentional set is typically used to refer to either static features or dynamic properties specific to a to-be-identified target, but can more broadly refer to non-feature based goals, such as those related to rewarded stimuli (Anderson & Folk, 2010). In search studies, the attentional set can additionally include a search mode or strategy such as feature mode and singleton-detection mode (Lamy et al., 2006; Leber & Egeth, 2006; Wolfe, 1994). Despite being widely referenced as playing a critical role in the top-down mediation of capture, little is known or understood about how and when an attentional set develops, although evidence suggests that attentional capture can change as a result of implicit learning (Cosman & Vecera, 2014) and experience with the distractor itself (Zehetleitner et al., 2012). **The second aim of the present study is therefore to test whether top-down**

influences on attentional capture are present at the throughout an experiment, or if they develop as a result of experience with the task and stimuli. If the presence or strength of attentional capture is the result of both task goals as well as stimulus and task experience, it would suggest a more complex interaction between top-down and bottom-up factors than has previously been discussed.

Many studies that demonstrate how top-down goals and task set can suppress or attenuate attentional capture explore the effects of an attentional set, taking for granted that the set is established as soon as task instructions are given and are relatively consistent across trials. However, there is reason to believe that this kind of attentional control takes time to develop (Zehetleitner et al., 2012); and that an attentional set can develop incidentally and without explicit instruction (Cosman & Vecera, 2014). In a study directly aimed at exploring the how an attentional set is established, Cosman and Vecera (2014) found that participants adopted an attentional set for a specific color cue without awareness through a statistical learning mechanism. Using a two-location cueing paradigm, participants were given a lengthy training phase in which they had to indicate which of two possible target letters was present (B or H). Even though the cue was non-predictive, and was equally like to be either green or red, one of the target colors would appear 80% of the time, which induced an attentional set in participants, without their awareness. As a result, there was significantly more attentional capture to the cue that matched the trained (i.e. more likely) target color during both training and a subsequent testing phase. Interestingly, the effect of the higher probability target color on capture was only found in the first two blocks of testing, and was then eliminated, indicated a short-lived effect of statistical learning and suggesting a highly flexible system. To assess the effect over time, Cosman and Vecera (2014) performed Bonferroni-corrected t-tests on mean valid versus invalid RTs for each block. Although this method yielded an informative picture of the effects over time, by reducing the number of time points from trials to blocks, it may not have had the sensitivity to detect when the effect of training ceased to impact capture during testing. In summary, this study demonstrated that once acquired, an attentional set may change as a result of implicit information gained through experience with the task.

There is also evidence to suggest that top-down mediation of reflexive capture is caused by experience with the distractor itself (Zehetleitner et al., 2012) and can be flexible on a trial-by-trial basis (Lien et al., 2010), although the evidence is mixed (Lien et al., 2014). For example, during a search task, when participants are presented with blocks in which the target's critical features change on a trial-by-trial basis, there is a higher cost of distractor present trials leading to slower reaction times (Muller & Krummenacher, 2006; Pinto, Olivers, & Theeuwes, 2005). In a cueing study, Lien, Ruthruff & Johnston (2010) found evidence of interference when target properties switched from one trial to the next, but no evidence that top-down suppression of irrelevant singletons was disabled when participants had to switch between target colors rapidly. However, more recently, some members of the same team (Lien et al., 2014) found a breakdown of top-down suppression when people had to rapidly switch between search modes (feature versus singleton) <u>randomly</u> mixed within a block. These studies all looked at the development and duration of an attentional set by design, and collapsed across trial types to calculate effects by using trial type (repeat vs switch) as a factor in a repeated measures ANOVA.

Averaging across trial types can answer some questions about the effects of one trial type on another, but does not allow for questions about changes in capture due to overall or ongoing experience with the stimuli. Additionally, by averaging all trials within a block and looking at overall capture at only 4 time points we can only have a crude picture of the potential changes in the effects of an attentional set on capture over time. Understanding the time course of the development of an attentional set has important implications for the various theories of attentional capture. If attentional settings do take time to develop, as a result of experience with the stimuli, it would indicate that top-down suppression of capture does not function in an all or nothing manner but may be stochastic in nature, as has been found with the effect of saliency on capture (Zehetleitner et al., 2013). Finding capture throughout the course of the experiment supports the more extreme contingent capture point of view (Folk et al., 1992). Additionally, modeling the development of capture over time provides a way to compare capture across various experimental conditions that goes beyond mean RTs collapsing across all blocks.

Some studies that wanted to quantify changes in attentional capture over the course of an experiment treated time (or more accurately, trial exposure) as a discrete factor and created chunks either using the blocks that were present in the design (Holguín, Doallo, Vizoso, & Cadaveira, 2009; Lien et al., 2010) or by averaging over several blocks to create fewer levels of the time factor, and reduce noise in the means at each level (Cosman & Vecera, 2014). To look at capture across these levels, separate t-tests are conducted and then corrected for multiple comparisons (e.g. Bonferroni). While this method can be useful for providing an initial picture of the effects, there are several problems. First, the decision to sub-sample time or trials down into smaller levels (e.g. 600 trials down to 4 blocks), is driven by the data and not by any specific theoretical question, making it highly variable across studies. This choice must be balanced by two competing goals: power and sensitivity. First, opting for fewer levels means less corrections and keeps alpha high enough to maintain power to detect effects (e.g. for 4 blocks, alpha=.05/4=.0125 vs. for 8 blocks alpha=.05/8=.006). Second, in order to detect when an effect begins or ends (i.e. no capture to capture), a sufficient number of block or time points must be sampled. The need for this kind of sensitivity may be particularly relevant if the goal of the study is to compare the effects of experimental conditions of attentional capture across time as is the case in the present study. In other words, in order to answer the question of whether condition A results in an earlier onset of attentional capture than condition B over the course of the experiment, we need the sensitivity to detect the point at which capture begins, as precisely as possible.

Rather than attempting to do this by choosing various levels and weighing the needs for power and sensitivity, it makes sense to try to use a statistical model that allows us to keep all of the trials or time points without having to conduct single t-tests at each one.

The second aim of the present study is to test whether attentional settings are immediately present when a task begins or if they build up over time. Specifically, I plan to include both the possibility of a trial-to-trial influence in the model, along with a predictor representing experience with the stimuli (i.e. exposure) in order to understand how selection history may result in the hypothesized attentional setting causing contingent attentional capture. Awh, Belopolsky, & Theeuwes (2012) argue that the dichotomization of attentional control into top-down and bottom-up factors fails to capture the full array of influences acting upon selection at a given moment. They argue that selection history is often subsumed by the idea of top-down factors and should be considered distinct. On a macro-level this could mean task history in the recent or distant past. On the micro level, selection history could refer to the trial-to-trial correlations assumed to be zero by most analyses (Baayen & Milin, 2010). One of the aims of the present study is to not only include the possibility of a trial-to-trial influence but to explicitly model it in order to understand how selection history may result in the hypothesized attentional setting causing contingent attentional capture by using multilevel modeling.

Using multilevel or mixed models rather than a repeated measures ANOVA for repeated measures data is not a novel practice (MacCallum, Kim, Malarkey, & Kiecolt-Glaser, 1997), however, most applications involve longitudinal designs with measurements taking place over days, weeks or years (cf. Baayen & Milin, 2010; Kristjansson, Kircher, & Webb, 2007). Cognitive studies in which hundreds of trials occur in a a single hour-long session typically involve making inferences from single mean values of the dependent variable (usually RT or accuracy). A notable exception comes from an increasing number of psycholinguistic studies which utilize multi-level models to account for item or word level effects that may interact with person level factors (Baayen, Davidson, & Bates, 2008).

<u>Individual Differences</u>

The third aim of the study is to determine the role of individual differences in attentional capture. Within this goal there are two distinct questions. The first question is whether or not explicitly modeling individual variability in reaction times enhances our understanding of the effects of task manipulations on behavior. Until recently, attention researchers have typically been interested in how similar people are on measures of attention, rather than in their differences. Because of this, most studies examining attentional control settings treat individual differences in RT as random noise, including these differences only as the variance term used to calculate probability of an observed mean difference between conditions. Even studies that make use of the full distribution of reaction times, do so, for example, to examine differences in fast versus slow responses across all participants, rather than between them (Leber, Lechak, & Tower-Richardi, 2013). However, in the present study, allowing for individual differences (i.e. randomness) in the effects of task conditions on RTs will likely result in more realistic and appropriate models of behavior, and moreover, allow us to test whether person-level traits or cognitive abilities predict different trajectories across the span of the experiment. For example, a person who is particularly fast to begin with may not show any changes in RTs or effects of condition on capture as a result of experience with the stimuli as compared with someone who starts out more slowly.

The second question regarding how individual differences impact attentional capture is whether or not certain person-level variables predict RTs or interact with within-subject factors to impact RTs. Specifically, measures of working memory capacity (WMC), distractibility, and impulsivity were be measured and included in the models. There is evidence that people who have been diagnosed with decreased attentional control, tend to have more variability in their reaction times (Leth-Steensen, King, & Douglas, 2000), so including distractibility and impulsivity as covariates may allow us to more clearly find within-person effects, otherwise confounded by these differences. Additionally, differences in working memory capacity have been correlated with attentional capture (Fukuda & Vogel, 2009, 2011).

Working Memory Capacity

There are several reasons to hypothesize a critical role for individual differences in WMC in attentional capture to relevant and irrelevant stimuli. Working memory has been indicated in the creation and maintenance of a top-down attentional set (Bundesen, Habekost, & Kyllingsbaek, 2005), which in turn may determine which stimuli capture attention (Downing, 2000). In fact, people with low WMC may be more distractible, possible reflecting a weaker attentional set (Kane, Bleckley, Conway, & Engle, 2001). In their study examining the relationship between individual differences in WMC and attentional control during a cueing task, Kane et al., (2001) found people with lower WMC were selectively impaired when the cue was anti-predictive (i.e. predicted that the target would appear at an alternate location). Broadly, the authors interpreted the deficits in performance as evidence that working memory capacity reflects both short-term memory storage as well as attentional control. They make no specific interpretations about the mechanisms supporting attentional control that might be specifically impacted by WMC differences, but the results of their experiments suggest a selective impairment in the ability to recovery following distraction. Indeed, this interpretation is supported by a series of more recent experiments that found that people with low working memory capacity did not show differences in voluntary attentional allocation but did show a decrement in their ability to override attentional capture after initial capture (Fukuda & Vogel, 2009, 2011).

The relationship between WM and attentional control that was found between people (Fukuda & Vogel, 2009, 2011; Kane et al., 2001) can also been seen within people, across task conditions that differentially require WM (Lavie & de Fockert, 2005). When participants were required to complete both a search task, and a concurrent verbal task, capture to a distractor in the search task increased. In other words, when the need for working memory increased, people were more susceptible to attentional capture, potentially indicating a shared resource underlying both visual working memory and visual attentional control (Lavie & de Fockert, 2005). Given the evidence that the ability to resist distraction by salient visual objects may contain a great deal of between-person variability, including a measure of WMC as a factor in our models of attentional capture may provide a more accurate portrait of our effects. Critically, if the effects of a given task condition differ across people due to differences in WMC, there may be opposing effects present in the data that cancel each other out, preventing us from properly modeling the within-person effects. Therefore, WMC may help explain why certain people show capture under conditions in which others do not.

Cognitive Failures Questionnaire & Barratt Impulsiveness Scale

The Cognitive Failures Questionnaire is a self-reported measure of daily distractibility and absentmindedness (CFQ, Broadbent, Cooper, FitzGerald, & Parkes, 1982). Higher scores on the CFQ have been correlated with the inability to successfully inhibit distractor words presented above and below a target word (Tipper & Baylis, 1987), and with increased reaction times during a search task in which a distractor letter was presented peripherally (Forster & Lavie, 2007). Kanai et al. (2011), used a distractibility subscale of the CFQ (CFQ-D, Wallace, 2004; Wallace, Kass, & Stanny, 2002), and found that individuals with higher CFQ-D scores showed larger effects of attentional capture to a physically salient non-target, with longer reaction times in a search task. By including this measure, we can test whether or not RT cueing effects are positively correlated with CFQ or CFQ-D scores, suggesting that individuals with high self-reported levels of cognitive failures may also be more sensitive to attentional capture by salient but uninformative distractors. Additionally we can look at whether or not individual differences in the development of an attentional set are related to this self-report measure of daily distractibility.

The Barratt Impulsiveness Sale is a widely used self-reported measure of impulsivity, with a hypothesized factor structure which loads on three higher order factors of attentional impulsiveness, motor impulsiveness and non-planning impulsiveness (revised BIS-11, Patton, Stanford, & Barratt, 1995). Trait impulsivity is thought to reflect the degree to which people can control their behavior (Dickman & Meyer, 1988), and has been correlated with performance decrements in a value-driven attentional capture task (Anderson, Laurent, & Yantis, 2011), an attentional blink tasks (Ray Li, Chen, Lin, & Yang, 2005), and an involuntary spatial attention task (Landau, Elwan, Holtz, & Prinzmetal, 2012). People who reported higher levels of impulsivity showed larger validity effects in an involuntary cueing paradigm, with greater invalid-valid RT differences than those who reported lower levels of impulsiveness (Landau et al., 2012). Therefore, including a measure of impulsiveness may be critical as both a covariate and a factor in the present study of reflexive attentional capture. Specifically, it is reasonable to expect that individual differences in impulsiveness may account for differential effects of condition and task on attentional capture both in the aggregate as well as over time. In summary, including individual differences, both analytically as well as through specific measured variables will enrich our portrait of attentional capture along and provide potential explanations for differences observed between people.

CHAPTER 2: EXPERIMENT 1

CATCH TRIALS CATCH SPATIAL ATTENTION WHEN TARGET ABSENCE IS RELEVANT

The first goal of the study is to determine if top-down mediation of attentional capture can be disrupted by introducing alternative task demands without that go beyond changing the relationship between the target and distractor**.** Studies of contingent attentional capture have found that items trigger a reflexive orienting of spatial attention only when the cue stimuli are congruent with task-relevant features of the target stimuli (e.g. Eimer & Kiss, 2008; Folk & Remington, 1998; Folk et al., 1992). These results have been interpreted as demonstrating a top-down suppression of capture to salient items, potentially due to a particular search mode or strategy (Lamy et al., 2006; Leber & Egeth, 2006). Alternatively, it has been shown that characteristics of the distracting stimuli may cause the capture in a manner that is unrelated to top-down attentional control settings (Franconeri et al., 2005; Liao & Yeh, 2013; Schreij et al., 2008; Theeuwes, 2004).

While much of the support for goal-directed influences at both pre- and postattentive stages comes primarily from cueing paradigms (Eimer & Kiss, 2008; Folk & Remington, 1998; Folk et al., 1992; cf. Leber & Egeth, 2006), support for saliency-driven capture at the earliest stages of sensory processing typically comes from additional singleton and search paradigms (Theeuwes, 1991). The contradictory results and interpretations can, in part, be accounted for by the different role of time in these two paradigms. There are two ways in which the temporal task demands fundamentally differ in these two tasks. First, the array containing the distractor may also contain the target in the additional singleton paradigm but will <u>never</u> contain the target in the spatial cueing paradigm. For this reason, it is possible that participants adopt a strategy in which they prevent preattentive processing of all items in the distractor-containing array in the case of the latter experimental design, although this is not in line with the disengagement hypothesis (Theeuwes, 1991, 2010). Second, in additional singleton (i.e. search) paradigms, stimuli typically remain on screen until a response is made, whereas in cueing paradigms, stimuli duration is extremely brief (e.g. 50ms) and typically not dependent upon a response.

Folk and Remington (1998) interpreted the contradictory findings from cueing and search paradigms as evidence of two distinct forms of attentional capture. Specifically, they argue that capture in cueing paradigms results in spatial orienting to the cue, whereas capture in search paradigms constitutes a non-spatial filtering cost. However, studies since then have found evidence of <u>spatial</u> attentional capture to irrelevant distractors (Hickey et al., 2006; Theeuwes & Godijn, 2002) even under conditions in which participants had likely adopted a feature search mode (Schreij et al., 2008). Critically, in all of these cases of saliency-driven capture, which seem to contradict the contingent attentional capture hypothesis, the distracting item was presented <u>simultaneously</u> with a to-be identified target. In his disengagement hypothesis, Theeuwes (2010), accounts for these differences by positing that in all cases, attention is captured by a salient distractor, but when given enough time to disengage, such capture may no longer be present in response times. He dismisses ERP evidence that points to a lack of capture to non-congruent cues by arguing that the component used to indicate capture (N2pc) does not necessarily reflect capture alone, but rather capture along with higher order processing that results due to top-down set.

In a direct examination of the influence of time on attentional capture during search-like paradigms, differing temporal demands were found to impact attentional capture, while holding the target and distractor features constant (Kiss, Grubert, Petersen, & Eimer, 2012). Specifically, when search arrays remained on the screen until a response was made, researchers found ERP evidence of capture to, and processing of a salient distractors (N2pc), followed by an ERP index of suppression (the distractor positivity, Pd). However, when the arrays were on screen for a brief and fixed amount of time, only the ERP index of suppression was elicited. Despite the assertion by the authors that these results clearly support early top-down mediation, the results do not necessarily contradict a rapid disengagement hypothesis account as it is unclear if the Pd is an index of suppression or disengagement or both (Toffanin, de Jong, & Johnson, 2011), and many studies explicitly refer to the Pd as an index of disengagement (Sawaki & Luck, 2010).

ERP results have also differed depending on whether or not the distractor is presented simultaneously with the target (i.e. additional singleton paradigm) or is presented before or after (cueing paradigms). On the one hand, an N2pc was elicited by a salient but task-irrelevant distractor when simultaneously with the target in an additional singleton paradigm (Hickey et al., 2006). An N2pc to the target was found immediately after the component elicited to the cue, suggesting that participants were captured by the salient distractor but quickly disengaged and reoriented to the target in order to discriminate its orientation and respond. In contradiction to Hickey et al. (2006) salient but task-irrelevant have repeatedly not elicited the N2pc component when presented before the target in cueing paradigms (Ansorge et al., 2011; Eimer & Kiss, 2008; Lien et al., 2008). For example, in a color-cue / color-target experiment, with color match between the cue and target as the critical manipulation, Lien et al. (2008) found that the color matching cue elicited a robust N2pc similar in magnitude and latency to that of the target. These results were taken as evidence supporting contingent attentional capture, specifically that task-demands result in a feature-specific attentional set, and only items matching those in the set will capture attention reflexively. However, rather than capture being due to a setting specific to a given color, the mechanism for this capture could be the potential relevance of the array, which shares more in common with the target array than just the single color of the target. Indeed, in most cueing studies the cue array with the feature match cue contains the same number of items as the target array, occupying the same locations as the target array objects.

These results suggest the possibility of an alternative interpretation of contingent capture evidence. Specifically, instead of interpreting spatial capture as being the result of a match between the specific cue features and those belonging to a target set, it could be that when the cue display matches the target display (as is the case with congruent cue arrays that elicit contingent attentional capture), participants attend to the entire display, as it may be relevant. Once the array is attended to, capture to the salient distractor is automatic. For congruent cues, the cue-array typically contains a similar number of items as the target array with similar configurations (e.g. Eimer & Kiss, 2008). This interpretation of contingent attentional orienting may help reconcile the seemingly contradictory results of cueing and additional singleton paradigms, because in the latter, the array containing the distractor may also contain the target and is therefore always relevant.

To test this alternative interpretation of contingent attentional capture and simultaneously demonstrate conditions under which top-down settings are disrupted, we included an additional task which made the event containing the cue behaviorally relevant. Critically, although the cue event was behaviorally relevant, the physical properties and the spatial location of the cue were not. The design of the stimuli and procedure were based on an earlier study by Eimer and Kiss (2008) which demonstrated that a non-predictive, and therefore irrelevant, salient singleton cue only captured attention in a reflexive manner when its features (color) matched those of the target. When the cue array was a single red item surrounded by black distractors, and the target was similarly a red singleton among black distractors, a cueing effect was observed with faster RTs to targets appearing in the same spatial location as the cue, relative to those appearing in one of the three invalid target locations. Conversely, when a single onset white item followed the same cue stimuli, there was no evidence of capture to the cue. In experiment 1, we presented participants with similar stimuli and tasks, however, included an additional task that directed participants attentional to the cue array, but not necessarily to the location or features of the unique distractor within the array. If capture to the salient distractor cannot be suppressed when the event containing it is behaviorally relevant, then we would expect to find a cueing effect in this case, even if the target does not share critical features with the distractor. Additionally, the same cue-target pairing should not result in capture when the additional task goal is removed. If, however, contingent capture to distractors only occurs when their features match those contained within a target set, then we should find a validity effect only when the cue and target array both contain color singletons (1d).

Experiment 1a

In the first experiment we created a condition in which the entire cue array was behaviorally relevant as an event, but the specific features and the location of the color-singleton within the array were not. This was done within the traditional cueing paradigm framework by including a detection task for target-absent trials in addition to a discrimination task for target-present trials. Critically, the color-singleton cue never matched the features of the single onset target. If the attentional control settings underlying the contingent attentional capture effect are related to feature matches between objects, then no capture is expected. If, however, capture to a salient singleton is automatic when an entire event is (potentially) behavioral relevant, then the inclusion of these target-absent responses would result in capture to the spatial location of an irrelevant color-singleton cue.

Methods

Participants

Eight undergraduate students from the University of North Carolina at Chapel Hill served as participants after giving informed consent. For all experiments, all participants were right-handed, had normal or corrected-to-normal vision, had no history of neurological disorder or concussion and received course credit in exchange for their participation.

Materials and Procedure

The experimental sessions took place in an electrically shielded room with visual stimuli presented on a CRT monitor 75cm from the subject. The commercial software package, Presentation (Neurobehavioral Systems; San Francisco, CA), was used to present stimuli and record response times and accuracy levels.

Following an initial training block, in which participants became familiar with the task and with maintaining fixation throughout all trials, 8 experimental blocks, each consisting of 46 trials, were completed. A central fixation dot remained on the screen throughout the entire block, including when cue and target stimuli were on screen. Each trial sequence began with a fixation screen for 1000-1500ms, followed by a cue array for 50msec (Figure 3). The cue array consisting of six square outline boxes (each 1.3˚ x 1.3˚), five black and one red, each presented 5.2˚ from fixation at the 12, 2, 4, 6, 8, and 10 o'clock positions. The red singleton was presented in either the upper right or upper left visual field with equal likelihood, and did not predict the location of the subsequent target stimulus. On 70% of trials a target display appeared 150ms after the cue. The target, a single black rectangle (0.7˚ long) presented 5.2˚ from fixation, appeared in either the upper right or upper left visual field (i.e. same location as the two singleton cue locations) and remained on the screen for 50ms, before being replaced by the background fixation screen. The non-predictive cue resulted in two equally likely target conditions: valid (i.e. target appeared in the same location as the preceding cue), and invalid (i.e. target appeared in the location not occupied by the preceding cue), with 128 trials in each target-present condition when collapsing across visual field.

Participants were asked to indicate whether the target stimulus was oriented vertically or horizontally and were instructed to respond as quickly as possible without sacrificing accuracy. Within each block, the trial sequence was pseudo-randomized, such that a given trial type (e.g. right cue – right target) did not occur more than four times before a different trial type was presented (e.g. right cue – left target). This was done in an attempt to control for idiosyncratic strategies that may arise because of trial expectancies being formed due to longer sequences of a certain trials type. Trial sequence for the practice block and eight experimental blocks was consistent across participants and experiments (1a, 1b & 1d).

During 30% of all experimental trials (i.e. 112 trials per participant), the cue was not followed by a target display. These trials served as cue-only ("catch") trials, and required that participants respond by pressing a third ""target-absent" button. Catch trial responses were included in order to make the cue array event behaviorally relevant (i.e. participants had to know that a cue array had occurred in order to judge the lack of a target appearance). Critically, the *location* of the red singleton within the cue array was irrelevant to the target-absent response task.

Results & Discussion

For target-present trials, a significant effect of validity was found as participants responded significantly faster to valid targets (M = 543.27 ms, SD = 85.33 ms) as compared with invalid targets (M = 560.06 ms, SD = 79.37 ms; $t(7)$ = 2.87, p = 0.02, d = 1.05; Table 1, Figure 5). There were no significant effects on accuracy (Valid: M = 97.5%, SD = 1.7%; Invalid: M = 96.4%, SD = 3.4%; $t(7)$ = 1.20, p = 0.27).

Although no specific hypothesis was made about the target-absent RTs, it is worth noting that catch trial RTs fell in between valid and invalid trial RTs (M = 550.71 ms, SD = 68.78 ms), and were not significantly different from either target-present condition (Catch vs. Valid: $t(7)$ = 0.33, p = 0.75; Catch vs. Invalid: $t(7)$ = 0.43, i = 0.68). Additionally, accuracy for these trials was as high as that for target-present trials (i = 97.0%, SD = 1.8%). These results indicate that performance for the target-absent detection task was fast and accurate, and participants were able to judge when a target should have appeared, but did not.

One of the goals of the study is to investigate whether or not attentional capture to the cue was present throughout the experiment or rather developed as a result of experience with the stimuli (i.e. time). To answer this question, reaction times for each condition were averaged within blocks and compared using t-tests, Bonferonni corrected for multiple comparisons (Cosman & Vecera, 2014). Blocks 5, 6 and 7 were all significant at $p<0.05$ but none survived the Bonfernni correction criteria of $0.05/8 = .006$. To increase our power to detect differences, RTs for each condition were averaged within every two blocks, resulting in only 4 time points for comparison (Figure 6). T-tests reveal a significant difference between valid and invalid RTs only at combined blocks 5 & 6 ($t(7) = 4.10$, $p = 0.005$) and blocks 7 & 8 ($t(7) = 4.58$, $p = 003$), indicating that capture only occurred in second half of the experiment.

The results indicated that attention was captured by the singleton cue, resulting in faster responses to targets appearing at the same vs. different location. These results stand in contrast to those indicating that a singleton cue will only capture attention when its features overlap in some way with those of the target (Eimer & Kiss, 2008; Folk et al., 1992). In the present experiment, the inclusion of the catch trials and the required target-absent detection response appears to have induced a contingency not typically found when the cue and target features are incongruent. Additionally, capture was only present in the second half of the experiment, potentially indicating that capture was induced only after a sufficient amount of experience with the task and stimuli. These results support the hypothesis that capture to the location of a salient singleton is automatic when the entire array in which it occurs is behaviorally relevant and must be attended to, even when the specific features of the array are irrelevant. Moreover, the evidence refutes claims that saliency-driven capture does not occur unless the distractor is defined by a feature dimension contained within an attentional set (Anderson &

Folk, 2010; Töllner, Müller, & Zehetleitner, 2012).

It is not clear why capture, evident when averaging across all trials, seems to only have emerged in the second half of blocks. One interpretation is that capture occurred throughout the experiment (Theeuwes, 2010), and disengagement became more difficult as participants made more and more responses to the cue-only (i.e. target absent) condition. Alternatively, participants may have adopted a strategy of attending to the red singleton within the cue array in order to make their target-absent responses after some experience with the task, as has been found with search strategies in tasks with changing search tasks (Harris, Remington, & Becker, 2013). Finally, it could be the case that participants were not captured to the cue until the point at which such capture was evident in the behavior. Given that most cueing studies examining attentional capture to irrelevant singletons average across all trials, we do not know if such results are typical. It will therefore be useful to similarly analyze capture across time under conditions in which we expect to see contingent attentional capture (Folk et al., 1992) to determine if the present experiment's "learned" capture is specific to the present event-relevance capture, or is generalizable to other cases of attentional capture. Additionally, something idiosyncratic about our set-up or stimuli could have caused the overall validity effect. Experiments 1b, 1c and 1d were conducted to address these possibilities.

Experiment 1b

Experiment 1b was conducted to ensure that the results of the experiment 1a were not due to peculiarities of the stimuli, apparatus or other aspects of the design, other than the inclusion of responses to catch trials. To test this alternative account, we tested a new group of participants under identical conditions, but no longer required a target-absent response. If the capture by the cue, as evidenced by faster valid vs. invalid target RTs, in experiment 1a was due solely to the inclusion of catch trial responses, we should not find any validity effect now that these responses are not required.

If, however, the validity effect was an artifact of something unique to our specific experimental parameters, we might still find an effect of cue-target spatial congruency (i.e. a validity effect) not typically found in experiments of this kind (Ansorge et al., 2011; Eimer & Kiss, 2008; Folk & Remington, 1998; Folk et al., 1992; Leber & Egeth, 2006).

Methods

Participants

A new group of nine undergraduate students from the University of North Carolina at Chapel Hill served as participants after giving informed consent. One participant was excluded due excessive errors, resulting in a sample of eight individual.

Materials and Procedure

Experiment 1b was identical in materials and procedure to experiment 1a (Figure 3), except that no response was required to catch trials. Catch trials still comprised 30% of all experimental trials and participants were advised that there would be cue-only trials mixed in with target trials, but were instructed to only discriminate and respond to the orientation of the target.

Results & Discussion

As predicted, when the catch trial response was no longer required, we found no evidence of capture to the color-singleton. The results indicate no difference between valid and invalid RTs (Valid: M = 534.31 ms, SD = 73.98 ms; Invalid: M = 530.91 ms, SD = 72.13 ms; $t(7) = 0.73$, $p = 0.49$; Figure 7). Additionally, there were no significant effects on accuracy (Valid: M = 97.2%, SD = 1.7%; Invalid: M = 96.9%, SD = 1.7%; $t(7) = 0.57$, $p = 0.58$). As was done in experiment 1a, capture was assessed across blocks by averaging RTs for each condition across sets of two blocks (to increase power).

T-tests for each combined block set indicate a significant difference only for combined blocks 1 & 2 ($t(7) = 3.81, p = 0.007$). However, the significant difference was due to faster RTs for invalid relative to valid trials, which does not indicate capture but suggests an anti-cueing effect in which participants may have been actively shifting to the location not occupied by the cue. It is not clear why participants would have adopted such a strategy, and more importantly, there is no cueing effect in either direction in the aggregate.

Experiment 1b was conducted in order to establish that the validity effect observed in experiment 1a was due to the inclusion of catch trial target-absent responses, and not to a peculiarity of our stimuli, design, set-up, etc. When the same experiment was conducted, using identical timing, stimuli, and apparatus, but when no catch response was required, we no longer find evidence of spatial capture to the irrelevant color-singleton. These results replicate the findings of multiple studies demonstrating contingent attentional capture, in which, only stimuli that match target features held in an attentional set capture attention (Ansorge et al., 2011; Eimer & Kiss, 2008; Folk & Remington, 1998; Folk et al., 1992; Leber & Egeth, 2006). Although these results provide compelling evidence that capture to the cue is exclusively due to catch trial results, our conclusions up to this point were based on between subject comparisons, and could therefore be an artifact of a particular sample. Experiment 1c was conducted to address this concern.

Experiment 1c

In a third experiment, we tested whether the between-subject results found in experiments 1a and 1b would be replicated in a within-subjects experiment. We presented individuals with the same trial sequence and proportion of target-present/target-absent trials in all blocks, but only required catch trial responses in either the first or second half of the experiment. If responses to catch trials are critical in order to observe spatial capture to the color-singleton, we should find a validity effect (valid

RT faster than invalid RT) only for the blocks in which these responses were made.

Methods

Participants

A new group of fourteen undergraduate students from the University of North Carolina at Chapel Hill served as participants after giving informed consent. One individual was falling asleep during the experiment and was excluded, resulting in a total of thirteen participants included in the analysis. A larger sample size was included in this experiment (as compared with the first two) due to the increased complexity of the design, which now includes a 2x2 interaction.

Materials and Procedure

All materials and procedures were identical to those used in experiment 1a (and 1b) with the following exceptions. Participants were presented with 12 full blocks, with the first and seventh treated as practice blocks for each of the two conditions. The cue-location was still not predictive of the target, with an equal number of valid-location targets and invalid-location targets in each block (80 of each condition, for each task). Catch trials still comprised 30% of trials within and across all blocks. Participants were instructed to respond to the catch trials in either the first or second half of the experiment (counter-balanced across participants) and told not to respond during the other half of blocks. The within-subject manipulation allowed us to look at the main effect of target-type (valid vs. invalid) as well as any interaction with condition (catch response vs. no catch response) on both RT and accuracy.

Results & Discussion

The within-subject results replicated the pattern found between subjects in the first two experiments. RTs and accuracy were each submitted to a 2 (Validity: valid, invalid) x 2 (Task: Catch, No_Catch) repeated measures ANOVA. Examining the effects on RT, we found a significant main effect of Validity [$F(1,12) = 30.88$, $p < 0.001$, $\eta^2 = 0.72$] with faster responses to valid versus invalid targets across both conditions; and a significant main effect of Task [$F(1,12) = 22.87$, $p < 0.001$, $\eta^2 = 0.66$], with faster responses during the no catch trial response blocks. Importantly, we found a significant interaction between target type and condition [$F(1,12) = 9.11$, $p = 0.011$, $\eta^2 = 0.43$]. As revealed by planned post-hoc comparisons, the validity effect was present for responses made in the catch response blocks [Valid: $M = 585.45$ ms, $SD = 66.81$ ms; Invalid: $M = 622.03$ ms, $SD = 82.00$ ms; $t(12) = 4.58$, $p = 0.001$, $d = 1.27$; Figure 8] and was not present during the no catch trial response blocks [Valid: $M = 532.46$ ms, $SD = 82.41$ ms; Invalid: $M = 536.63$ ms, $SD = 73.06$ ms; $t(12) = 0.92$, $p = 0.38$; Figure 9].

When we include the order in which participants performed the two tasks as a between subject factor (i.e. Catch_First vs. No_Catch_First) we find a significant three-way interaction between Task, Validity and Order [$F(1,12) = 4.86$, $p = 0.05$, $\eta^2 = 0.43$]. Specifically, the interaction between task and validity was present for both groups, but was larger when participants saw No_Catch trial blocks first, and there may have been some carryover of the cueing effect into the No_Catch response blocks when participants saw catch response trial blocks first.

We found no significant effects on accuracy for Task [$F(1,12) = 0.18$, $p = 0.68$], Validity [$F(1,12) = 0.77$, $p = 0.40$], nor was there an interaction [$F(1,12) = 0.24$, $p = 0.64$].

Looking at the effect of task on capture over time, we found significant capture during the catch trial task in block 2 [$t(12) = 4.50$, $p = 0.001$] and block 5 [$t(12) = 3.46$, $p = 0.005$], and no capture in when catch trials did not require a response. However, examining the effect of capture across time is not as straight forward in this experiment as it was in experiments 1a and 1b for two reasons. First, there are fewer blocks per task in which to see change over time, and with five task blocks, it isn't clear whether we should test valid versus invalid at each of the five blocks or collapse across blocks 1&2 and then 3, 4 & 5. Second, the order of the task presentation (Catch first vs. No_Catch first) may have interacted with or confounded the effect of stimulus experience on capture for each task. For example, although we seem to find capture for Catch blocks beginning in blocks 1 and 2, we must somehow account for the fact that for half of the sample, these occurred after seeing the cue and performing the target discrimination task for 6 previous blocks. For these reasons, the question of how time or exposure to the stimuli may have interacted with condition to impact capture will be addressed by experiments 2 and 3, both of which were designed more explicitly to answer these questions.

Overall, the pattern of results replicates those found when comparing the reaction time effects between subjects in the first two experiments. Participants responded faster when targets were presented at the same location as the preceding color-singleton cue (i.e. validly-cued targets) as compared with targets presented at the invalidly-cued location, but only during blocks in which the target-absent response was required for catch trials. These results support our hypothesis that the inclusion of the catch trial responses results in spatial attentional capture by the color-singleton cue, despite the fact that these responses do not require the use of the cue's location, but only the awareness that a cue event has occurred in order to judge when a target's presence would have been expected.

Experiment 1d

Experiment 1d was conducted to test whether we would find the classic contingent attentional capture effect (e.g. Eimer & Kiss, 2008; Folk et al., 1992) using the same cue array as was used in experiments 1a - 1c. In other words, it will test whether we find evidence of spatial attentional capture to an irrelevant color-singleton when the features of the target match those of the target singleton. Some but not all previous studies have included catch trials, although none required the target-absent response made by participants in experiments 1a and 1c of the present study. This experiment will also allow us to compare the magnitude of the attentional capture found when the cue and target features are congruent, with that observed when the features are not congruent, but capture occurred because of the cue array's behavioral relevance. Additionally, if capture is found when the cue and target features match and no response is required to catch trials, we can rule out the possibility that the lack of capture found in experiment 1b was the result of including trials that did not require an overt response. Based on previous studies of contingent capture (Eimer & Kiss, 2008, 2008; Hopfinger & Ries, 2005)(Folk et al, 1992; Hopfinger & Ries, 2005; Eimer & Kiss, 2008), we expected the cue to capture spatial attention without requiring catch trial responses since the target features matched those of the cue.

Methods

Participants

A new group of nine undergraduate students from the University of North Carolina at Chapel Hill served as participants after giving informed consent. One participant was excluded due excessive errors, resulting in a sample of eight individual.

Materials and Procedure

Experiment 1d was identical to the experiment 1a with the exception of the target stimulus. The target array consisted of 6 rectangles (all 0.7° long), presented in the same locations as the preceding boxes in the cue array. The target was a red rectangle, oriented either vertically or horizontally, while all 5 non-target distractors black and were oriented at non-orthogonal rotations (Figure 4). The discrimination task remained the same: indicate the orientation of the target as quickly and as accurately as possible. Once again, the color-singleton cue did not predict the location of the color-singleton target as targets were presented at the same location as the cue on half of target-present trials. Critically, although the cue array contained 6 boxes, and the target array contained 6 rectangles, the target only appeared in either the upper right or upper left position (as was the case in experiments

1a - 1c). Again, 30% of trials were catch trials; however, no target-absent response was required.

Results & Discussion

Replicating previous studies of contingent attentional capture (e.g. Eimer & Kiss, 2008), we found a significant effect of validity with faster responses to valid as compared with targets (Valid: M = 593.38 ms, SD = 72.43 ms; Invalid: M = 612.00 ms, SD = 72.59 ms; $t(7) = 3.27$, i = 0.01, $d = 1.15$; Figure 9). There were no significant effects on accuracy (Valid: M = 96.9%, SD = 3.1%; Invalid: M = 96.1%, SD = 2.6%; $t(7) = 0.67$, $p = 0.52$). T-tests for each combined block set indicate that the difference between valid and invalid RT reaches significance at the Bonferroni corrected $p<0.0125$ level only in combined blocks 7 & 8 [($t(7) = 3.68$, $p = 0.008$; Figure 10] However, both combined blocks 3 & 4 [($t(7) = 3.26$, $p = 0.014$], and blocks 5 & 6 [($t(7) = 2.92$, $p = 0.023$] are significant at $p<0.05$, suggesting that capture may begin as early as block 2 or 3 in this experiment. This appears to occur sooner than it did in experiment 1a, however, such a comparison must be made cautiously, given the different samples. To directly examine the question of whether or not capture develops at the same rate in these two tasks we should use a within-subject design, and an analysis that includes more time points (see experiment 2).

The results of experiment 1d indicate that attention was captured by the singleton cue for a target with features matching those of the non-predictive cue, when catch trial responses were not required and replicate those found in previous studies of contingent attentional capture (e.g. Eimer & Kiss, 2008; Folk & Remington, 1998; Folk et al., 1992). As suggested by the results of experiments 1a and 1c, attention can be captured to an irrelevant but salient singleton if the array in which the singleton appears may be behaviorally relevant, as was the case when participants had to use the cue's presentation to prepare to make a target-absent response. It is possible that in this final experiment, the cue array was also potentially relevant because of its high degree of overlap with the features in the target array, either because of a strategic choice by participants to attend to all multi item arrays or because of confusion about whether or not the cue array was actually target array. Previous interpretations of the contingent cueing effect interpret the selective capture by target feature matching cues as a reflection of an attentional set for features (e.g. Folk et al., 1992). The present experiment does not rule out this interpretation, although the results of experiments 1a and 1c suggest that it is not the only type of attentional control setting.

Comparing results across experiments

In experiment 1, attention was captured to an irrelevant but salient distractor when the color of the singleton distractor matched the color of the to-be-discriminated singleton target (experiment 1d) and also when the distractor *did not* match the target features, but instead was embedded in a temporally relevant event (experiments 1a & 1c). Only the former type of capture has been previously found (Eimer & Kiss, 2008; Folk et al., 1992; Gibson & Kelsey, 1998). The capture observed in the latter case cannot be due to peculiarities of the stimuli used as no capture was found in experiment 1b, in which no response was required for catch trials, rendering the cue array no longer behaviorally relevant. To further investigate this novel type of capture, we can also compare the average cueing effect in each experiment (i.e. Invalid RT – Valid RT). It could be the case that although attention was captured by the cue due to event relevance in the Catch task (1a, 1c), the strength of the capture, or more specifically, hold of attention, was not as great as that found when the features of the cue matched those held in a hypothesized attentional setting containing target feature information.

To answer this question, RTs from experiments 1a, 1b and 1d were submitted to a mixed effects model with validity (valid, invalid) as a within-subjects factor and experiment (1a, 1b, 1d) as a between-subject fixed effects factor. We found a main effect of validity, $F(1,21) = 11.61$, $p = 0.003$, and more importantly, a significant validity by experiment interaction $F(2,21) = 5.07$, $p = 0.016$. The interaction reflects the fact that there was a significant InvalidRT – ValidRT difference found for experiments 1a and 1d, but not 1b. Invalid - Valid RT difference scores were submitted to a univariate ANOVA and revealed a significant effect of experiment, $F(2,21) = 5.86$, $p = 0.010$. Post-hoc comparison's using Tukey's HSD indicated that the cueing effects in both experiments 1a and 1d were significantly higher than that in 1b (M_{1A} = 24.71ms, M_{1B} = -2.01ms, M_{1D} = 22.13ms) but that there was no difference between the cueing effects in 1a and 1d. These results suggest that the effects found in both the classic contingency case (experiment 1d) and in our novel event-relevance condition (experiment 1a) are equal at the level of behavior. However, these results were found across relatively small samples and represent average RTs over the entire experiment. By looking at the effect of capture on RT over time, we can determine if these processes are in fact the same.

General Discussion

The purpose of these experiments was to determine if a salient but task-irrelevant distractor would capture attention when it was presented in a behaviorally relevant array. Using cueing paradigms, a large body of research investigating top-down mediation of capture in cueing paradigms has found that salient distractors only cause behavioral evidence of attentional capture when they share critical features with the target (e.g. Ansorge et al., 2011; Eimer & Kiss, 2008; Folk & Remington, 1998; Folk et al., 1992). In experiment 1, we made the visual array containing the distractor behaviorally relevant while keeping the features and location of the distractor task-irrelevant, to test whether doing so would result in spatial capture to the distractor. The results of experiments 1a and 1c suggest that it does, with behavioral evidence that attention was captured to the cue, but only when the cue-array was behaviorally relevant. When it was not relevant, there was no evidence of attentional capture to the cue with identical cue-target pairs.

There are several possible interpretations for the pattern of results found in experiment 1.

First, we could conclude that in experiments 1b, 1c (No_Catch blocks), and 1d, top-down set mediated attentional capture, possibly through a mechanism of suppression, but this suppression was disabled when attention was directed to to the visual event or array containing the salient distractor. The breakdown of top-down suppression could have been the result of an increased attentional or working memory load that occurred as a result of the additional task demands in 1a and 1c (Fukuda & Vogel, 2009; Lavie & de Fockert, 2005). Alternatively, participants may have had to adopt a different strategy for the target-absent response task relative to the target discrimination task, resulting in a break-down of top-down settings (Lien et al., 2014)

Another interpretation of the results is that some degree of saliency-driven capture to the cue occurred throughout all experiments, but was only evident in the behavior when participants did not rapidly disengage from the cue's location either due to features of the cue (1d) or to its temporal relevance (1a, 1c). Such an interpretation is supported by ERP evidence of cueing effects by non-congruent cues (Fellrath et al., 2014; Hopfinger & Ries, 2005), and processing of irrelevant distractors in a search paradigm (Hickey et al., 2006).

When looking at the validity effect within each experiment across time, the results suggested, surprisingly, that capture wasn't present at the start of each experiment, but rather, took time to develop across blocks (1a, 1d). However, this was not the case for the within-subject version (1c); but the effects of capture across blocks in the within-subject design may have been confounded by overall stimuli and response experience due to the design. Additionally, when testing validity across blocks in experiments 1a, 1b and 1d, we averaged across sets of 2 blocks as is often done to reduce noise (Cosman & Vecera, 2014). However, this may have also reduced our ability to detect when exactly capture appeared (or disappeared). Finally, we are unable to test or compare model-implied rates of change across experiments in the present experiment. Such a comparison may help us answer questions about the underlying mechanisms supporting the two types of capture. Experiment 2 was conducted to answer these outstanding questions.

CHAPTER 3: EXPERIMENT 2

THE MECHANISMS AND TIME COURSE OF ATTENTIONAL CAPTURE

The results of experiments 1a-1d indicate that attention can be reflexively captured to an irrelevant, yet salient distractor that does not share critical features with the target, but only when the array containing the distractor was behaviorally relevant. These results are in-line with post-attentive models of top-down control that predict initial capture to the most salient stimulus in the visual environment, which is either followed by further processing for relevant information, or suppression and disengagement for irrelevant stimuli (Theeuwes, 2010; Zehetleitner et al., 2013). Additionally, a coarse examination of capture over time, revealed a changes in capture over the course of the experiment. Specifically, when binning reaction times into two-block chunks in experiments 1a and 1d, attentional capture was not found until the final half of the experiment(s). These findings are contrary to predictions of the contingent capture hypothesis in which an attentional set is driven by task instructions and participant goals which are presumably present at the start of the experiment. Instead, the pattern indicates that experience with the stimuli plays a role in capture. However, these mean effects cannot tell us whether capture is weaker throughout the experiment or is roughly equivalent at first and changes as a function of experience with both the stimuli and task. If the former is the case, it would suggest different mechanisms underlying attentional capture for the two target types (congruent and incongruent). If the latter, it could be the case that capture is driven by different mechanisms, or that capture is initially caused by similar saliency-driven factors and additional mechanisms, such as top-down factors which boost capture and active suppression which diminish it come online at some point during the experiment (Sawaki, Geng, & Luck, 2012).

In most studies of attentional capture, behavior is averaged across many trials, and only the average of each condition, for each person is submitted to the repeated-measures ANOVA for analysis. They do not typically include any information about within-subject variability, or changes in the effect across time that may arise due to experience with the stimuli and tasks (cf. Fukuda & Vogel, 2009, 2011; Jaeggi, Buschkuehl, Shah, & Jonides, 2014). Of course, most experimental aims do not include understanding the effects across time or within individuals, so the analyses not necessarily inappropriate. Even in studies that do look at the effects of time or experience, researchers tend to either take averages of conditions to examine trial-by-trial effects (e.g. number of repetitions, Lamy et al., 2006), or take means of a given block or experimental session (Awh et al., 2012; Cosman & Vecera, 2014; Kim & Cave, 1999), resulting in a loss of information and inability to compare rates of change across conditions.

The goals of this experiment were to 1) use a novel analysis to test if attentional capture changes as a function of experience with the stimuli (i.e. time), 2) to compare hypothesized changes in capture over time across tasks to detect different mechanisms driving seemingly similar behavioral effects, and 3) test how individual differences in working memory capacity, self-reported daily distractibility, and self-reported impulsivity relate to our task measures of both attentional capture. All of these goals ask why and how capture occurs in these tasks, and what role attentional control settings play in both capture by, and active suppression of, salient stimuli.

To directly test and compare change across time in the present experiment, RTs were analyzed in a series of multilevel models that included time as a factor (i.e. experience with or exposure to the task and stimuli). By using a multilevel model, we were also able to test whether any changes in RT over time varied across different people, reflecting individual differences. Although multilevel models are prevalent in psychological research in which nesting and/or repeated measures dictate their use, such as developmental psychology (Smokowski et al., 2014) and psycholinguistics (Baayen et al., 2008), their use remains relatively rare in most other areas of cognitive psychology. For most cognitive studies using fully balanced within-subject designs, traditional repeated measures ANOVAs are appropriate, however, they limit our ability to test for effects over time, random effect in rates of change, and the inclusion of alternative error structures.

The third goal of the experiment is to determine if individual differences cognitive traits, including working memory capacity, distractibility and impulsiveness predict the effects of task, condition, and time on attentional capture. It is possible that the that no-target present response required in the Catch condition taxes working memory and increases conceptual attentional load, making people more susceptible to attentional capture. Given that people may be differentially susceptible to manipulations of load, depending on the WMC, it may be critical to control for these differences (Fukuda & Vogel, 2009; Kane et al., 2001; Lavie & de Fockert, 2005). Therefore, by including a measure of working memory capacity in our models we can test whether WMC predicts capture overall, or whether it interacts with task, potentially only predicting capture when working memory may have been more involved in the task. Additionally, we measured and tested whether individual differences in impulsiveness and distractibility may account for differential effects of condition and task on attentional capture both in the aggregate as well as over time, as both have been associated with attentional control (Landau et al., 2012; Tipper & Baylis, 1987).

The primary goal of this experiment was to explore attentional capture over time, and specifically the validity effect as a function of cue exposure. Because of concerns over carryover effects, specifically in regards to contamination of a time-course reflecting exposure to the distracting stimuli, a between-subject design was used. Therefore the experiment was split by task into two experiments (2a and 2b, Table 3).

Methods

Participants

Participants were recruited for experiments 2a and 2b from the pool of undergraduate research volunteers and given one hour of class credit for participation in the study. All participants were right handed, with 20/20 or corrected-to-20/20 vision, had no history of head injury or ADHD, and were not taking any psychotropic medications (e.g. antidepressants). For experiment 2a, thirty-four students were recruited and four participants were removed from the final sample due to low accuracy (more than 3 SD below the mean), extreme drowsiness (e.g. falling asleep during the task), and age (participant was 48 years old, while all others were 17-21). The final sample for 2a consisted of thirty undergraduate students (19 female, average age = 18.76). For experiment 2b, thirty-three students were recruited and two were removed from the final sample due to low accuracy (more than 3 SD below the mean) and extreme drowsiness (e.g. falling asleep during the task). The final sample for 2b consisted of thirty-one undergraduate students (15 female, average age = 18.2).

Stimuli & Procedure

The attention tasks in experiment 2a and 2b followed the design of experiment 1a (Catch) and 1d, respectively, with identical stimuli and procedures except for the following changes. Participants completed fewer blocks (6 rather than 8) of the task, however, each block had 68 trials (versus 46 per block in experiment 1) resulting in a total of 144 validly-cued, 144 invalidly-cued and 120 catch (no-target) trials. Following a shortened block which served as practice, participants completed sets of two blocks, with timed two-minute breaks following blocks 2 and 4. This was done to maintain consistency across subjects and to facilitate trial-by-trial modeling. Other than these changes, the task stimuli and responses were the same as those in experiments 1a and 1d (See Figure 11).

The commercial software package, Presentation (Neurobehavioral Systems; San Francisco, CA), was used to present stimuli and record response times and accuracy levels. Participants were instructed to respond as quickly as possible without sacrificing accuracy. Within each block, the trial sequence was semi-randomized such that a given trial type (e.g. right cue — right target) did not occur more than four times before a different trial type is presented (e.g. right cue – left target). This was done to ensure that unintentional probabilities did not arise, leading to different strategies across participants (e.g. probability of an invalidly-cued target after three or more validly-cued targets is higher than after only one validly-cued trial).

Following the six task blocks, participants were given the two surveys to complete: the Cognitive Failures Questionnaire (CFQ, Broadbent et al., 1982) and the Barratt Impulsiveness Scale (BIS-11, Patton et al., 1995). Lastly participants were given two tasks to assess their working memory span: Operations Span and Symmetry Span (Oswald, McAbee, Redick, & Hambrick, 2014). One participant in the final sample of experiment 2a was unable to complete the Symmetry Span task due to time constraints. The order of events was consistent across all participants (i.e. task, surveys, WM tasks). In particular, we did not want to ask people about attention and then conduct an experiment measuring attention in case it biased performance.

Cognitive Failures Questionnaire & Barratt Impulsiveness Scale

All participants were given two short self-report measures, the CFQ and BIS-11. The Cognitive Failures Questionnaire (CFQ, Broadbent et al., 1982) a self-reported measure of everyday absentmindedness and distractibility (e.g., memory lapses and spatial orientation difficulties), consisting of a sum-score of 25 questions to be answered on a 5 point Likert scale (i.e., 0 = never, 4 = always), with higher scores indicated more self-reported cognitive failures (included as Appendix A). The Barratt Impulsiveness Sale is a widely used self-reported measure of impulsiveness, with a hypothesized factor structure which loads on three higher order factors of attentional impulsiveness, motor impulsiveness and nonplanning impulsiveness (BIS-11, Patton et al., 1995). It consists of 30 items to be answered on a 4 point scale from (i.e., 1 = never, 4 = always), which are summed such that higher scores indicating more impulsiveness. Eleven out of 30 of the items are reverse scored (Appendix B).

Working Memory Tasks

After completing the full cueing task and surveys, participants completed two automated complex span tasks to measure working memory capacity: Operation Span and Symmetry Span. Stimuli were presented using the E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA). We used shortened versions of these tasks developed by Oswald et al (2014). The tasks are known as *complex* span tasks because they require participants to remember a list of either letters or spatial locations presented sequentially (storage component), while performing a task (processing component. At the beginning of each task, participants are given two trials of each component separately. They first practice the storage component by observing a sequence of digits or spatial locations (both are list length of two) and are then prompted with a matrix of letters, or a matrix of squares, and are asked to recall, in order, the sequence of letters or locations that they saw. They then practice the processing component. For the processing component of the operation span task, participants view simple arithmetic problems and are asked to judge if the answer given is true or false. In the symmetry span task, participants are instructed to indicate whether or not an image is symmetric (yes/no).

A full trial consists of alternative presentations of the storage and processing components, after which participants are prompted to recall the list or locations and are then given feedback both on their memory performance as well as their distractor task performance. In the operation span task, participants see a total of 6 trials with two each of list lengths 4, 5 and 6, presented in random order, resulting in a maximum possible score of 30. The symmetry span task is similar with a total of 6 trials with two each of list lengths 2, 3 and 4 presented in random order, resulting in a maximum possible score of 24. For each task, both an absolute and a partial score are generated. Following the authors suggestions, we used the partial scores, which reflect the total number of items correctly remembered, in the correct order, even for trials in which errors were made (Oswald et al., 2014).

Results

Descriptive statistics and correlations

The means and standard deviations for all variables in both experiments 2a and 2b can be found in Table 2. Critically, average scores on both the measures of individual differences (ie. span tasks and surveys) were not different across the two samples.

In addition to looking at the variables separately, we examined the pattern of relationships among the variables both within and across the two tasks (2a and 2b, Table 3) in advance of using them in the general linear models below. There were several interesting relationships among the variables in the experiment 2a sample. There was a significant relationship between self-reported distractibility and working memory in the experiment 2a sample. There was a significant moderate negative correlation between CFQ scores and partial sum scores on both span tasks (OSpan: $r(30)=-4.21$, $p=0.021$; SSpan: $r(29)=-0.418$, $p=0.024$), indicating that people who are report higher levels of distractibility tend to have lower working memory capacities. We also found that people who had higher levels of self-reported distractibility (CFQ) also had higher levels of self-reported Impulsiveness (BIS; $r(30)= 0.544$, $p=0.002$). These relationships were not found in experiment 2b; however, this does not reflect an overall difference in scores on the scales as means did not differ across the samples (Table 2).

There was also a significant relationship between reaction time and accuracy, again, only in the experiment 2a sample. Specifically, a set of significant negative correlations indicate that on average, participants with faster reaction times were also more accurate (Invalid RT with Invalid ACC $r(30)=-.483$, $p=.007$ and with $r(30)=-.409$, $p=.025$; Valid RT with Valid ACC $r(30)=-.418$, $p=.021$ and with Invalid ACC $r(30)=-.468$, $p=.009$). Again, these relationships were not observed in the experiment 2b sample.

Analysis of target response times experiment 2a

Reaction times for correct trials only were included in the analyses. Additionally, although responses to catch trials were recorded, they were not included in the analysis as they do not reflect whether attention was spatially captured to the location of the pop-out cue. Incorrect manual responses and reaction times faster than 150ms or slower than 1450ms (at which point the following trial began) were scored as errors.

Replicating the results of experiments 1a and 1c, there was a significant effect of validity on reaction time [$t(29)=4.08$, $p<0.001$] reflecting that people responded, on average, 12.6 ms faster to a validly-cued target (Table 2, Figure 12). These results once again demonstrate a novel form of attentional capture to an incongruent salient stimulus that does not match top-down goals challenging the argument that top-down goals mediate bottom-up capture due to attentional control settings for features (Eimer & Kiss, 2008; Folk & Anderson, 2010; Folk et al., 1992). The was no evidence of a significant effect of validity on accuracy [$t(29)=0.38$, $p=0.145$; Table 2]. Although we did not find an effect of validity on accuracy, due to the significant relationships between RT and accuracy (as reported in previous section), an analysis of RT controlling for accuracy was conducted. RTs were submitted to a repeated-measures ANOVA with validity (valid, invalid) as a within-subject factor and accuracy as a between-subject covariate. To account for overall performance as well as condition-specific accuracy, each participant's mean accuracy (for target-present conditions) along with their average accuracy difference (i.e. valid-invalid accuracy) were first mean-centered and then entered into the model as covariates. The significant main effect of validity remained significant [$F(1,27)=15.81$, $p<0.001$], and results also indicated a significant between subject effect of mean accuracy [$F(1,27)=7.57$, $p=0.010$], but no effect of accuracy difference [$F(1,27)=0.17$, $p=0.69$], and no interactions with validity.

A final rmANOVA on RT was run with all other mean-centered covariates included (BIS, CFQ, age, sex, OSpan, and SSpan). There were no between-subject effects, nor any interactions with validity other than the between-subject effect found in the previous model of mean accuracy.

Analysis of target response times experiment 2b

As expected, and in line with the results of experiment 1d, there was a significant effect of validity on reaction time $t(30)=8.00$, $p<0.001$ reflecting that on average, people responded 26.15 ms faster to a validly-cued target (Table 2, Figure 12). There was also a significant effect of validity on accuracy $t(30)=2.93$, $p=0.006$, indicating that people were, on average 1.6% more accurate when responding to validly-cued rather than invalidly-cued targets (Table 2). The validity effect on reaction time remained significant in a model which included both mean accuracy and average accuracy difference (invalid-valid) as between-subject covariates [$F(1,28)=61.41$, $p<0.001$]. Unlike in experiment 2a, there was no evidence of a between subject effect of mean accuracy [$F(1,28)=1.42$, $p=0.244$], but there was a trending effect of accuracy difference [$F(1,28)=3.56$, $p=0.07$], and again, no interactions with validity.

A final rmANOVA on RT was run with all other mean-centered covariates included (BIS, CFQ, age, sex, OSpan, and SSpan). There were no between-subject effects, nor any interactions with validity, unsurprising given the lack of any relationships observed among the variables.

Comparison of target RTs: 2a vs 2b

Reaction times for both experiments 2a and 2b were submitted to a mixed ANOVA, with validity as a within-subject factor, task as a between-subject factor and each person's average accuracy as a covariate. The results indicate a significant main effect of validity [$F(1,58)=75.53$, $p<0.001$] suggesting that on average, people responded 19.39ms faster to validly-cued targets than invalidly-cued targets (Figure 12). There was also a significant between-person effect of mean accuracy [F (1, 58)=4.00, p=0.05], suggesting that reaction times differed as a function of average accuracy (likely due to the significant relationship in the 2a sample suggesting that people who are more accurate also respond more quickly). Importantly, mean accuracy did not interact with validity [$F(1,58) = 0.642$, p=0.43], indicating that the validity effect did not differ depending on people's level of accuracy. Although we did not find a significant between-subject effect of task [F (1, 58) = 0.61, p=0.44; Figure 12], results indicated a significant validity by task interaction [$F(1,59) = 9.15$, p=0.004], reflecting the fact that the validity effect was significantly larger for participants in the color target task as compared with the catch response task (Figure 12). This result contradicts the results comparing the validity effect found in experiments 1a and 1d, in which the magnitude of the effect was equivalent, confirming that caution should be made when comparing effects between small groups of participants. Critically, the within-subject conclusions remain the same, with a significant validity effect found for both the color target and catch response tasks.

Multilevel Models experiment 2a

Reaction times for correct responses were analyzed using a series of multi-level models that were built up, beginning with the simplest empty model, used to evaluate the sources of variance, to the most complex model, which included within-subject predictors of time (i.e. trial), validity, interactions between time and validity, and mean-levels of accuracy. Additionally, the possibility of trial-by-trial influences on reaction times was tested by including serially correlated residuals along with a random slope for the exposure variable (Appendix C. Multilevel Model Equations). Prior to running the models, reaction times were log-transformed due to violations of the distributional assumption of normality (skew = 1.6; kurtosis = 4.1). Following transformation, the variable more closely approximated a normal distribution (skew = 0.6; kurtotisis = 0.9, Figure 13). Given that all of the models were run on log-transformed RT, rather than the raw RT values, all estimates and effects were then backtransformed to ms by expontiating the values to improve interpretability. Therefore all effects will be reported in milleseconds moving forward. Additionally, the time variable (i.e. trial) in all models was rescaled such that for models looking across the entire experiment, a single time point represents 100 trials, and for models looking within blocks, one time point represents 10 trials. This rescaling was necessary to allow the models to compute the random variance in the slope term (made mathematically difficult with extreme differences in scales between the log-transformed RT and raw trial variable). The rescaling procedure does not average across trials or bin trials into smaller units as every trial is still present in the analysis.

The results from the random-effects ANOVA model (Appendix C, model 1) are useful to explore the sources of variance in the data. The intra-class correlation (ICC) was 0.274, which indicates that 27.4% of the total RT variance can be attributed to between-person mean differences (or alternatively, represents the proportion of total variance attributable to within-person similarities). Conversely, 72.6% of the total variance can be attributed to within-person differences, which is not surprising, given our sample and our within-subject manipulation, and the fact that each person contributes more than 400 data points to the sample. Furthermore, both the within and between-person variance terms in this model are significant. The significant between-person variance term (τ) tells us that, on average, participant's mean RT was an average of (approximately) 8.35ms faster or slower than the average person's mean RT of 599.3ms (z=2.93, p=0.0017). The significant within-person variance parameter (σ^2) indicates that, on average, participant's scores varied approximately 23ms around their own mean RT (z=63.19, p<0.0001).

The next model was an unconditional growth model with time (i.e. trial) included as the only predictor, to test whether reaction times changed over the course of the experiment and whether or not random effects of the intercept and/or slope should be included in the model (Appendix C, Model 2a). The fixed effects revealed an intercept of 610.09ms (t(29)=289.01, p<0.0001) representing the average reaction time for the first trial of the experiment and a significant slope (t(8240)=-4.85, p<0.0001), indicating that, on average, people's reaction times decreased by 12.45 ms every 100 trials. The random effects revealed significant variance across people in both the intercept (z=3.63, p=0.0001) and slope (z=2.93, p=0.002) parameters according to both significant Wald tests as well as the graphical representation of the predicted trajectories for each person across time (Figure 14), suggesting significant variability both in how fast people were at the start of the experiment as well as in their rate of change. Both of these random terms were retained for the more complex models moving forward. There was no evidence of a significant covariance between these two terms, suggesting that the variability in these parameters was independent (i.e. it was not the case that people who changed the most were significantly slower or faster to begin with). The possibility of a non-linear effect of time on RT was examined by plotting both raw and log RTs as a function of time (raw trial variable) for a subset of participants (6 per experiment). There was no evidence of a non-linearity effect of time on either measure of RT.

In the next model (Appendix C, Model 2ab), we found a significant first-order autoregressive error structure parameter (z=9.69, p<0.0001), indicating a significant amount of covariance between each time point, and the previous one, above and beyond what is explained by the parameters in the model (Schwartz & Stone, 1998). This parameter remained significant across all analyses and was retained for all models going forward.

We then included the main effect of validity on RT as well as the interaction between validity and time (Appendix C, model 3), which both supported and extended the results found in the repeated measures ANOVA, reported above. The fixed effects revealed a main effect of validity ($t(29)=4.20$, $p<0.001$) indicating that on average, people responded 21.81 ms faster to valid trials as compared with invalid trials at the beginning of the experiment. Critically, the validity by trial interaction was trending towards significance ($t(8238)=1.88$, $p=0.06$) indicating that, on average RTs changed at a faster rate for invalid relative to valid trials (Figure 15). Including the within-subject factor of validity in the model reduced the within-person residual variance by 2% and reduced the predicted variance in slope by 1%.

Next, mean accuracy was also included as a person-level covariate to account for differences in overall accuracy (Appendix C, model 4). Both fixed and random effects remain virtually unchanged from model 3, with the addition of a significant fixed effect of mean accuracy ($t(28)=-2.11$, $p=0.044$) suggesting that at the start of the experiment, participants were significantly faster for valid trials. This model was retained as the final model to examine the effects of validity across the full set of experimental trials. The additional covariates (span tasks and surveys) were not included due the lack of relationships found between their scores and our task measures both when looking at the bivariate correlations as well as the rmANOVAs reported above.

The results from these models confirm the conclusion from the repeated measures ANOVAs that attention was captured by the cue in this catch-trial response condition. Critically, by modeling RTs as a function of both validity and time, we are able to learn that the size of capture is changing as a function of experience with the stimuli and task. Specifically, the reaction time difference between valid and invalid trials is larger at the beginning, and changes at different rates for the two conditions. Additionally, the models revealed significant variance between our participants in the rate of change in RT across time. Not only is time not included in the rmANOVA framework, but neither is the ability to have this random variance represented and quantified. These results therefore, suggest that something is changing about the nature of capture by the cue in this task, over time.

To compare the results using the full distribution of trials and those derived from the more traditional analyses of means, we looked at whether validity changes over the course of the experiment by binning trials into blocks (6 total) as was done in experiment 1, and compared mean RTs for valid and invalid trials within each block. RTs for correct responses were submitted to 2 (valid, invalid) by 6 (blocks 1-6) repeated measures ANOVA. The results indicate a significant main effect of Validity [$F(1,145)=19.31$, $p<0.001$] representing the fact that, on average, participants responded 14.53 ms faster to validly-cued targets. There was also a significant effect of Block [$F(5,145)=19.31$, $p<0.001$], reflecting the fact that average RTs differed across blocks (Figure 16). However, there was no evidence of the critical Block by Validity interaction [$F(5,145)=1.15$, $p=0.34$], suggesting that the validity effect did NOT differ across blocks, contradicting the results of models 3 and 4 which demonstrated changes in validity over time. However, blocks were not explicitly included in those models, so to directly compare the results of models using the full distribution of RTs versus those using binned means, additional models were examined.

The next two models looked at the effect of validity on attentional capture, not only across the entire experiment, but also within each block (Appendix C, models 5 and 6). Model 5 was an unconditional growth model to examine the effect of time on RT *within* an average block. The fixed effects results indicate that, on average, RT at the start of a block was 573.93 ms, and changed, significantly, over the course of the block at a rate of 3.29 ms per 10 trials. Unlike across all trials in the experiment, there does not appear to be significant between-person variance in the rate of change of RT over the average block ($z=0.61$, $p=0.27$). Moving forward, the random slope term was not retained. Model 6 included Validity and Block, as well as all interactions to test whether or not Validity changed as a function of time within a block, across blocks, and whether or not the change in Validity within a block was different depending on the block. The fixed effect model results revealed all main effects and interactions were significant. Critically, the Validity by Block interaction was significant [$F(5,145)=11.24$, $p<0.0001$], indicating that the validity effect differed across blocks. Moreover, the three-way, Validity by Block by Time interaction indicates that, not only is validity different across blocks, but also the change in validity as a function of time within each block differs across blocks [$F(5,8218)=12.55$, $p<0.0001$]. Separate models testing the interaction between Validity and Time within each block revealed that the validity effect differed across time in all but the fifth block (Figure 17).

The above models indicate that the effect of capture is changing as a function of time, both within and between blocks. This effect was not evident when looking at means for each condition across the six blocks, but rather, only emerged when including the full distribution of trials in our analysis. Critically, the changes in validity over time in this experiment add to our understanding of the novel capture found to a non-congruent cue singleton when catch responses are required and can give us a deeper understanding of the underlying mechanisms, particularly when contrasting the effects over time with those found in experiments 2b and 3.

Multilevel Models experiment 2b

Reaction times for correct responses were analyzed using the same set of multilevel models as were used in 2a (Appendix C. Multilevel Model Equations). As in experiment 2a, reaction times were log-transformed due to violations of the distributional assumption of normality (Figure 13), and time was rescaled to allow for computation of variance in the slope variable.

The results from the random-effects ANOVA model (Appendix C, model 1) indicated an ICC=0.273, which indicates that 27.3% of the total RT variance can be attributed to between-person mean differences (or alternatively, represents the proportion of total variance attributable to within-person similarities). Conversely, 72.7% of the total variance can be attributed to within-person differences. Furthermore, both the within and between-person variance terms in this model are significant. The significant between-person variance term (τ) tells us that, on average, participant's mean RT was an average of (approximately) 8.8.ms faster or slower than the average person's mean RT of 569.87 ms (z=3.84, p<0.0001). The significant within-person variance parameter (σ^2) indicates that, on average, participant's scores varied approximately 23 ms around their own mean RT (z=65.34, p<0.0001).

In the unconditional growth model with time as the only predictor (Appendix C, Model 2a), the fixed effects revealed an intercept of 596.21 ms (t(30)=272.46, p<0.0001) representing the average reaction time for the first trial of the experiment and a significant slope (t(8538)=-5.10, p<0.0001), indicating that, on average, people's reaction times decreased by 13.03 ms every 100 trials. As was the case in experiment 2a, the random effects revealed significant variance across people in both the intercept (z=3.74, p<0.0001) and slope (z=3.18, p<0.0001) parameters (Figure 18), suggesting significant variability both in how fast people were at the start of the experiment as well as in their rate of change. Both of these random terms were retained for the more complex models moving forward. Additionally, there was no significant covariance between the distributions of these error terms (z=-1.28, p=0.20). Additionally, the continuous-time autoregressive error structure parameter was significant (z=7.60, p<0.0001), and was retained for all models going forward.

We then included the main effect of validity on RT as well as the interaction between validity and time (Appendix C, model 3), which both supported and extended the results found in the repeated measures ANOVA, reported above. The fixed effects revealed a main effect of validity (t(30)=6.51, p<0.001) indicating that on average, people responded 32.87 ms faster to valid trials as compared with invalid trials at the beginning of the experiment. Critically, the validity by trial interaction was not significant (t(8536)=-1.21, p=0.225) indicating that, on average RTs changed at the same rate for both valid and invalid trials (Figure 19). Including the within-subject factor of validity in the model reduced the within-person residual variance by 1.4% and reduced the predicted variance in the slope and intercept by less than 1% each. The inclusion of each person's average accuracy (Appendix C, model 4), does not change the model in any substantial way, nor is the effect of accuracy significant (t(29)=-0.02, p=0.98), supporting the results of the rmANOVA when accuracy was included as a covariate.

Although these results do not suggest a change in the capture as function of time, we again looked at validity both within and across blocks to test 1) whether effects may be present within blocks, not found across the entire experiment and 2) whether this analysis revealed effects not found by analyzing binned means, as was the case in experiment 2a. Looking first at binned means, RTs for correct responses were submitted to 2 (valid, invalid) by 6 (blocks 1-6) repeated measures ANOVA. The results indicated a significant main effect of Validity [$F(1,150)=57.50$, $p<0.001$] representing the fact that, on average, participants responded 26.29 ms faster to validly-cued targets. There was also a significant effect of Block [$F(5,150)=14.58$, $p<0.001$], reflecting the fact that average RTs differed across blocks (Figure 20) However, there was no evidence of the critical Block by Validity interaction [$F(5,150)=1.69$, $p=0.14$], suggesting that the validity effect did not differ across blocks, in agreement with the lack of a time by validity interaction found in model 3.

Contrary to the results of the rmANOVA testing validity by block, the multilevel model which included validity, time (within each block) and block number, as well as their interactions (Appendix C, models 6), revealed that all main effects and interactions were significant. Critically, the Validity by Block interaction was significant [$F(5,150)=3.12$, $p<0.01$], indicating that the validity effect differed across blocks. Moreover, the three-way, Validity by Block by Time interaction [$F(5,8516)=3.29$, $p<0.01$], indicates that, not only was validity different across blocks, but also the change in validity as a function of time within each block differs across blocks. Separate models testing the interaction between Validity and Time within each block revealed that the validity effect did not differ across time in blocks 1, 5 and 6, but did increase in blocks 2 and 3. Once again, by including the full distribution of trials, we are able to detect changes in the effects of capture over time which aid us in our understanding of the underlying mechanisms, particularly when comparing these effects across the tasks, as will be discussed in detail in chapter 4.

Discussion

The results of the analyses of means (rmANOVA) for experiments 2a and 2b supported and extended the findings from experiment 1. Specifically, contrary to the predictions of the contingent attentional capture hypothesis (Folk & Anderson, 2010), we found attentional capture to a singleton distractor both when it was congruent and incongruent with attentional control settings. As was the case in experiment 1a and 1c, capture was observed for incongruent targets when additional task demands caused the cue array to be behaviorally relevant (see Table 3 for summary of conditions across tasks). In experiment 1 we also found a main effect of task reflecting the fact that people in the onset target task responded faster to targets than those in the color target task, potentially reflecting perceptual differences between the tasks (Eimer & Kiss, 2008). However, in the present experiment, there was no main effect of task but instead a significant interaction of task by validity (not found in experiment 1) reflecting the fact that the validity effect on RT was significantly larger in the color target task (2b) than in the catch task (2a). These results suggest that overall, capture to the red singleton is stronger in color target condition, not surprising as the distractor is congruent with the task set (Folk et al., 1992). The reason why we are finding a larger effect of capture in the contingent cueing task in experiment 2 when none was found in experiment 1 may simply be reflecting the fact that we have a much larger sample in the present experiment, and therefore have more power to detect this between-subject effect.

Based on the interaction found in the repeated-measures ANOVA, we might conclude either that there is a single mechanism causing capture followed by differing degrees of disengagement, or that there are distinct mechanisms of capture in the two tasks. If a single mechanism exists, capture in both tasks would occur in a saliency-driven fashion initially, followed by disengagement in the catch response task (2a) because the distractor is incongruent with target features (Theeuwes, 2010). Conversely, we would expect no disengagement in the color target task (2b) because of its match with attentional control settings (Folk et al., 1992), suggesting that top-down factors exert influence later in the processing stream (Theeuwes, 2010). In this case, the difference in the magnitude of the validity effect across the tasks might reflect the differential disengagement from the cue. Alternatively, capture in the color target task might be due entirely to top-down influences acting at the earliest stages of processing, in contrast to saliency-driven factors causing capture in the catch response task. If so, the validity effect differences across tasks may reflect the fact that distinct processes are causing capture.

We explicitly modeled the effect of capture over the course of the experiment to try to distinguish between the competing hypotheses about the causes of capture and the resulting RT effects. Critically, we found that capture was roughly equivalent in both tasks at the beginning of the experiments, but diminished both within and between blocks only in the catch response task (Figure 15, Figure 19). These results suggest that a similar saliency-driven mechanism caused capture in both tasks. It appears that participants in the catch response task were captured to salient distractor both at the beginning of the experiment, and again at the beginning of each block (Figure 17) and that this capture was followed by either active suppression (Sawaki & Luck, 2013; Zehetleitner et al., 2012) or habituation to the saliency effects (Cohen, 2011). In the color task experiment, although people get faster across the experiment, there is no evidence that the validity effect changes as a function of experience with the task and stimuli. These results contradict the pattern observed in experiments 1a and 1d in which capture in both tasks appeared to increase over time. However in those analyses we were unable to explicitly test the observed change in validity over time, nor could we directly compare the slopes across conditions.

The third goal of these experiments was to compare and contrast two different analytic tools to test changes in RTs across time. Researchers often use mean RTs binned by blocks (or groups of blocks) to try examine how time within and experiment impacts attention effects such as habituation (Sörqvist, Nöstl, & Halin, 2012) and statistical learning (Cosman & Vecera, 2014). However, the results of the present experiments indicate that by including the all trial data and explicitly modeling time as a factor, we are able to detect effects that were not evident when binning RTs into chunks of trials. Additionally, the multilevel model framework allowed us to include a random effect of time to capture the significant variance among people in the rate of change in RT. Failure to properly specify random effects can inflate type I error rates (Barr, Levy, Scheepers, & Tily, 2013).

Lastly, in this experiment we also tested whether or not measures of individual differences in working memory capacity, self-reported daily distractibility, and self-reported Impulsiveness correlate with our task measures of attentional capture. Although the CFQ (Broadbent et al., 1982) was not related to either RT or accuracy measures in our samples, we did find that individuals reporting more distractibility also displayed lower working memory capacity as measured by the operation and symmetry span tasks. This is the first experiment, to our knowledge, to report a relationship between scores on these two tasks. The finding supports evidence that individuals who report higher cognitive failures have more difficulty disengaging following distraction under higher attentional load conditions (Berggren, Hutton, & Derakshan, 2011), and serves as evidence that working memory critically supports attentional processes. One of the proposed explanations for why we find capture in experiments 1a, 1c and 2a (catch response, Table 3) is by requiring that participants both attend to and respond to the cue array, we increased the working memory load, making participants more susceptible to attentional capture by irrelevant but salient objects that the additional task demands increase attentional load, making people more susceptible to distraction(Lavie, 2005; Lavie & de

Fockert, 2005). This is supported somewhat by the fact that responses were slower overall in experiment 1a relative to 1b, in which the tasks were identical with the exception of the response to catch trials. Although such a relationship between increased load and distraction within a task has been found previously (Kane et al., 2001; Pratt, Willoughby, & Swick, 2011) in the present study, we do not find a link between working memory capacity and our task measures of distractibility (i.e. RT validity effect). These null effects suggest that the catch response task may not have increased working memory load in the task. If working memory load was in fact not increased, leading to a break down in the hypothesized pre-attentive top-down suppression of distracting items, the alternative explanation is that capture occurred in a bottom-up saliency-driven manner initially.

Turning to the self-reported measures of distractibility and impulsivity, we found a significant relationship between the two trait measures, but no evidence that either one is related to our task-measure of capture. Borrowing from the state-trait theories of anxiety and anger (Spielberger & Sydeman, 1994), we could conceive of two constructs comprising distractibility: state referring to stable characteristics and trait referring to transient characteristics that occur in response to a particular situation. In the present study, we found evidence that capture changed not only across the experiment, but also within a single block, reflecting the transient nature of the capture induced by the experimental conditions. A similar application of the theory has been made in regards to impulsivity (Lai, Ip, & Lee, 2011). Although other studies have found links between the CFQ and experimental measures of distraction in search and cueing tasks (Berggren et al., 2011; Forster & Lavie, 2007; Tipper & Baylis, 1987), the lack of relationship in the present study may reflect a fundamental difference between the trait distractibility measured by the CFQ and the more transient or "state" distractibility captured in our task measures.

In conclusion, Experiment 2 demonstrated that capture occurs to a salient distractor when there is a task-related reason to attend to the array containing the distracting item. Critically this capture was observed even when the distractor is not contained within a feature-based attentional set. Through the novel use of a model of reaction times that included the full distribution of trials, we were able to explicitly model changes in capture over time and compare rates of change across task conditions. This was not possible within the more commonly used ANOVA framework. This novel analysis revealed that capture occurs initially when the salient item's features do not match attentional control settings but is then reduced both within and across blocks suggesting that top-down suppression may take time to build-up. These results suggest a critical role of experience in the deployment of top-down attention not predicted by existing models of contingent capture (Ansorge et al., 2011; Lamy & Kristjánsson, 2013; cf. Zehetleitner et al., 2012).

CHAPTER 4: EXPERIMENT 3

COMPARING THE EFFECTS OF COMPETING ATTENTIONAL CONTROL SETTINGS

Experiments one and two demonstrated that attentional control settings suppress capture by distracting stimuli unless the distractor matches the contents of the top-down set (1d, 2b) or is contained within a behaviorally relevant array (1a, 1c, 2a). Critically, by modeling capture over time in experiment 2, we found evidence to suggest that top-down suppression develops over time as a result of task and stimuli experience when the distractor is not part of the top-down set (2a). The present study further examines how attentional control settings influence capture by creating conditions in which two settings are competing against each other, specifically, feature relevance versus spatial relevance. Given that one of the key findings from experiment two was the improved interpretability of the underlying attentional mechanisms gained by testing the change in capture over time, experiment three was designed to allow a similar analysis of within-task effects, as well as a comparison between this task and those used in experiment two.

The contingent attentional capture hypothesis predicts that a top-down attentional set containing critical target properties should prevent (or suppress) capture to a color cue when the target is an onset (Folk & Remington, 1998; Folk et al., 1992). Accordingly, as long as the cue is non-predictive the number of target locations should not impact capture, and is typically not considered to be an influencing factor in studies of contingent capture. Conversely, the disengagement hypothesis implies that reducing the cue's validity will increase the motivation to disengage from the cue, and predict either reduced or absent attentional capture in the color-target task (Theeuwes, 2010). Additionally, changing an endogenous cue's validity modulates the size of the cueing effect both behaviorally and neurally (Vossel, Thiel, & Fink, 2006), reflecting the role of validity in how attentional control settings impact spatial orienting.

In experiment three, we tested whether or not a non-predictive cue's validity affects top-down mediation of distraction, specifically testing if reduced validity increases active suppression of a cue, even when the cue's features are part of an attentional set. In a non-predictive cueing paradigm, the cue predicts the target at a chance level, so changing the number of target locations necessarily changes the cue's validity. For example, a valid cue in a 2 location paradigm is valid on 50% of trials whereas a valid cue in a 6 location paradigm is only valid for 16.7% of the trials. In both cases, the cue is non-predictive, and does not include any spatial information about the upcoming target, but with more target locations, the target is far more likely to be in one of the multiple invalidly-cued locations, potentially encouraging a strategy of disengagement from the cue. To test whether or not reducing a cue's validity but not its predictability increased suppression of an irrelevant but salient distractor, the present experiment increased the number of potential locations in which a color-singleton target could appear. Because the salient features of the distractor matched the identifying feature of the target (i.e. color), the contingent orienting hypothesis predicts that capture should occur (Folk et al., 1992), but knowledge of the extremely low validity (and conversely high invalidity) of the cue may cause active suppression of the color-matching cue. Critically, because exposure to the task may be necessary in order for participants to "learn" the validity (Chun & Jiang, 1999; Risko & Stolz, 2010), we may see that active suppression of the distractor increases as a function of experience with the task and stimuli.

Methods

Participants

Thirty-two students were recruited from the pool of undergraduate research volunteers and given 1 hour of class credit for participation in the study. All participants were right handed, with

20/20 or corrected-to-20/20 vision, had no history of head injury or ADHD, and were not taking any psychotropic medications (e.g. antidepressants). Two participants were removed from the final sample due to low accuracy (more than 3 SD below the mean) and extreme drowsiness (e.g. falling asleep during the task). The final sample consisted of thirty undergraduate students (21 female, average age = 18.9).

Stimuli & Procedure

The task and stimuli in this experiment were similar to those used in both 1d and 2d (color target task, Table 3). The critical difference between this task and the previous ones is that the number of possible target locations was manipulated such that both the cue and target could appear at any of the six possible locations. The resulting cue validity was 16.7%. Critically, the cue remained "non-predictive" because it did not give participants any additional information about the possible target location (i.e., targets are always equally likely at any of the possible target locations, and cue provides no further predictive value regarding the location of the target).

There was an increase to 72 trials per block in experiment 3 (from 68 in experiment 2 and 46 in experiment 1) because more trials for each target type were required to ensure that the cue remained non-predictive (i.e. 6 trials needed for every cue location versus 2 in experiments 1 and 2). Additionally, there were no cue-only (catch) trials, as catch trial responses were not required. As in experiment 2, there were also 6 blocks total resulting in 96 cued and 480 uncued locations. Both the number of blocks and trials within a block were also chosen to allow for the comparison of time by validity effects across experiments.

All participants were first given the task blocks and then completed the CFQ (Broadbent et al., 1982; Appendix A) and BIS-11 (Patton et al., 1995; Appendix B) after the task was performed.

Results

Analysis of target response times experiment 3

Correct reaction times given between 150 and 1450 ms following the onset of the target were analyzed. There were was a significant effect of validity on reaction time $t(29)=5.10$, $p<0.001$ reflecting that on average, people responded 22.36 ms faster to a validly-cued target (Table 2). There was also a significant effect of validity on accuracy $t(29)=2.53$, $p=0.017$, indicating that people were, on average 1.0% more accurate when responding to validly-cued rather than invalidly-cued targets (Table 2). The validity effect on reaction time remained significant in a model which included both mean accuracy and average accuracy difference (invalid-valid) as between-subject covariates [$F(1,27)=24.84$, $p<0.001$]. Neither accuracy measures showed between subject effects, nor any interaction with validity. The final rmANOVA model revealed that BIS, CFQ, age, and sex did not have significant between-subject effects on reaction time, nor any interactions with validity. Overall, these results indicate that participants were captured to a distractor matching attentional control settings for color leading to spatial shifts of attention, despite the low probability that the target would subsequently appear at the location of the distractor. Evidence of capture was present only in reaction time measures, but not in accuracy differences. Additionally, individual measures of working memory, distractibility and impulsiveness were unrelated to the effect of the distractor's location on RTs.

Multilevel models experiment 3

Reaction times for correct responses were analyzed using the same set of multilevel models as were used in 2a (Appendix C. Multilevel Model Equations). As in experiment 2, reaction times were log-transformed due to violations of the distributional assumption of normality (Figure 13), and time was rescaled to allow for computation of variance in the slope variable.

The results from the random-effects ANOVA model (Appendix C, model 1) indicated an

ICC=0.275, which indicates that 27.5% of the total RT variance can be attributed to between-person mean differences (or alternatively, represents the proportion of total variance attributable to within-person similarities). Conversely, 72.5% of the total variance can be attributed to within-person differences. It is interesting to note that the ICC's were nearly identical across all three experiments, suggesting that the sources of variance were similar across all experiments, again unsurprising given the population (undergraduate students aged 18-22) and our design (within-subject manipulations). Furthermore, both the within and between-person variance terms were once again significant. The significant between-person variance term (τ) tells us that on average, participant's mean RT was 9 ms different than the overall average RT of 551.04 ms (z=3.79, p<0.0001). The significant within-person variance parameter (σ^2) indicates that participant's scores varied an average of 24ms around their own average RT (z=78.58, p<0.0001).

In the unconditional growth model with time as the only predictor and an AR(1) residual variance structure (Appendix C, Model 2b), the fixed effects revealed an intercept of 560.43 ms (t(29)=269.58, p<0.0001) representing the average reaction time for the first trial of the experiment. The slope was significant (t(~12,000)=-1.95, *p*=0.05), indicating that, on average, people's reaction times decreased by 4.30 ms every 100 trials. Once again, the random effects revealed significant variance across people in both the intercept (*z*=3.68, *p*=0.0001) and slope (*z*=3.10, *p*=0.001) parameters (Figure 23), suggesting significant variability both in how fast people were at the start of the experiment as well as in their rate of change. Both of these random terms were retained for the more complex models moving forward. Additionally, there was no significant covariance between the distributions of these error terms (*z*=-0.67, *p*=0.50). Additionally, the continuous-time autoregressive error structure parameter was significant (*z*=15.81, *p*<0.0001), and was retained for all models going forward. Although the fixed effect of time was significant, there was a fairly small model-implied slope estimate of 4.3 ms as compared with 12 and 13 ms respectively for experiments 2a and 2b. In other words, it may be the case that there is no change in RTs as a function of time, despite the p-value. The possible difference across experiments will be explored further in the next section.

We then included the main effect of validity on RT as well as the interaction between validity and time (Appendix C, model 3). The fixed effects revealed a main effect of validity ($t(29)=6.69$, $p<0.001$) indicating that on average, people responded 35.51 ms faster to valid trials as compared with invalid trials at the beginning of the experiment. The main effect of time is no longer significant ($t(\sim12500)=-0.18$, $p=0.86$), indicating that, on average, there is no change in reaction times across the experiment. However, the validity by trial interaction was significant ($t(\sim12{,}500)=-2.09$, $p=0.037$) indicating that, on average participants were getting faster when responding to invalidly-cued trials, but not when responding to validly cued trials (Figure 24). Including validity in the model reduced all of the variance components (intercept, slope and residuals) by less than 1%. The inclusion of each person's average accuracy (Appendix C, model 4), does not change the model in any substantial way, and revealed a marginal effect of accuracy significant ($t(28)=2.02$, $p=0.053$), suggesting that people responded significantly more accurately to invalid trials at the beginning of the experiment. This is not entirely surprising as trial 1 occurs after a practice block in which participants responded to far more invalid than valid trials.

Once again, to examine the effect of validity over time using the rmANOVA framework, RTs for correct responses were submitted to 2 (valid, invalid) by 6 (blocks 1-6) repeated measures ANOVA. The results indicated a significant main effect of Validity [$F(1,145)=38.02$, $p<0.001$] representing the fact that, on average, participants responded 24.63 ms faster to validly-cued targets. There was also a significant effect of Block [$F(5,145)=3.79$, $p=0.017$, using the Greenhouse-Geisser correction], reflecting the fact that average RTs differed across. However, once again, this analysis failed to detect any differences in the validity effect across blocks [$F(5,145)=1.09$, $p=0.37$; Figure 25].

In comparison to the rmANOVA testing validity by block which did not detect an interaction, the multilevel model which included both validity and block, as well as time within block (Appendix C, models 6), did reveal that all main effects and interactions were significant (except for slope, which once again is not significant). Interestingly, unlike in experiments 2a and 2b, there was a significant random effect of slope ($z = 2.22$, $p=0.13$), reflecting the fact that within a block, there was significant variability in people's rate of change over time (Figure 23). Critically, the Validity by Block interaction was significant [$F(5,145)=7.35$, $p<0.0001$], and the significant three-way Validity by Block by Time interaction [$F(5,\sim12,500)=6.79$, $p<0.0001$] indicates that, not only was validity different across blocks, but also the change in validity as a function of time within each block differs across blocks. Separate models testing the interaction between Validity and Time within each block revealed that the validity effect did not differ across time in blocks 1, 2, 3 and 6, but did increase in blocks 4 and 5 (Figure 26). Once again, by including the full distribution of trials, we are able to detect changes in the effects of capture overtime which enrich our understanding of the underlying mechanisms.

Comparison of multilevel models (2a vs. 2b vs. 3)

As reported above, the mixed ANOVA revealed a significant interaction between validity and task, indicating that the validity effect was significantly larger for participants in the color target task as compared with the catch trial response task. However, that analysis was unable to tell us whether or not the interaction was reflecting weaker capture overall, or rather a difference in the size of capture over time, reflecting . The multilevel model results for the two experiments taken separately suggest differences in the effect of capture over time, which critically differ across the two tasks. Specifically, the models suggest that in the color target task (experiment 2b), there is a strong effect of cue validity, at the beginning of the experiment, which remains strong over the course of the experiment, with some build up locally within a few blocks. Conversely, in the catch response task (experiment 2a), there is strong effect of capture initially, but it appears to disappear both over the course of the experiment, and locally within each block. In experiment three capture diminishes somewhat over time, but is driven entirely by faster reactions to invalidly-cued trials, and the change is not as pronounced as what is seen in experiment 2a.

A task by validity by time interaction was formally tested in an additional model (Appendix C, model 7). The ICC for the full sample was 0.29, higher than what was found in each experiment separately, suggesting that an additional amount of variance is due to between-person differences, unsurprising given the fact that we now have a critical person-level factor of task in our dataset. The fixed effects results from the model indicate main effects of time [F(1,~29,000)=42.71, p<.0001], validity [F(1,88)=98.28, p<.0001] and task [F(2,88)=5.83, p=.004], reflecting the fact that a) RTs are decreasing over time, b) RTs are significantly faster for validly-cued trials and c) on average RTs were significantly faster in experiments 2b and 3 relative to experiment 2a. There was a trending two-way validity by time interaction [F(2,88)=2.73, p=.07], but more critically there was a significant three-way validity by time by task interaction [F(4,~29,000)=2.55, p=.038]. This three-way interaction is driven by the fact that the difference between valid and invalid RTs (i.e. validity effect) changed significantly (decreased) across time in experiment 2a and 3, but not in experiment 2b (see Figure 15, Figure 19, and Figure 24).

Discussion

In experiment three we tested whether or not attentional control settings for features would override learned cue probabilities or vice verse. Specifically, a non-predictive distractor's salient feature matched the critical feature of the upcoming target, resulting in a match with the task attentional control settings, which is known to result in spatial shifts of attention to the cue's location. Additionally, because both the cue and target could appear with equal likelihood at any of the six possible target locations, the target appeared at an invalidly-cued spatial location on 5/6 or 83.3% of trials resulting in a competing top-down signal to disengage and reorient from the often invalid cue location (Corbetta, Patel, & Shulman, 2008; Seiss et al., 2009; Thiel & Fink, 2008; Vossel et al., 2006). The results indicate that the attentional settings for color exerted a stronger influence on spatial shifts of attention than the low validity. On average, participants were slower to respond to trials in which the target was invalidly-cued, just as they did in experiment 2a when the validity was at 50%, reflecting spatial attentional capture by the cue. Looking at the mean RTs alone, these results support the predictions made by the contingent attentional capture hypothesis (Folk et al., 1992).

Multilevel models were once again used to test whether or not capture to the cue varied either within or between blocks of the experiment as a function of time and experience with the task. This method for examining the effects of time was also directly compared with the often used method of binning RTs into blocks and using an rmANOVA treating time as a discrete factor. Using the binned blocks as a factor in an rmANOVA we once again failed to detect a validity by time interaction. However, using the multilevel model framework, there was a significant validity by time interaction reflecting the fact that participants got significantly faster over the course of the experiment only when responding to invalidly-cued trials (and not when responding to validly-cued trials). This indicates that participants were either reducing the degree to which the cue captured their attention spatially, or that they were improving their ability to disengage from the cue as the validity percentages were reinforced across time (i.e. as they saw more and more invalid relative to valid trials). If capture was diminished, possibly due to some element of suppression, this suggests that attentional capture is not binary (i.e. capture vs. no capture) but rather may reflect a continuum of processing which can included varying degrees of match with attentional control settings, as has been seen in both behavioral (Anderson & Folk, 2010) and ERP studies (Ansorge et al., 2011). Alternately, the faster RTs for invalidly-cued trials over time might reflect an improvement in the ability to disengage from the cue's location. However, if this were the case, we might expect a corresponding increase in validly-cued trial RTs, which does not appear to be the case. None-the-less, we cannot rule out the disengagement interpretation without additional measures, which will be discussed in the final chapter. There are also five times as many invalid trials as valid trials, which may be reducing our ability to see change in the valid condition.

Similar to experiment two, we found no relationship between the self-reported measures of distractibility and impulsivity and the experiment three task measure of capture (i.e. cueing effect). As discussed in the previous chapter, it may be that our task manipulates state distractibility whereas the surveys are assessing trait distractibility (Spielberger & Sydeman, 1994). It is unlikely that our analysis is suffering from a restriction of range issue since the means and standard deviations for the CFQ scores we found in both experiments 2a, 2b and 3 are very close to those reported in a confirmatory factor analysis of the CFQ consisting of 335 undergraduate students and navy personnel (Wallace et al., 2002).

Looking across both experiments two and three, we found a significant three-way interaction reflecting the fact that the change in validity over time was dependent upon which task was completed (Figure 15, Figure 19, and Figure 24). The three-way interaction further supports the interpretation of the effects in experiment 2 that capture occurs to the salient distractor initially, followed by top-down suppression either because the distractor's features are not part of the attentional control settings (experiment 2a) or because the cue's validity motivates a suppression of capture (experiment 3). In the catch response task (experiment 2a) it appears that capture to the distractor occurs initially, due to its local feature contrast (i.e. saliency) but as participants gain experience with the task and exposure to the stimuli, they actively suppress the capture and respond only to the target and absence of the target without shifting spatial attention to the distracting pop-out in the cue array. In the color target task (experiment 2b) and multiple location task (experiment 3), the cue's salient features remain relevant for target discrimination throughout the experiment, although the feature's relevance may also be competing with the cue's validity causing changes over time in experiment 3.

In both experiments we also found significant block by time by validity three-way interactions indicating that changes in the validity effects across time *within* a block significantly differed between blocks, as can be seen by examining the validity by time interactions within each block for each experiment (Figure 17, Figure 21, and Figure 26). Critically, what is obvious from the graphs alone is that in experiment 2a (catch response task, Table 3), many of the blocks show an even more pronounced reduction or even elimination of the validity effect as a function of trial; whereas in both experiments 2a and 3, changes in validity over time go in the opposite direction, with the effect seeming to build up as a result of task experience. These local effects (as compared with the global effects seen by looking across all trials) somewhat match the results from experiment 1d as well in which we found that capture seemed to build up over the course of the experiment. The difference in the local changes in validity strengthens the interpretation that different processes occur in these two tasks over the course of the experiments.

CHAPTER 5: DISCUSSION

The goals of this study were to 1) test the contingent capture hypothesis' position that feature-based attentional control settings mediate involuntary capture by salient stimuli, 2) test whether the validity effect changes as a function of time within and between tasks to better define the underlying mechanisms of attentional capture, and 3) to include measures of individual differences to determine if working memory capacity, distractibility and impulsivity are critically related to attentional capture. Using a novel experimental paradigm, we found that alternative task demands resulted in evidence of saliency-driven capture (experiments 1a, 1c, and 2a). We also found that attentional capture changed significantly as a function of time and experience with the task and stimuli, but that this change critically depended upon the task (experiments 2 and 3). Moreover, we were only able to detect this critical task by time by validity interaction by using the multilevel model framework and including all time points (i.e. trials). There was significant evidence of individual variability in the rate of change of response time over the course of the experiment justifying its inclusion in our models. Finally, we did not find evidence of any relationship between our task measures of distraction and either working memory capacity or self-reported measures of distractibility or impulsivity, however, there was a significant relationship between individual differences in daily distractibility (CFQ) and WMC (span tasks) which has not been reported in the literature to date.

The first aim of the study was to test whether feature-based attentional control settings always mediate involuntary capture by salient stimuli (Ansorge et al., 2011; Folk & Anderson, 2010; Folk et al., 1992; Töllner et al., 2012). In experiments 1 and 2 an additional task demand (i.e. target-absent response) seems to have enhanced temporal awareness of the cue array, resulting in capture to a salient and irrelevant distractor. Importantly, although the cue array was behaviorally relevant, the physical properties of the salient distractor were not. According to the contingent capture hypothesis there is no saliency-driven attentional capture to irrelevant distractors without a match between elements of the distractor and those stored in an attentional set (Folk & Anderson, 2010; Folk et al., 1992). This position has been expanded upon with the suggestion that capture to incongruent distractors does not occur due to top-down interference reduction driven by an active suppression mechanism (Sawaki et al., 2012; Zehetleitner et al., 2012). When distractors are congruent, and therefore match attentional control settings, capture occurs. The results of experiments 1 and 2 challenge this hypothesis as capture was found to a salient distractor that was not part of the attentional set.

An explanation for the capture to a color cue in an onset target task when target-absent response were required is that by requiring that participants both attend to and respond to the cue array, we increased the conceptual attentional load (or working memory load) involved with the task, making participants more susceptible to attentional capture by irrelevant but salient objects (Lavie, 2005; Lavie & de Fockert, 2005). However, we failed to find a relationship between working memory capacity as measured by the symmetry and operations span tasks and any measures of performance on the task suggesting that an individual's WMC did not positively or negatively impact task performance. Although the evidence is somewhat indirect and based on null effects, the lack of relationship suggests that working memory load is not impacted by the additional task demands in experiments 1a, 1c and 2 (Table 3). It is more likely that capture occurred either because top-down suppression was disrupted due to the temporal relevance of the array or because top-down suppression exerts influence at a post-attentive stage of processing. The latter explanation is in in line with the disengagement hypothesis which argues that capture to the cue may have occurred in all tasks but was only evident in response times when participants were unable to quickly disengage from the spatial location of the cue (Theeuwes, 2010). Critically, by looking at capture over time we may be able to select between these two possible accounts.

Experiment 3 further addressed the first aim of the study by manipulating the validity but not predictability of the cue to test whether settings for probability would overwrite settings for features, resulting in suppression of the cue. On average, the results support the contingent capture hypothesis as RTs were faster for validily-cued trials. Based on the analysis of the average RTs across conditions, the low validity does not appear to have altered how attentional control settings for color influence attentional capture or disengagement following capture.

The second goal of the study was to test whether or not attentional capture is static across time. Most (if not all) theories of attentional capture do not make any predictions about whether capture changes over time primarily because experiments testing capture require many trials, both to boost the signal-to-noise ratio, and to include enough trials of each type and condition to ensure a balanced design. However, the results from the experiments in the present study reveal that by looking at capture over time, we are able to more finely distinguish between two conditions which both result in statistically significant capture in the aggregate. Specifically, in the catch response tasks, we see capture in the aggregate because the temporal relevance of the event containing the distractor causes trouble with disengagement. However, over time, when people have more experience with the stimuli, it appears that they are able to suppress capture because the color of the singleton is not a characteristic central to either the catch trial response task or the target orientation task. In the case of the color target, we see capture in the aggregate which does not change over time suggesting that participants are never able to suppress capture because the redness of the distractor is relevant to their target orientation discrimination task. Additionally, looking at the validity effect within blocks in the study, it appears that capture is present in all tasks (2a, 2b and 3) initially but diminishes in the catch response task and either remains stable or increases in the two versions of the color target task. These results suggest that a similar saliency-driven mechanism caused capture in both tasks and that this capture was followed by active suppression (Sawaki & Luck, 2013; Zehetleitner et al., 2012) or habituation to the saliency effects (Cohen, 2011) when the distractor's features were task irrelevant (i.e. experiment 2a).

Turning to the third goal of the study, we found evidence of individual differences in the form of variance in both the slope and intercept term in the multilevel models in both experiments 2 and 3. On average, people differed significantly both in how fast they responded at the start of the experiment, as well as in their rate of change in RT throughout the experiment. Additionally we found a novel connection between WMC and the CFQ suggesting that people who report more levels of distractibility in their daily life have lower working memory capacities as measured by both the operations span task and the symmetry span task (Oswald et al., 2014). We did not find a relationship between WMC and any of the task-related measures of attentional capture. This suggests that the capture in the tasks was likely not connected with working memory load, nor was capture dependent upon WMC in a way that would have resulted in different performance across people who demonstrate different levels of WMC in the span tasks. We did not find a connection between either impulsiveness as measured by the BIS (Patton et al., 1995; Stanford et al., 2009) or distractibility as measured by the CFQ (Broadbent et al., 1982) and any task measures of attentional capture, nor was there any indication that the measures predicted effects of capture on RT depending upon which task participants were completing. As discussed previously, one reason why we may not have found a connection between these self-report measures is that could be that they are measuring different components of attention and distraction. Specifically, the measures may be reflecting stable characteristics whereas our task manipulation may be producing transient states of distraction (Spielberger & Sydeman, 1994). Interestingly, we did find a significant relationship between scores on the two self-reported measures of impulsiveness and distractibility, likely reflecting the fact that both scales are thought to tap into attentional processing (Patton et al., 1995; Wallace, 2004; Wallace et al., 2002). In conclusion, evidence of individual differences related to task performance was constrained to differences in overall RTs as well as change in RT over time. Our other measures of individual differences were unable to account for these RT differences indicating that a) the variability is truly unrelated to individual levels of working memory capacity, distractibility and impulsivity, b) our measures are not properly measuring these cognitive functions, and better measures are needed or c) to overcome issues of measurement error we should model the relationships among the underlying latent variables rather than the observed variables.

Contributions to broader literature

The results of this study demonstrate that capture occurs when the distractor is presented simultaneously with a relevant event (i.e. cue array). These findings could help resolve contradictory results from the attentional singleton and cueing paradigms. In additional singleton paradigm, attention is deployed to items in order of decreasing saliency when entire array is relevant (Theeuwes, 2010). Saliency-driven accounts of attentional capture argue that top-down control follows initial capture, with rapid disengagement from non-feature match distractors. However, most evidence for this type of capture comes from additional singleton paradigms in which the array containing either the target or target and distractor is *always* relevant (Figure 2). On the other hand, in cueing paradigms such as those used in the present study, the distracting item is embedded in an event that has much less relevance because it is separated in time from the event containing the to-be-discriminated or detected target (Figure 1). The present findings, in which array relevance resulted in pop-out capture highlights this difference in paradigms and suggests that the add support to the disengagement hypothesis account for cueing paradigms, which argues that the absence of behavioral evidence for capture to the cue is a result of disengagement that occurs before the target is presented.

Another way in which these results might impact other research is that the catch trial response paradigm may be useful in studies that wish to assess deficits in specific attention mechanisms not necessarily isolated in a typical cueing paradigm. Unlike most attention capture paradigms, which have binary results of capture or no capture (although, whether these results reflect relatively static effects is unknown), we found that capture changed across time in the catch response task and did not change in the color response task. The task might therefore be useful in the study of disorders in which suppression of distracting stimuli (i.e. top-down attentional control) is associated with other wide-spread cognitive difficulties, such as schizophrenia (Gold, Fuller, Robinson, Braun, & Luck, 2007). Specifically, if individuals with schizophrenia show capture throughout the catch response task rather than the pattern of diminishing capture observed in experiment 2a, it may reflect intact saliency driven capture and selectively impaired top-down control.

One of the major contributions of the present study is the demonstration that the use of multilevel models, which allow us to include every instance of our repeated measure, enabled us to detect critical differences across tasks. Even though the task by validity interaction was apparent in the rmANOVA analysis, the source of this interaction is apparent only when looking at the validity effect over time. Despite the fact that these methods have been used for some time in other areas such as education (Singer, 1998), public health (Diez-Roux, 2000), and psycholinguistics (Baayen et al., 2008), their use remains rare in most other areas of cognitive psychology. However, there are several questions specifically within the attention literature that might benefit from using the multilevel framework rather than the more traditional repeated measures ANOVA. Specifically, many studies examine both the allocation of attention as well as the effects of attention once allocated, and make conclusions about how processes develop as a result of practice (Gazzaley, 2011; Zehetleitner et al., 2012), stimulus exposure and priming (Folk & Remington, 2008; Lamy et al., 2006) or implicit learning (Cosman & Vecera, 2014; Risko & Stolz, 2010). Many, if not all of these studies would benefit by looking not just at the average RT for trial type B when preceded by trial type A (Lamy et al., 2006), but rather by modeling the rate of change in RTs and including conditions as time-varying covariates, as was done in the present studies (Raudenbush & Bryk, 2002).

Limitation and future directions

There are a number of open questions resulting from the present study. First, although the behavioral results suggest that capture is replaced by active suppression in the catch response task (experiment 2a), our primary measure of capture is indirect. To measure attentional capture we are measuring behaviors (response time and accuracy) that occur almost a full second after the distracting visual stimulus appears. Because of the delay between capture and the behavioral measure of capture, we do not have direct evidence that capture itself is diminishing, despite the fact that this is the logical conclusion. A follow-up ERP study could clarify the specific mechanisms driving capture over time. In particular, such a study could test the hypothesis that in the catch trial response task, saliency driven-capture is followed by active suppression of the cue. Neural markers associated with attentional capture (N2pc, Luck & Hillyard, 1994) and active suppression (Pd, Sawaki & Luck, 2011) would be examined. One challenge will be that we would want to measure these components across time, rather than in the aggregate across all relevant trials ignoring trial order (as is typically and necessarily done in ERP research to improve the signal to noise ratio). An alternative approach might be to measure the ongoing electroencephalogram (EEG) and test hypotheses about neural oscillations, their frequency and synchrony, and how they are associated with attentional selection (Taylor & Thut, 2012).

The decision to use a between subjects design in all three experiments to avoid carryover effects (with the exception of 1c) could be viewed as a limitation as well. However, it was critical that capture to the cue in one condition did not contaminate the following condition either by reducing capture that would have otherwise occurred, or producing capture where none should be found. Although it didn't change the substantive conclusions from the experiment, there was some evidence of carryover in experiment 1c. A within-subject design would have been more sensitive to differences in the magnitude of the capture across tasks, but would have made modeling changes over time a great deal more complicated. If a within-subject study were conducted it would need to have either long breaks (as in days) between conditions or a sufficient distractor task. Such a design would potentially make conclusions about task-related time course differences stronger, and would be necessary for an EEG or ERP study design, but would not be without methodological challenges. Additionally, we did not model capture over time for the condition in which we do not expect to find capture (1b, Table 3). This task condition was not necessary in order to make the key conclusions about differences between the two cases in which we find capture (i.e. color target and catch response), but would have let us determine if top-down suppression of irrelevant distractors is indeed present at the start of experiments in which we do not find capture, as suggested by the results of experiment 1b.

Another limitation of the study is that when looking at trial-level data, we encounter quite a bit of noise and variability that is not necessarily related to the task. The inclusion of the first order autoregressive error structure partly addressed this noise (Schwartz & Stone, 1998), but the inconsistent trial by block by time effects within the tasks highlight one of the challenges when looking at small numbers of trials in these tasks. Although the general pattern of effects was informative, with capture diminishing within blocks only in the catch response (event relevance) task, not all blocks in the task showed this pattern. One reason could have been a quirk of the trial order for that given block. Nonetheless, the overall pattern matches the effects of capture over time that are found when looking across the entire experiment, and therefore don't appear to simply reflect random noise.

To examine the effect of time and validity on RTS, we conducted a series of linear multilevel models which assume that the dependent measure (RT) is normally distributed. To avoid violating this assumption reaction times were log-transformed. This transformation reduced the skew and kurtosis of the distributions, but also made interpreting the parameter estimates of both the fixed and random effects challenging. Future analyses might benefit from employing generalized linear mixed models in which the dependent variable can take on any number of distributions (Lo & Andrews, 2015). In particular, an inverse Gaussian distribution would better capture the typically positively skewed distributions found with response times. Although I feel it is unlikely that we would make substantively different conclusions about the effects of between and within subject conditions on RT, improved interpretability would likely make these models more palatable both to readers and to researchers who may be considering their use.

Another outstanding question from the present study is why we did not find a connection between the task-measure of attentional capture and the additional measures of individual differences in working memory, distractibility and impulsivity, despite the fact that such connections have been found previously (Berggren et al., 2011; Kane et al., 2001; Landau et al., 2012; Pratt et al., 2011). Many of these studies had similar sample sizes, so that is likely not the source of the null effect. Although it is tempting to claim that our sample of educated and young undergraduate students did not include enough variability in these measures, means and standard deviations of the CFQ are similar to what was found with a larger and more diverse sample (Wallace, 2004), and are fairly consistent across samples (Table 2). Interestingly, the BIS scores found in all three samples appear to be higher and less varied than those found in a large and similar sample (Stanford et al., 2009), so this may have contributed to the null effect. The span task scores were also similar in both their means and standard deviations to those found with a larger sample of undergraduate students (Oswald et al., 2014), which suggests that our sample is similarly representative of a population of college students but doesn't rule out the possibility that such a young and educated sample may still be restricted in their range of WMC scores. As mentioned previously, it is possible that the measures of individual differences were unable to account for RT effects because of issues of measurement error. A future analysis (or study) could address this by modeling the relationships among the underlying latent variables rather than the observed variables.

Conclusions

The two major findings of this study are that a novel type of attentional capture challenges the argument that saliency-driven capture is entirely mediated by top-down control (Töllner et al., 2012), and that the use of multilevel models to include time as a factor in an attentional capture paradigm enriches and expands the interpretation of the mean effects and their implication for the underlying mechanisms. In a series of experiments, we found capture to an irrelevant but salient distractor when task demands made the array containing the distractor relevant indicating saliency-driven capture (experiments 1a, 1c, and 2a). Critically, capture in this novel case was fundamentally different than the contingent capture observed when the distractor's key features were contained within the attentional set. Specifically, the magnitude of the capture in the event relevance task was smaller than that found in the contingent capture task. When looking at capture across participants over the entire course of the experiment by using multilevel models to include the random effects of time (i.e. trial), we also found that attentional capture changed significantly as a function of time and experience with the task and stimuli, but only for capture observed in the event relevance task. In a separate study examining the role of attentional control settings, we found that even when task settings for validity should motivate participants to rapidly disengage from, or actively suppress, a distracting cue, capture to the cue still occurred due its match with the attentional set for color. We also found, however, that over time, the validity effect was slightly reduced as a result of faster responses to the invalidly-cued trials only, possible reflecting implicit statistical learning of the cue's probability (Cosman & Vecera, 2014). Overall these studies contribute to our understanding of the complex influences of internal and external factors on attentional capture as well as the ways in which we can study them both experimentally and analytically.

<u>TABLES</u>

Table 1. Mean reaction times for Experiment 1in msec for valid-location and invalid-location targets.

	Valid RT	Invalid RT
Experiment 1a	543.3 (85.3)	560.1 (79.4)
Experiment 1b	534.3 (74.0)	530.9 (72.1)
Experiment 1c (Catch Trial Response Blocks)	585.4 (66.8)	622.0 (82.0)
Experiment 1c (No Catch Trial Response Blocks)	532.5 (82.4)	536.6 (73.1)
Experiment 1d	593.4 (72.4)	612.1 (72.6)

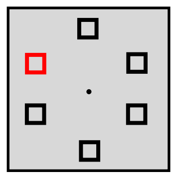
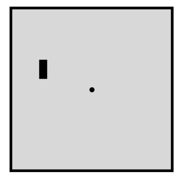
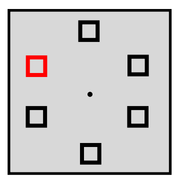
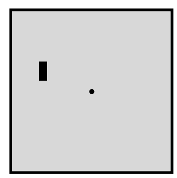
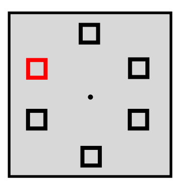
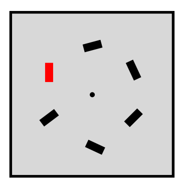
Standard deviations in parentheses

Table 2. Means for all variables for experiments 2 and 3.

	Valid RT (ms)	Invalid RT (ms)	Valid Accuracy %	Invalid Accuracy %	CFQ	BIS	OSpan	SSpan
Exp 2a	602.7 (77.44)	615.4 (76.33)	95.8 (3.1)	95.1 (3.6)	43.9 (12.57)	71.9 (9.24)	24.1 (5.57)	15.1 (5.62)
Exp 2b	582.8 (77.61)	608.9 (77.01)	95.97 (3.5)	94.4 (4.7)	41.5 (11.9)	68.5 (7.3)	23.0 (6.8)	15.5 (4.5)
Exp 3	556.1 (78.1)	578.4 (75.1)	95.5 (4.1)	94.5 (3.7)	39.1 (12.6)	70.6 (6.7)	n/a	n/a

Standard deviations in parentheses

Table 3. Conditions used in Experiments 1, 2 and 3. For the number of responses, 2 indicates that participants responded only to the orientation of the target (vertical versus horizontal); whereas 3 indicates that participants were additionally required to make a "no-target" detection response to catch trials. Critically, the cue was consistent across all conditions, and only the target was manipulated across conditions.

Condition	Full name	Cue Type	Target Type	# Responses	Experiment
CATCH	Onset target Catch response	Color 	Onset 	3	1A 1C 2A
NO_CATCH	Onset target No catch response	Color 	Onset 	2	1B 1C
COLOR_TAR	Color target No catch response	Color 	Color 	2	1D 2B 3

FIGURES

Figure 1. Contingent cueing paradigm adapted from Folk et al., 1992. Capture to the cue was only found when the cue's features matched those of the target.

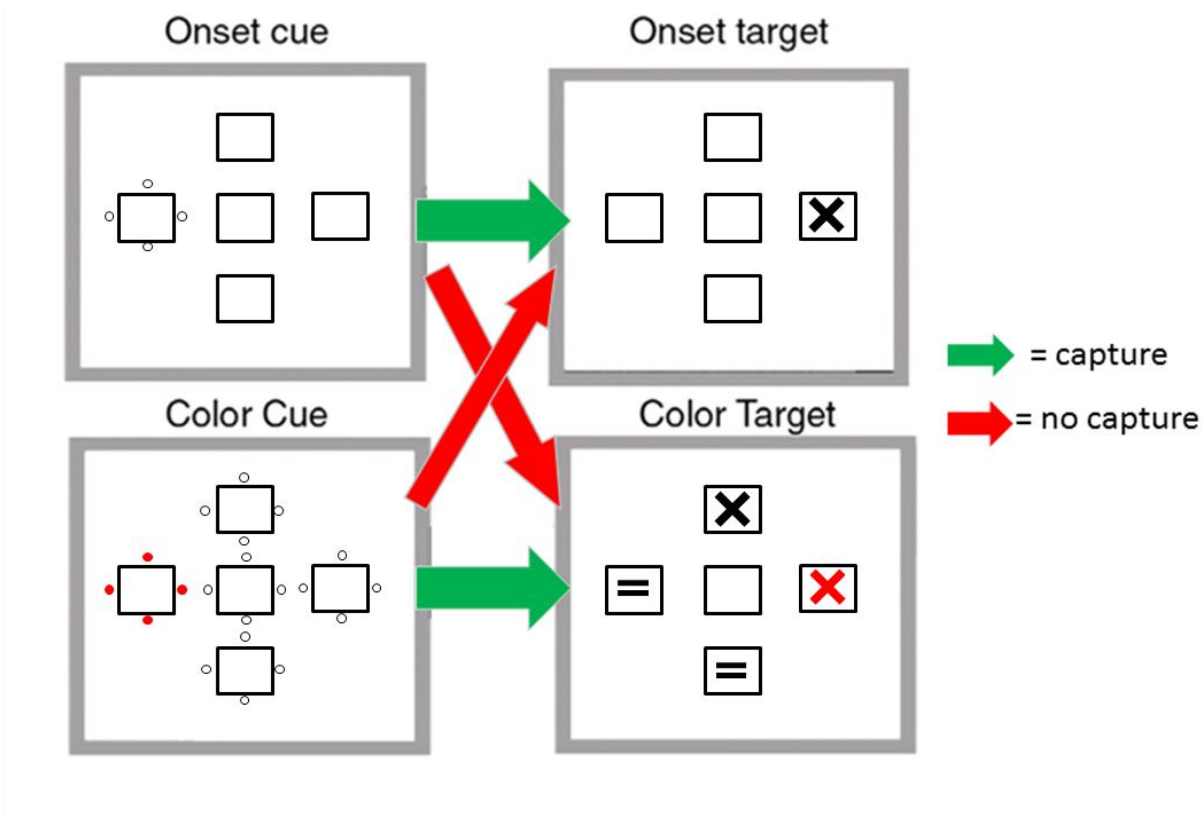


Figure 2. Additional singleton paradigm adapted from Theeuwes, 2010.Capture to the irrelevant distractor was found when saliency was high (red versus yellow), as evidence by slower reaction times to the target for distractor present vs. absent trials.

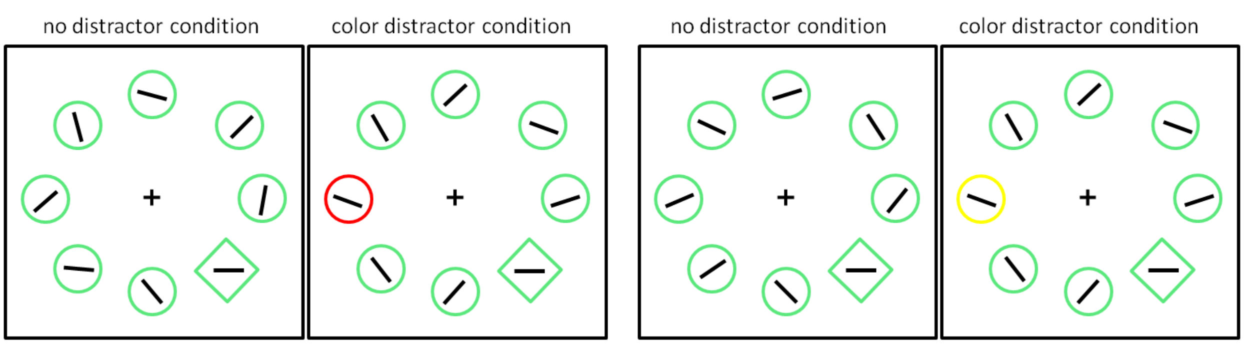


Figure 3. Paradigm for experiments 1a-1c.

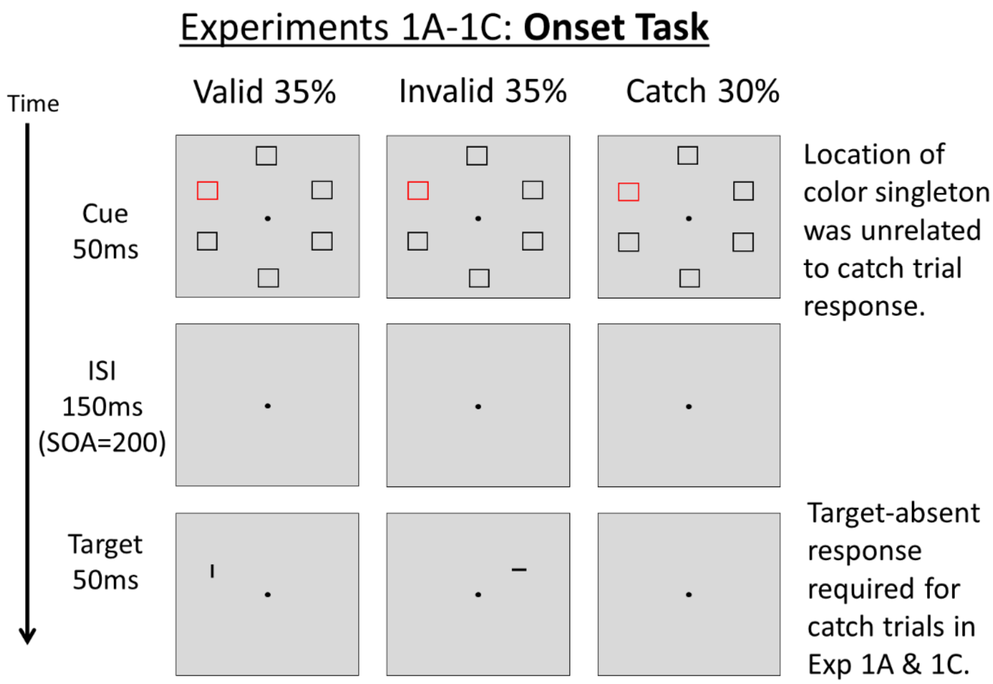


Figure 4. Paradigm for experiment 1d.

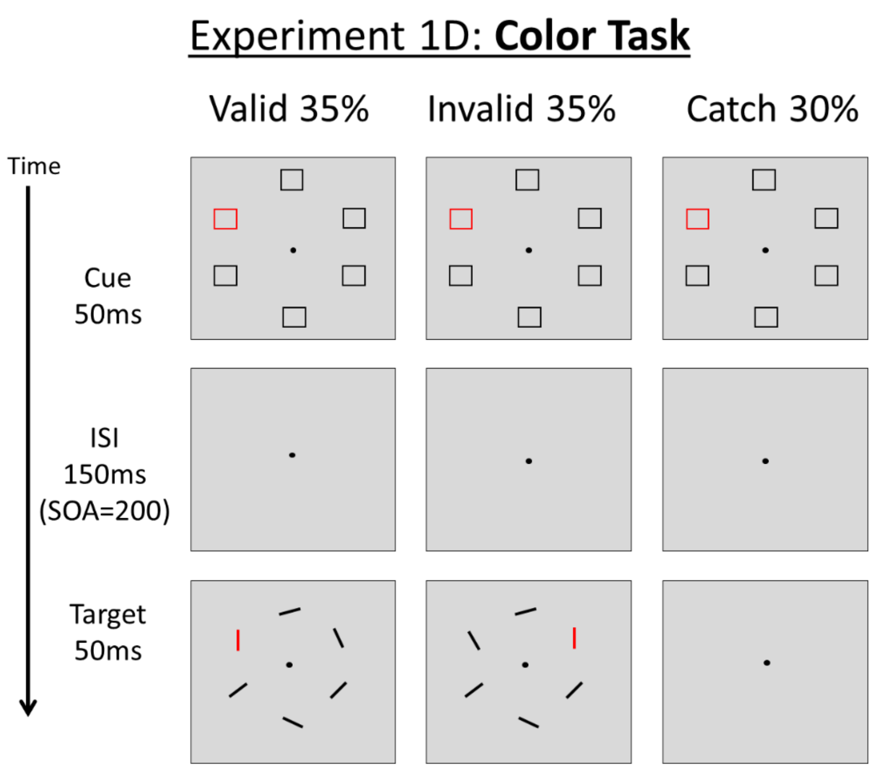
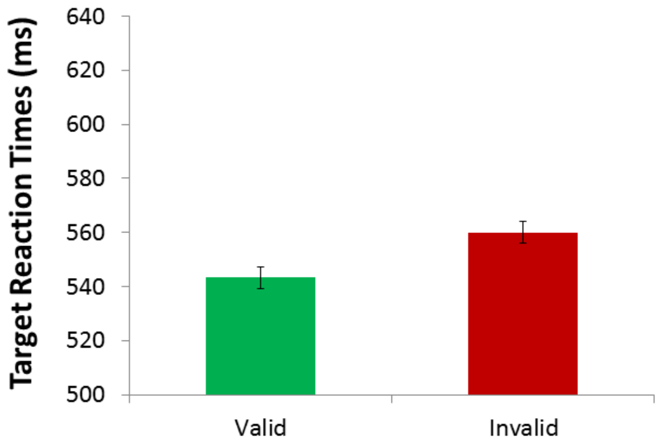
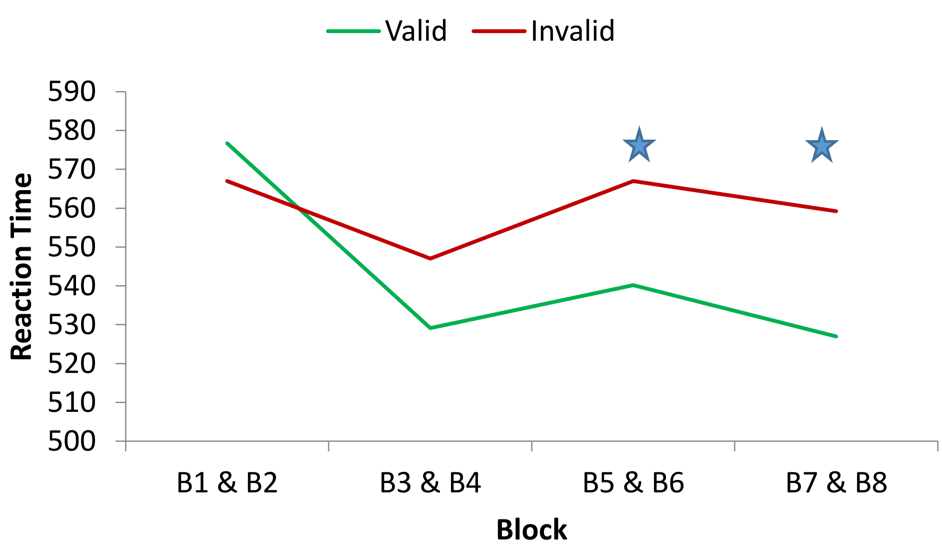


Figure 5. Experiment 1a reaction times.



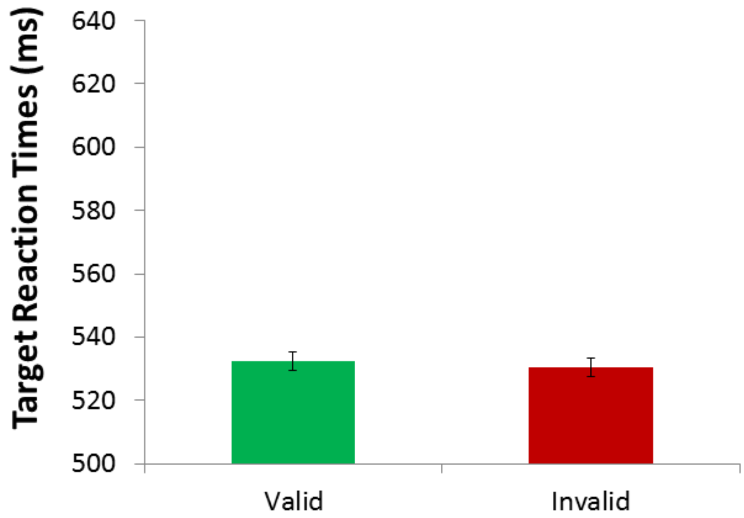
Error bars show unbiased within-subject SEM (Morey, 2008)

Figure 6. Experiment 1a capture effect across blocks.



Stars indicate significance at p<0.0125.

Figure 7. Experiment 1b reaction times.



Error bars show unbiased within-subject SEM (Morey, 2008)

Figure 8. Experiment 1c reaction times.

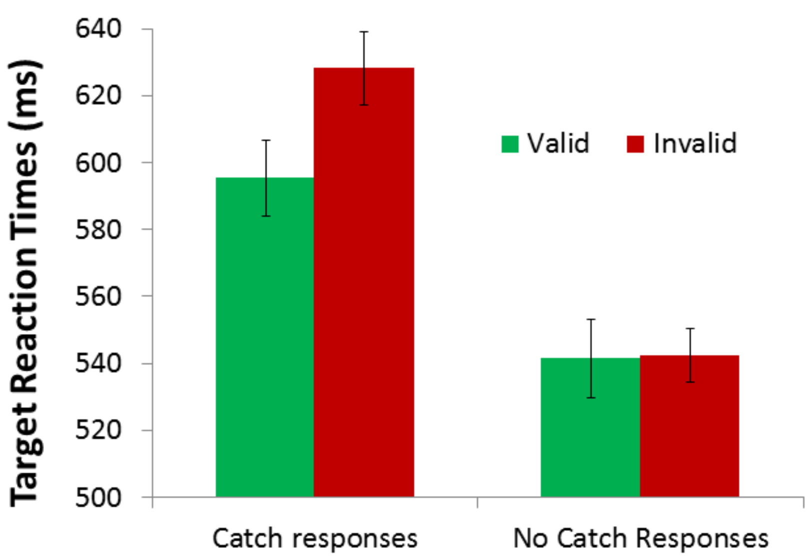


Figure 9. Experiment 1d reaction times.

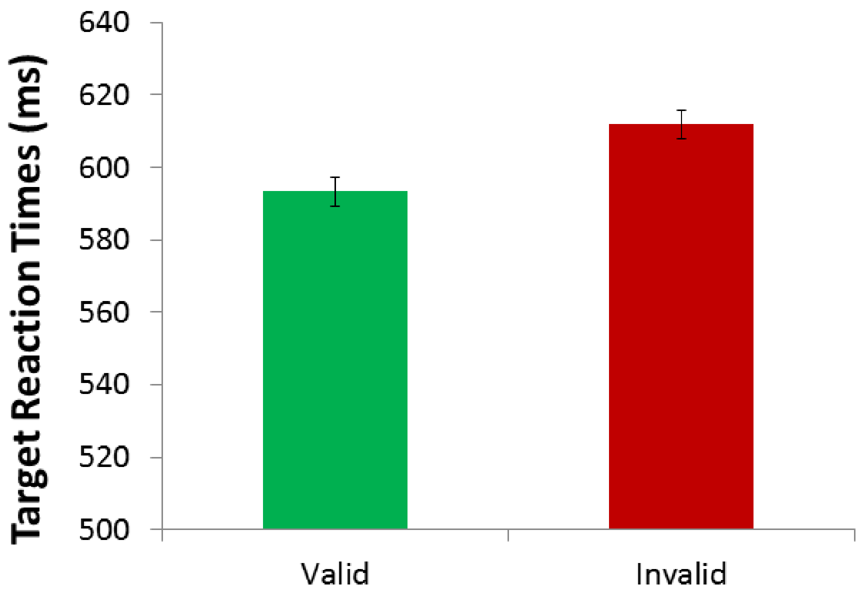
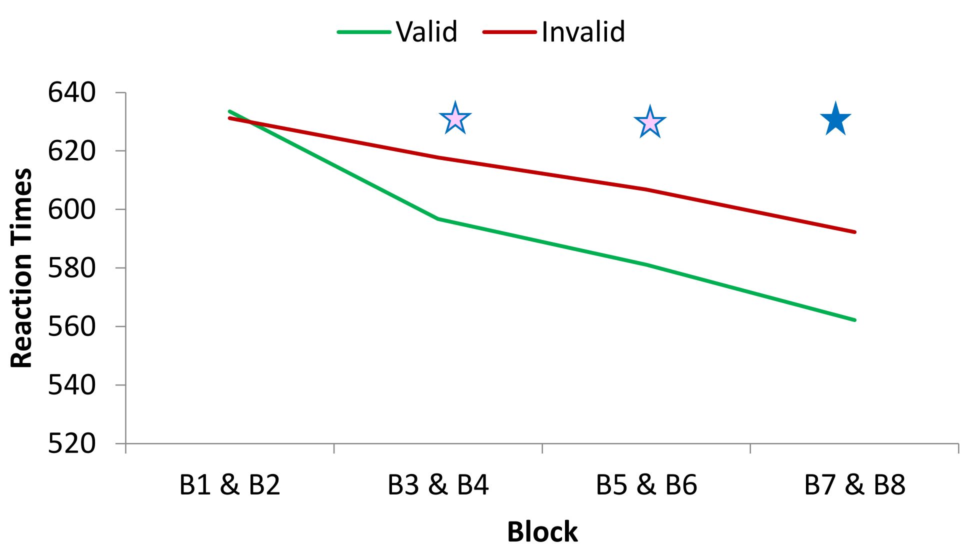


Figure 10. Experiment 1d. capture effect across blocks:



Yellow stars indicate significance at $p<0.0125$. Pink star indicates significant at $p<0.05$.

Figure 11. Experiment 2 paradigm. Catch trials (cue-only) occurred 30% of the time in each task, but a “target-absent” response to these trials is only required in experiment 2A.

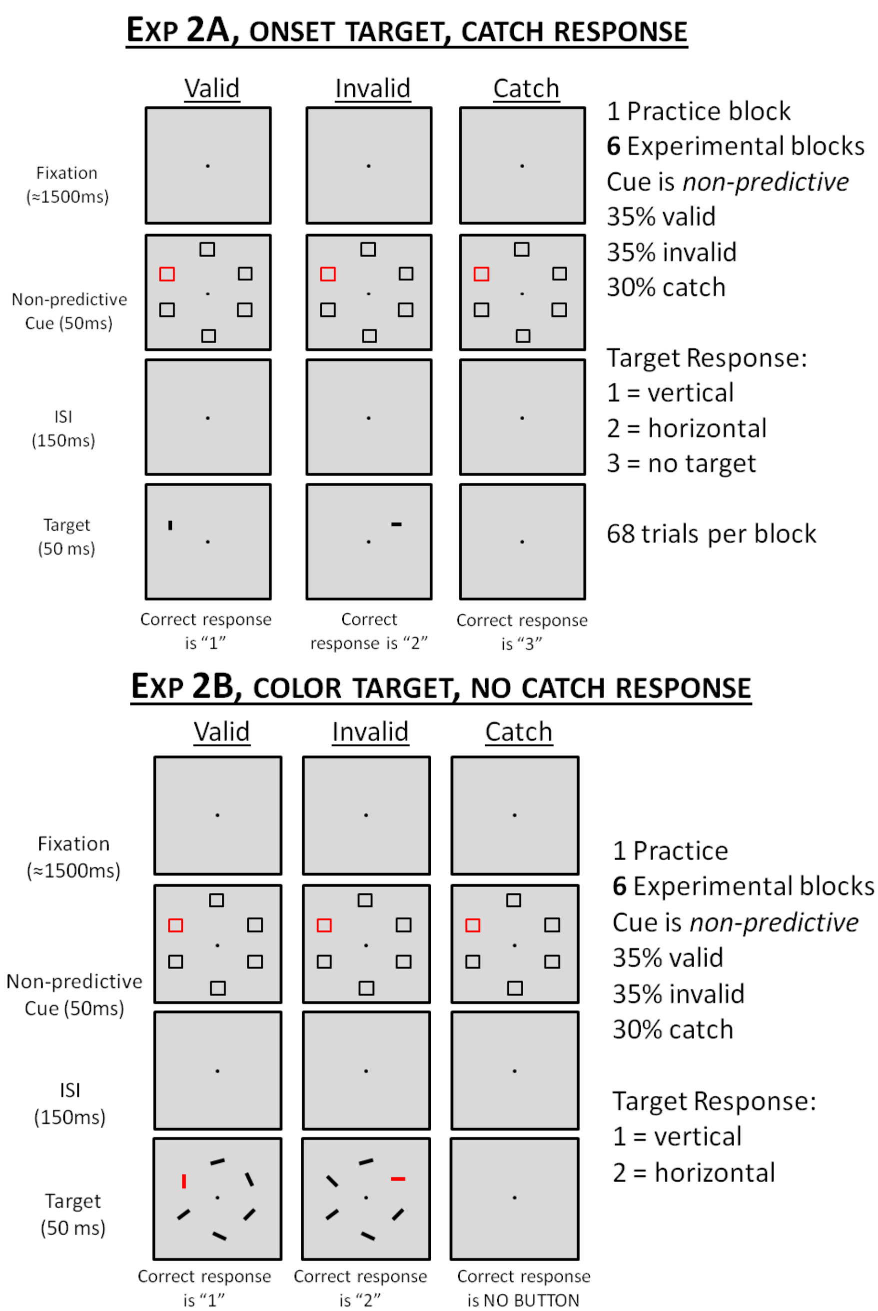


Figure 12. Experiments 2 and 3 mean reaction times.

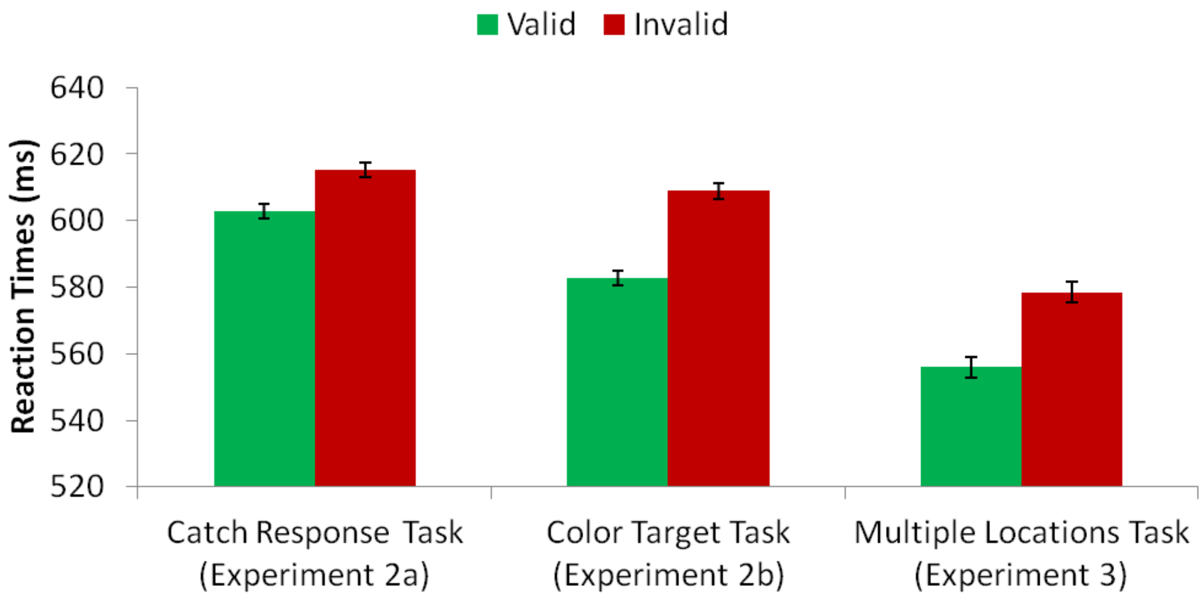
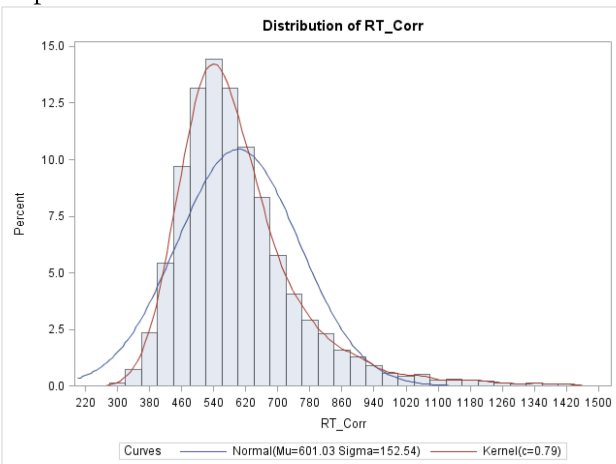
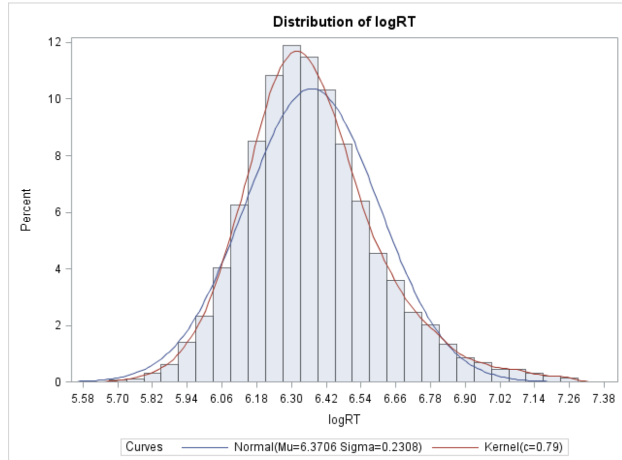


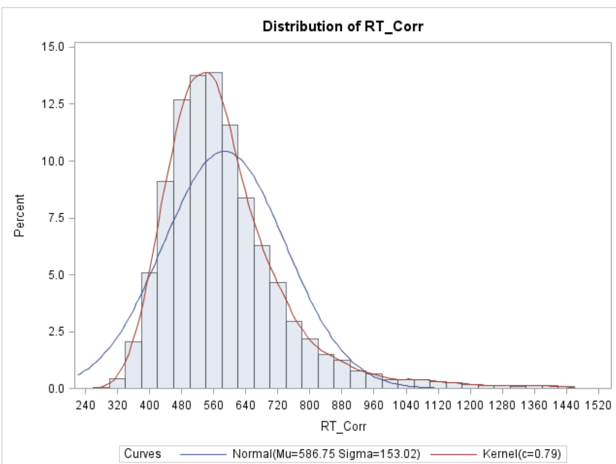
Figure 13. Histograms of raw and log-transformed RTs for experiments 2 and 3.

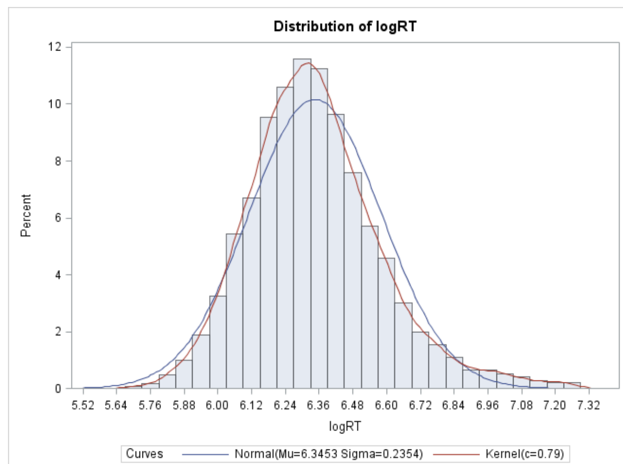
Experiment 2a



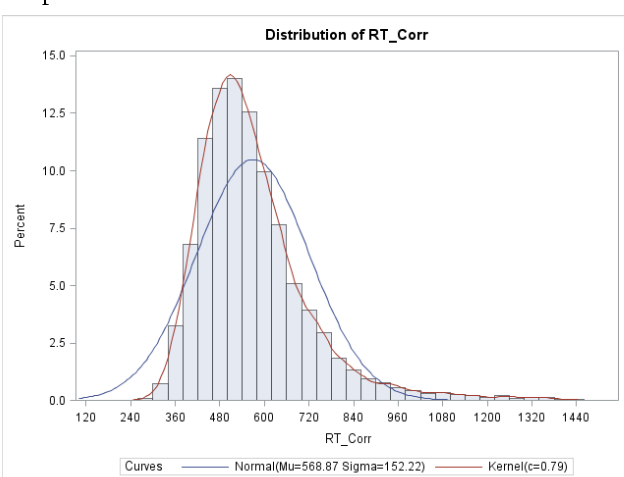


Experiment 2b





Experiment 3



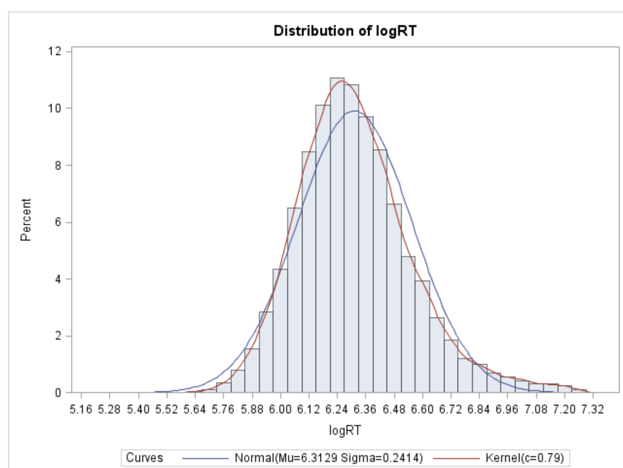


Figure 14. Experiment 2a individual variability in predicted RTs across time.

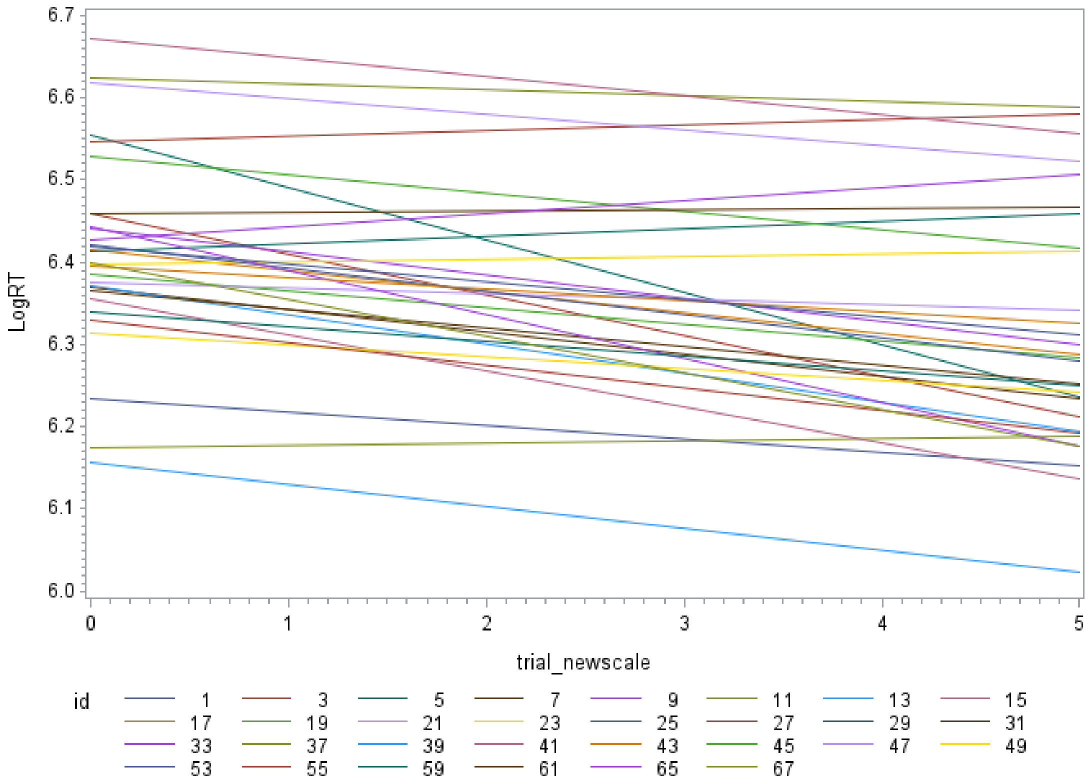


Figure 15. Experiment 2a effect of validity across all trials.

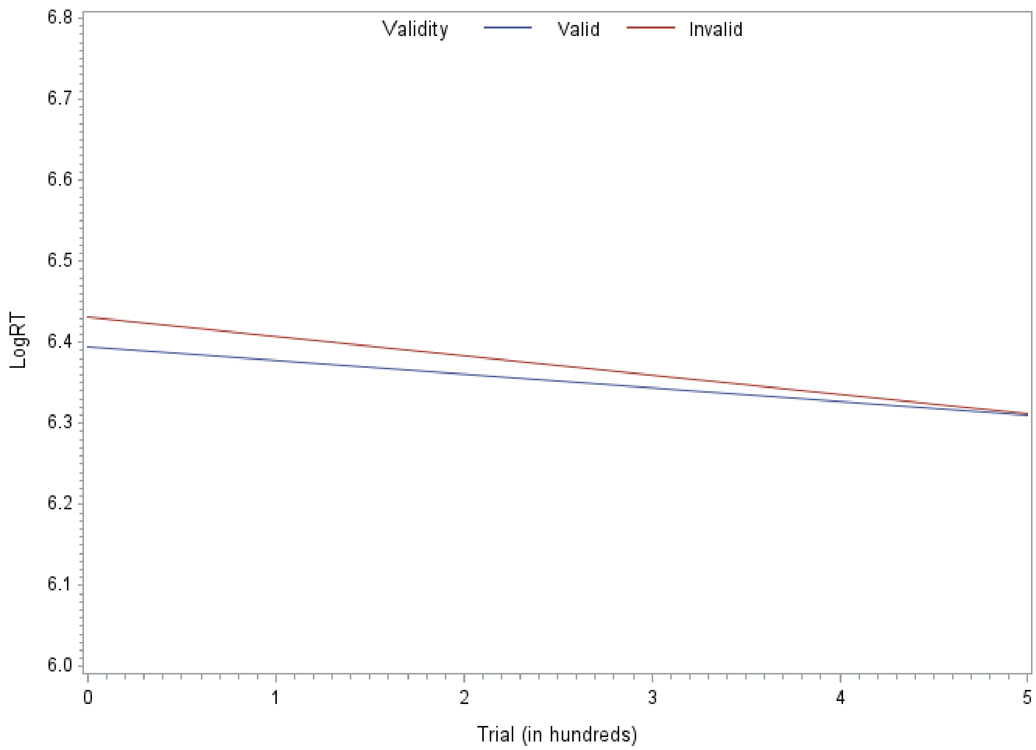


Figure 16. Experiment 2a means for rmANOVA test of validity by block effect

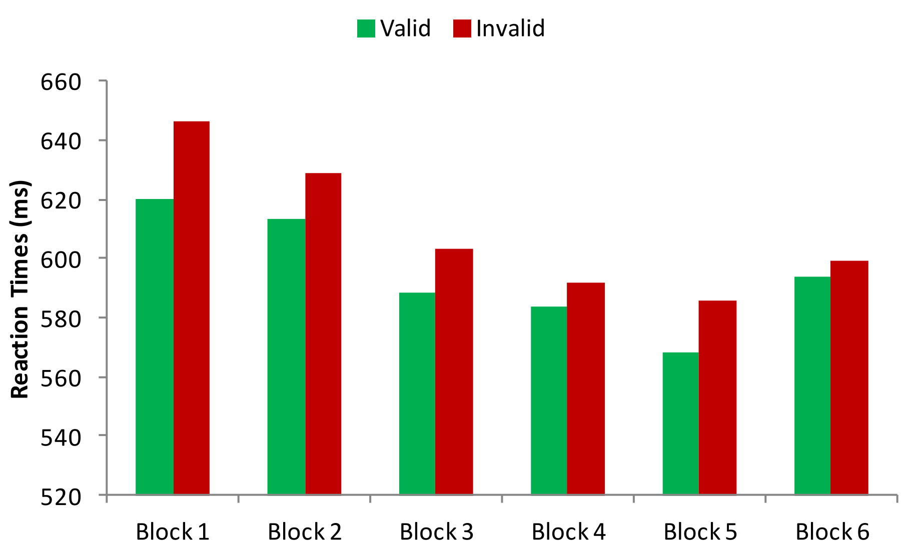


Figure 17. Experiment 2a validity by time effect within each block.

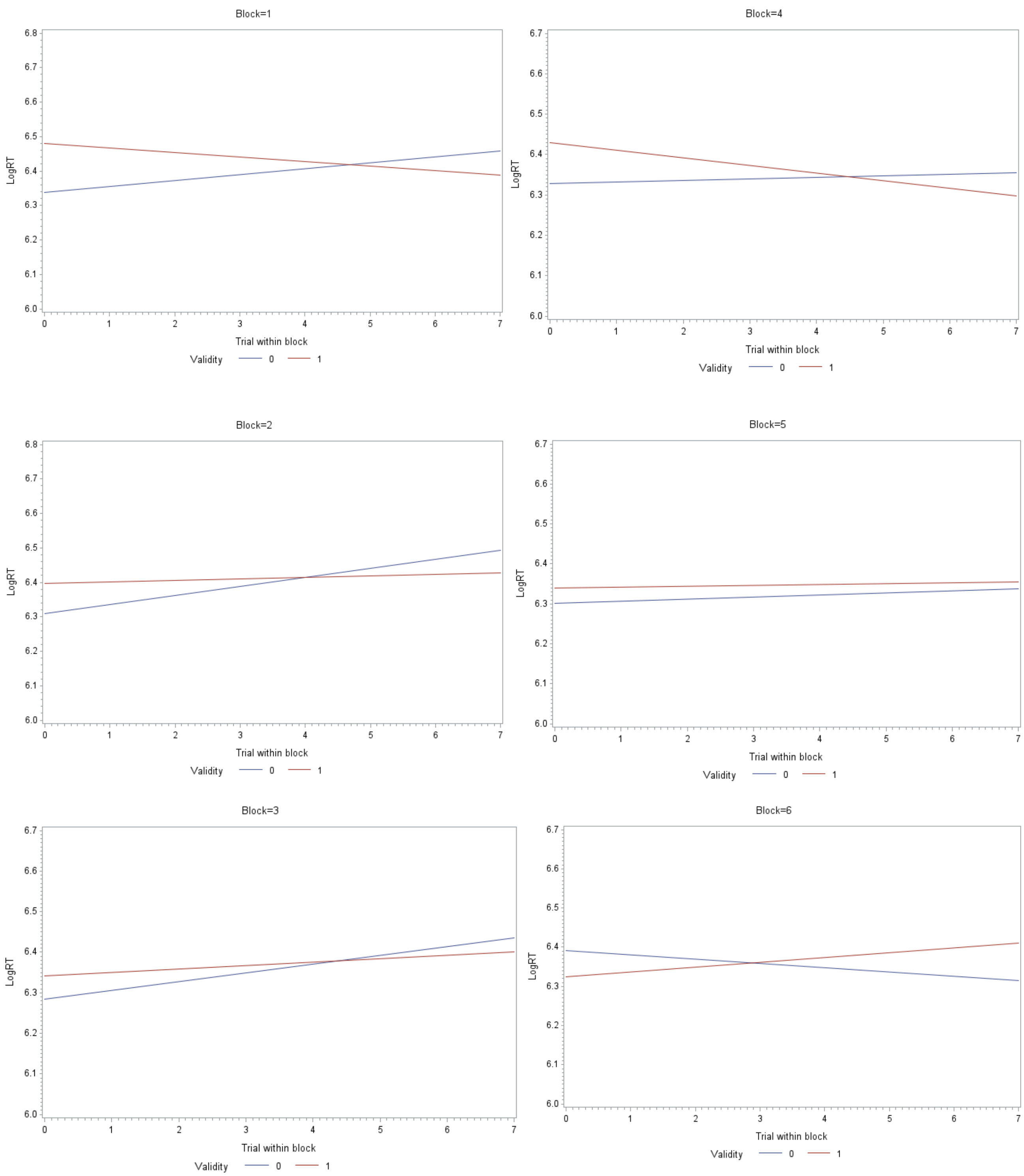


Figure 18. Experiment 2b individual variability in predicted RTs across time.

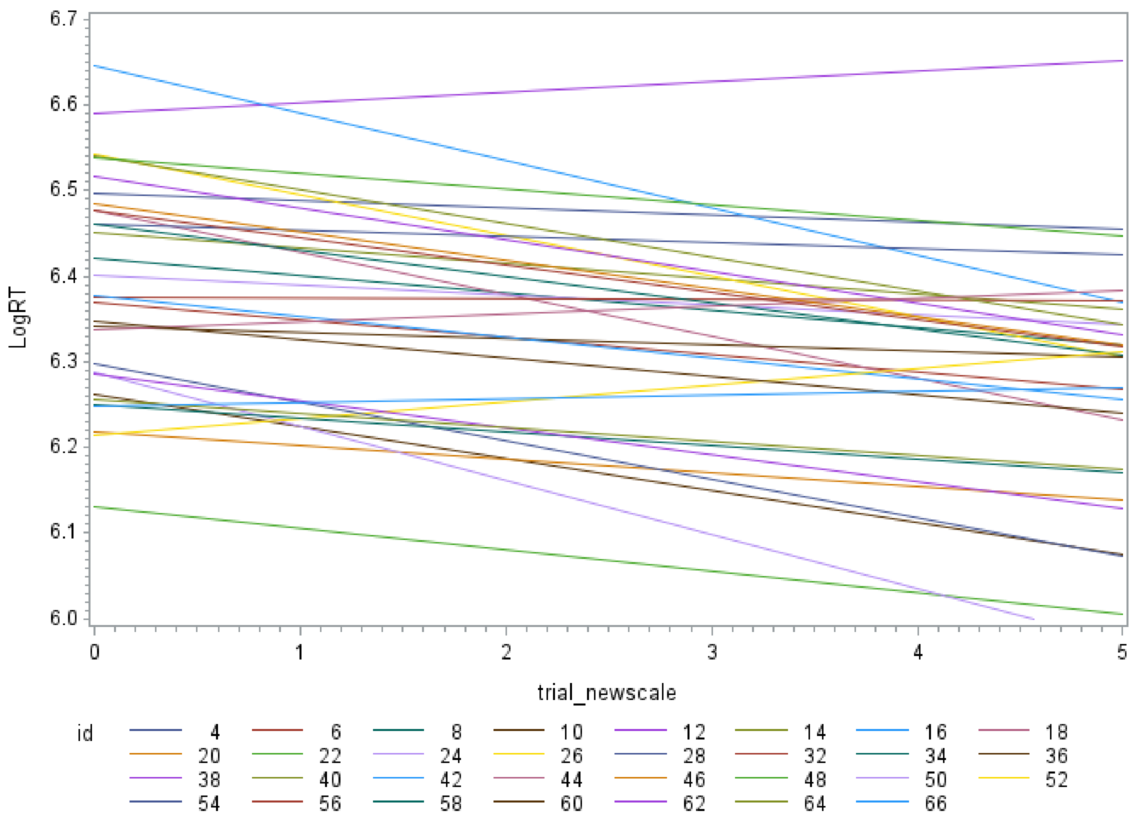


Figure 19. Experiment 2b effect of validity across all trials.

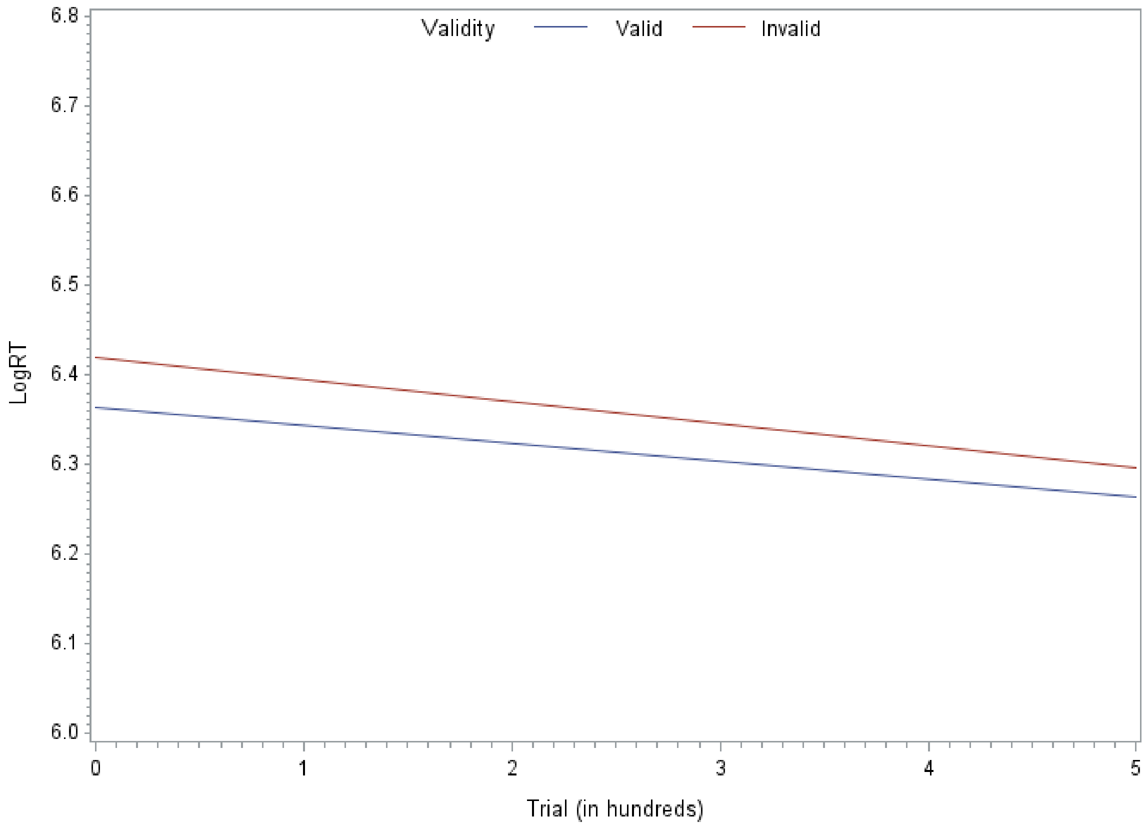


Figure 20. Experiment 2b means for rmANOVA test of validity by block effect.

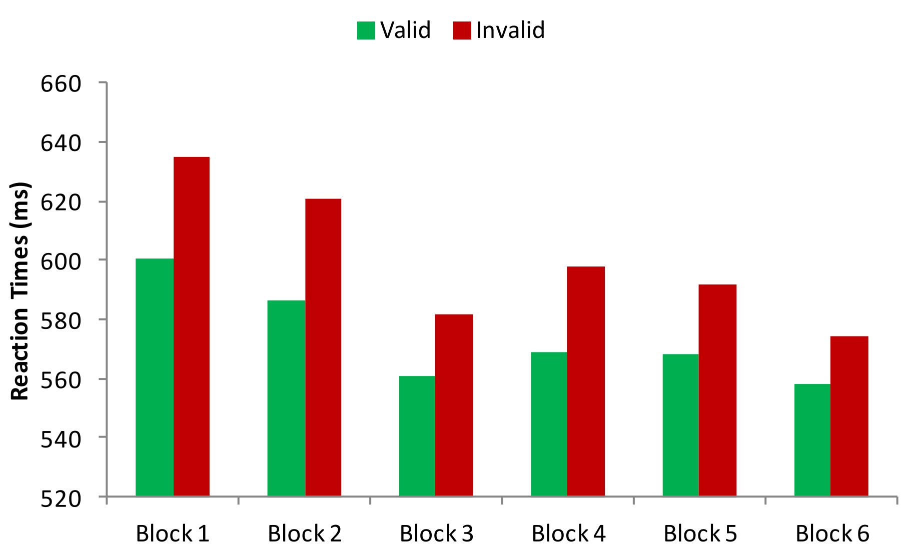


Figure 21. Experiment 2b validity by time effect within each block.

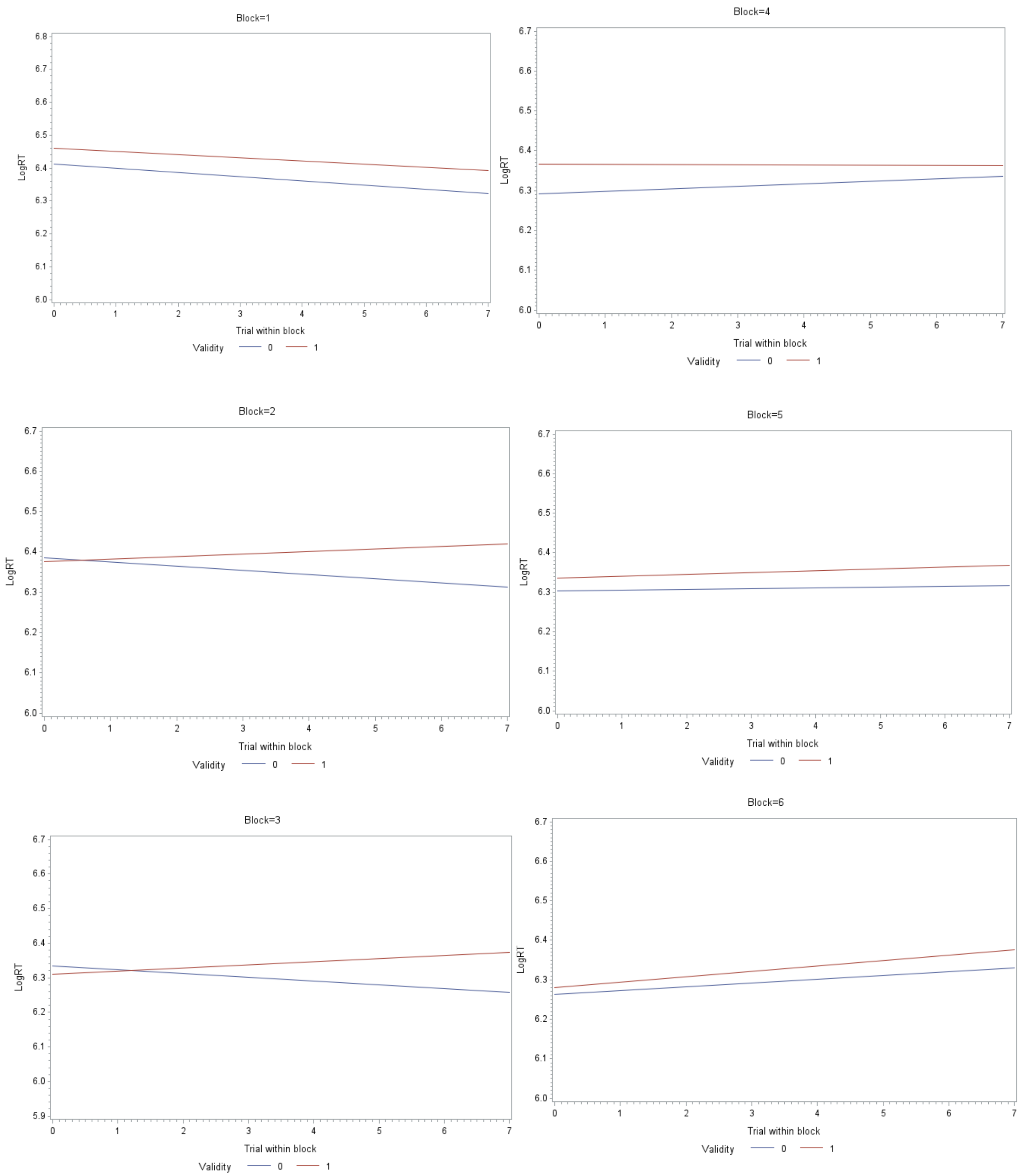


Figure 22. Experiment 3 paradigm.

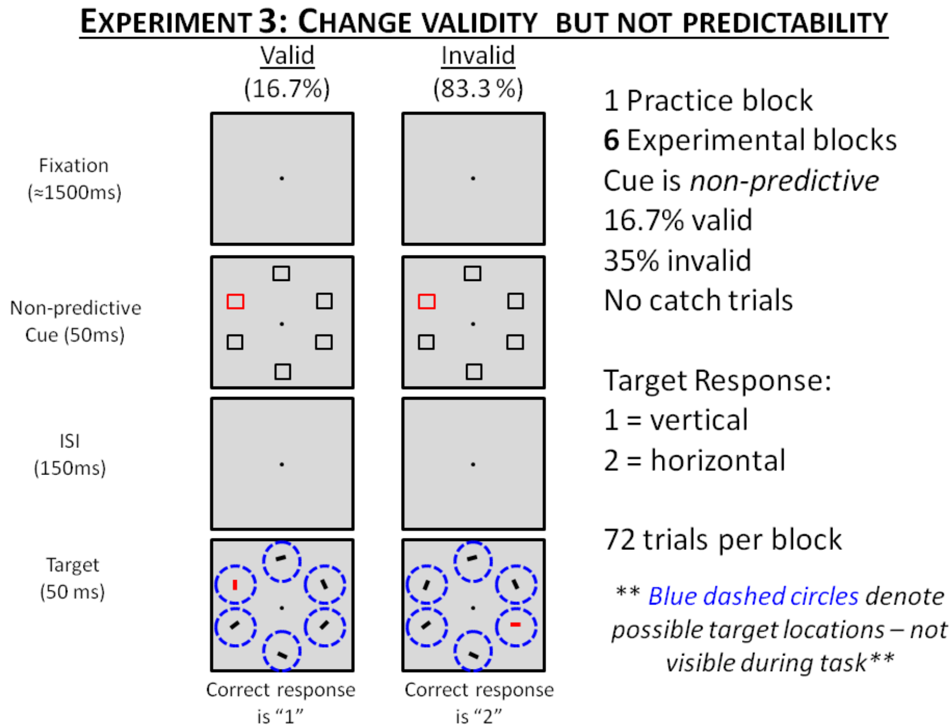


Figure 23. Experiment 3 individual variability in predicted RTs across time.

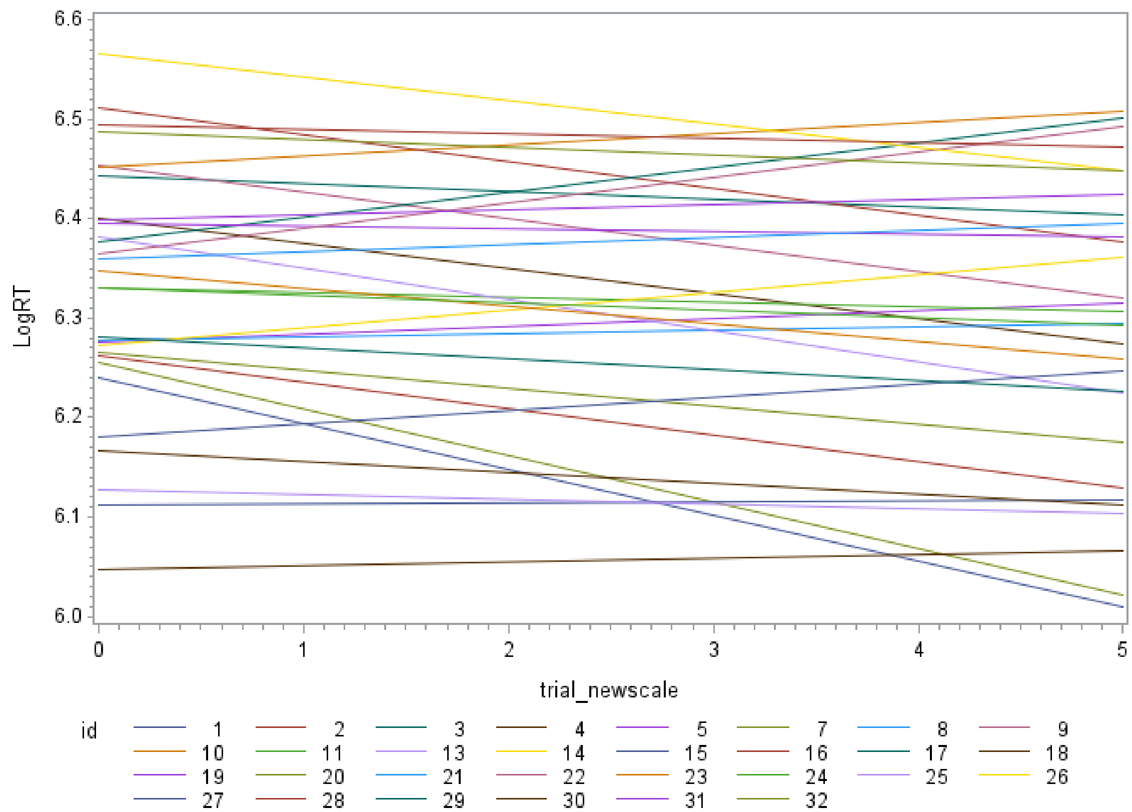


Figure 24. Experiment 3 effect of validity across all trials.

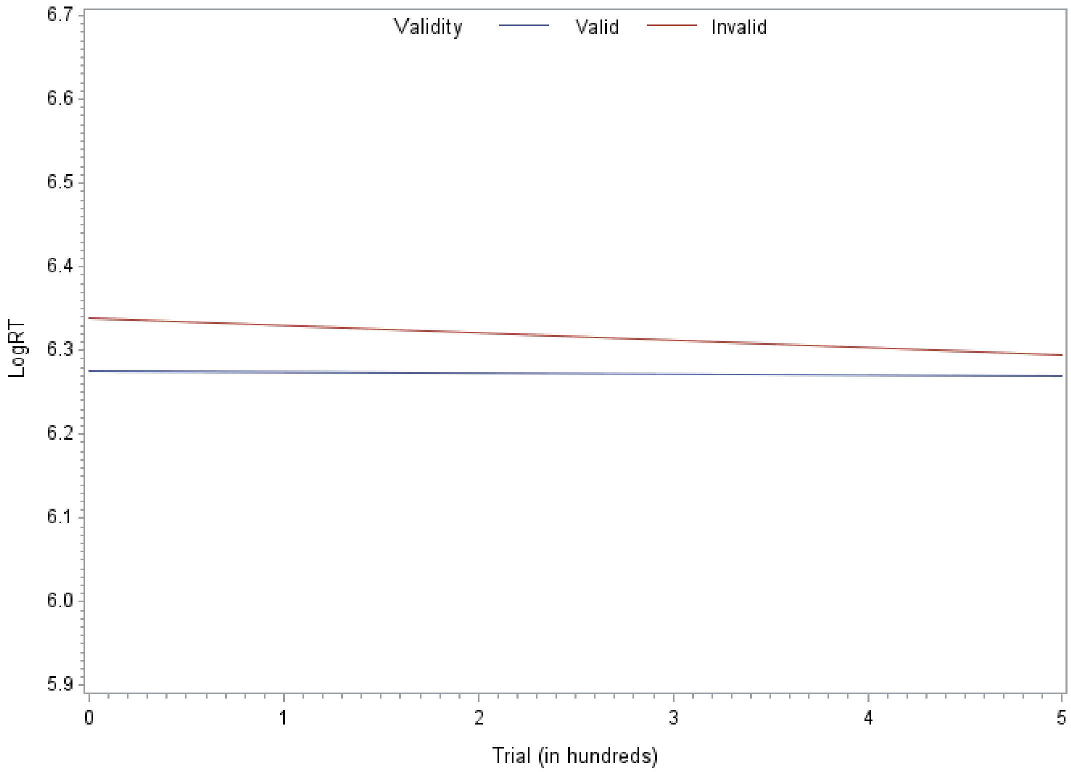


Figure 25. Experiment 3 means for rmANOVA test of validity by block effect.

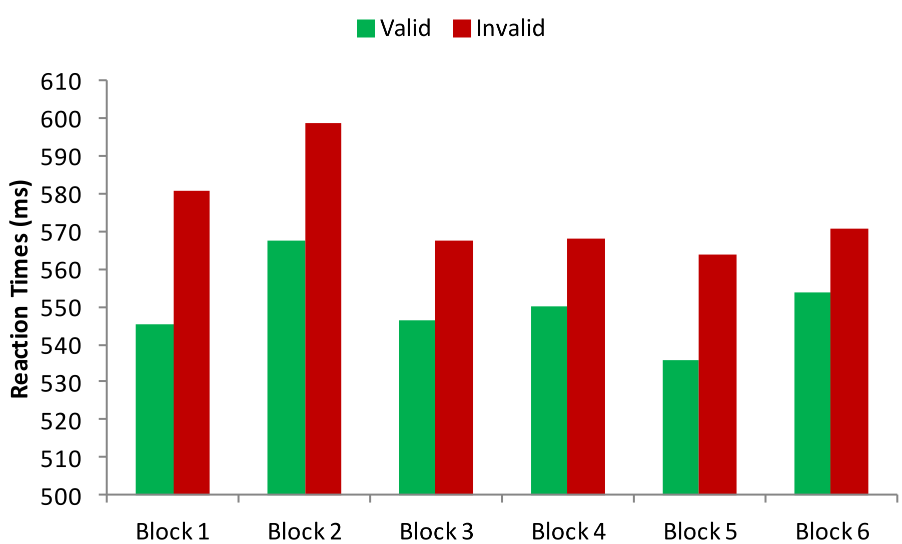
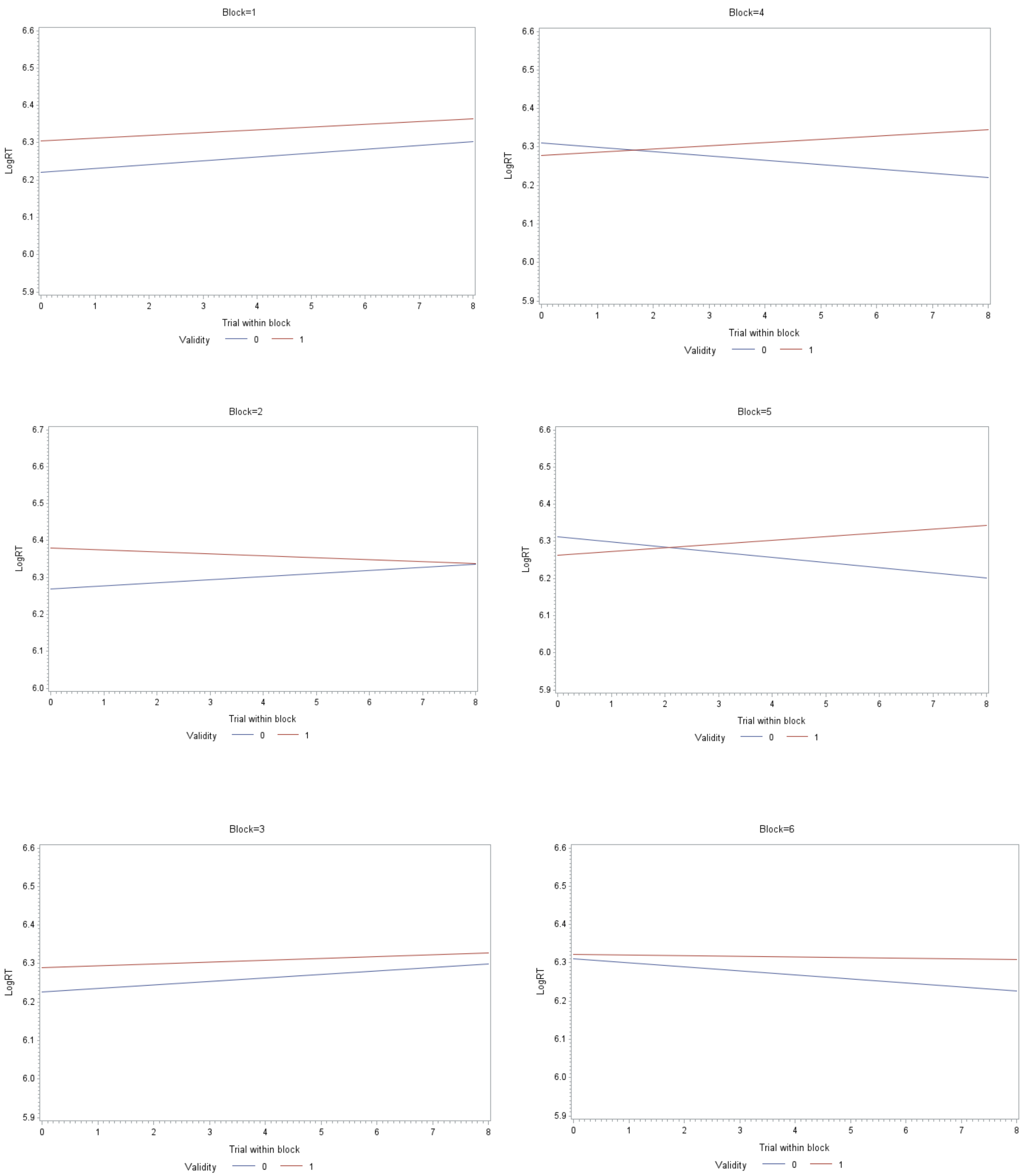


Figure 26. Experiment 3 validity by time effect within each block.



APPENDIX A. COGNITIVE FAILURES QUESTIONNAIRE (CFQ)

CFQ

The following questions are about minor mistakes which everyone makes from time to time, but some of which happen more often than others. We want to know how often these things have happened to your in the past 6 months. Please circle the appropriate number.

		Very often	Quite often	Occasion-ally	Very rarely	Never
1.	Do you read something and find you haven't been thinking about it and must read it again?	4	3	2	1	0
2.	Do you find you forget why you went from one part of the house to the other?	4	3	2	1	0
3.	Do you fail to notice signposts on the road?	4	3	2	1	0
4.	Do you find you confuse right and left when giving directions?	4	3	2	1	0
5.	Do you bump into people?	4	3	2	1	0
6.	Do you find you forget whether you've turned off a light or a fire or locked the door?	4	3	2	1	0
7.	Do you fail to listen to people's names when you are meeting them?	4	3	2	1	0
8.	Do you say something and realize afterwards that it might be taken as insulting?	4	3	2	1	0
9.	Do you fail to hear people speaking to you when you are doing something else?	4	3	2	1	0
10.	Do you lose your temper and regret it?	4	3	2	1	0
11.	Do you leave important letters unanswered for days?	4	3	2	1	0
12.	Do you find you forget which way to turn on a road you know well but rarely use?	4	3	2	1	0
13.	Do you fail to see what you want in a supermarket (although it's there)?	4	3	2	1	0
14.	Do you find yourself suddenly wondering whether you've used a word correctly?	4	3	2	1	0

		Very often	Quite often	Occasion-ally	Very rarely	Never
15.	Do you have trouble making up your mind?	4	3	2	1	0
16.	Do you find you forget appointments?	4	3	2	1	0
17.	Do you forget where you put something like a newspaper or a book?	4	3	2	1	0
18.	Do you find you accidentally throw away the thing you want and keep what you meant to throw away – as in the example of throwing away the matchbox and putting the used match in your pocket?	4	3	2	1	0
19.	Do you daydream when you ought to be listening to something?	4	3	2	1	0
20.	Do you find you forget people's names?	4	3	2	1	0
21.	Do you start doing one thing at home and get distracted into doing something else (unintentionally)?	4	3	2	1	0
22.	Do you find you can't quite remember something although it's "on the tip of your tongue"?	4	3	2	1	0
23.	Do you find you forget what you came to the shops to buy?	4	3	2	1	0
24.	Do you drop things?	4	3	2	1	0
25.	Do you find you can't think of anything to say?	4	3	2	1	0

APPENDIX B. BARRATT IMPULSIVENESS SCALE (BIS-11)

DIRECTIONS: People differ in the ways they act and think in different situations. This is a test to measure some of the ways in which you act and think. Read each statement and put an X on the appropriate circle on the right side of this page. Do not spend too much time on any statement. Answer quickly and honestly.

O O O O

Rarely/Never Occasionally Often Almost

Always/Always

1	I plan tasks carefully.	O	O	O	O
2	I do things without thinking.	O	O	O	O
3	I make-up my mind quickly.	O	O	O	O
4	I am happy-go-lucky.	O	O	O	O
5	I don't "pay attention."	O	O	O	O
6	I have "racing" thoughts.	O	O	O	O
7	I plan trips well ahead of time.	O	O	O	O
8	I am self controlled.	O	O	O	O
9	I concentrate easily.	O	O	O	O
10	I save regularly.	O	O	O	O
11	I "squirm" at plays or lectures.	O	O	O	O
12	I am a careful thinker.	O	O	O	O
13	I plan for job security.	O	O	O	O
14	I say things without thinking.	O	O	O	O
15	I like to think about complex problems.	O	O	O	O

16 I change jobs.	O O O O
17 I act "on impulse."	O O O O
18 I get easily bored when solving thought problems.	O O O O
19 I act on the spur of the moment.	O O O O
20 I am a steady thinker.	O O O O
21 I change residences.	O O O O
22 I buy things on impulse.	O O O O
23 I can only think about one thing at a time.	O O O O
24 I change hobbies.	O O O O
25 I spend or charge more than I earn.	O O O O
26 I often have extraneous thoughts when thinking.	O O O O
27 I am more interested in the present than the future.	O O O O
28 I am restless at the theater or lectures.	O O O O
29 I like puzzles.	O O O O
30 I am future oriented.	O O O O

Questions 1, 7, 8, 9, 10, 12, 13, 15, 20, 29 & 30 are reverse coded such that never = 4 and always = 1.

APPENDIX C. MULTILEVEL MODEL EQUATIONS

NOTE: In all models RT is actually the log of the raw RT scores

Model 1. Random effects ANOVA model (no predictors)

Level 1: $RT_{ij} = \beta_{0j} + r_{ij}$ $\quad r_{ij} \sim N(0, \sigma^2)$

Level 2: $\beta_{0j} = \gamma_{00} + u_{0j}$ $\quad u_{0j} \sim N(0, \tau_{00})$

Reduced-form: $RT_{ij} = \gamma_{00} + u_{0j} + r_{ij}$

γ_{00} = mean RT across all observations, adjusted for repeated measures
r_{ij} = difference between each observed RT and overall mean RT, for a given person
u_{0j} = difference between a person's mean RT and the overall mean RT
σ^2 = V(r_{ij}), or the average amount of within-person RT variance
τ_{00} = V(u_{ij}), or the average amount of between-person RT variance

Model 2a. Unconditional growth model with time (i.e. trial exposure) as only predictor

Level 1: $RT_{ij} = \beta_{0j} + \beta_{1j}Trial_{ij} + r_{ij}$ $\quad r_{ij} \sim N(0, \sigma^2)$

Level 2: $\beta_{0j} = \gamma_{00} + u_{0j}$ $\quad \begin{bmatrix} u_{00} \\ u_{10} \end{bmatrix} \sim N\left(\begin{bmatrix} 0, \tau_{00} \\ 0, \tau_{11} \end{bmatrix}, \begin{bmatrix} \tau_{00} & \\ \tau_{10} & \tau_{11} \end{bmatrix}\right)$

$\beta_{1j} = \gamma_{10} + u_{1j}$

Reduced-form: $RT_{ij} = \gamma_{00} + \gamma_{10}Trial_{ij} + u_{0j} + u_{1j}Trial_{ij} + r_{ij}$

τ_{00} = variance of intercepts, extent to which people differ in RT for the first trial.
τ_{11} = variance of slopes, or the extent to people have different rates of change in RT over the course of the experiment
τ_{10} = covariance between the slope and intercept, or the relationship between a person's initial RT their change in RT as a function of time

Model 2b. Random effect of Exposure with AR(1) residual structure:

Level 1: $RT_{ij} = \beta_{0j} + \beta_{1j}Trial_{ij} + r_{ij}$

$$\boldsymbol{r_j} \sim N(\boldsymbol{0}, \boldsymbol{\Sigma})$$
$$\boldsymbol{\Sigma_j}[i, i'] = \sigma^2 \rho^{\left|time_{i'j} - time_{ij}\right|}$$

Level 2: $\beta_{0j} = \gamma_{00} + u_{0j}$

$\beta_{1j} = \gamma_{10} + u_{1j}$

$$\begin{bmatrix} u_{00} \\ u_{10} \end{bmatrix} \sim N\left(\begin{bmatrix} 0, \tau_{00} \\ 0, \tau_{11} \end{bmatrix}, \begin{bmatrix} \tau_{00} & \\ \tau_{10} & \tau_{11} \end{bmatrix}\right)$$

Reduced-form: $RT_{ij} = \gamma_{00} + \gamma_{10}Trial_{ij} + u_{0j} + u_{1j}Trial_{ij} + r_{ij}$

Tests presence of a continuous-time autoregressive error structure.

Model 3. Conditional growth model with effect of target validity:

Level 1: $RT_{ij} = \beta_{0j} + \beta_{1j}Trial_{ij} + \beta_{2j}Validity_{ij} + \beta_{3j}Trial_{ij} * Validity_{ij} + r_{ij}$

$$r_j \sim N(0, \Sigma)$$
$$\Sigma_j[i, i'] = \sigma^2 \rho^{\left|time_{i'j} - time_{ij}\right|}$$

Level 2: $\beta_{0j} = \gamma_{00} + u_{0j}$

$\beta_{1j} = \gamma_{10} + u_{1j}$

$$\begin{bmatrix} u_{00} \\ u_{10} \end{bmatrix} \sim N\left(\begin{bmatrix} 0, \tau_{00} \\ 0, \tau_{11} \end{bmatrix}, \begin{bmatrix} \tau_{00} & \tau_{01} \\ \tau_{10} & \tau_{11} \end{bmatrix}\right)$$

$\beta_{2j} = \gamma_{20}$
$\beta_{3j} = \gamma_{30}$

Reduced-form: $RT_{ij} = \gamma_{00} + \gamma_{10}Trial_{ij} + \gamma_{20}Invalid_{ij} + \gamma_{30}Trial_{ij} * Validity_{ij} + u_{0j} + u_{1j}Trial_{ij} + r_{ij}$

γ_{20} = model implied change in RT during invalid target trials, at the intercept
γ_{30} = model implied interaction between Validity and Time (i.e. whether or not RT for a given validity condition is different across time)

Valid is the reference category.

Model 4. Includes mean accuracy for each person as a covariate:

Level 1: $RT_{ij} = \beta_{0j} + \beta_{1j}Trial_{ij} + \beta_{2j}Validity_{ij} + \beta_{3j}Trial_{ij} * Validity_{ij} + r_{ij}$

$$r_j \sim N(0, \Sigma)$$

$$\Sigma_j[i, i'] = \sigma^2 \rho^{\left|time_{i'j} - time_{ij}\right|}$$

Level 2: $\beta_{0j} = \gamma_{00} + \gamma_{01}MeanAccuracy + u_{0j}$ $\quad \begin{bmatrix} u_{00} \\ u_{10} \end{bmatrix} \sim N\left(\begin{bmatrix} 0, \tau_{00} \\ 0, \tau_{11} \end{bmatrix}, \begin{bmatrix} \tau_{00} & \tau_{01} \\ \tau_{10} & \tau_{11} \end{bmatrix}\right)$

$\beta_{1j} = \gamma_{10} + u_{1j}$

$\beta_{2j} = \gamma_{20}$

$\beta_{3j} = \gamma_{30}$

Reduced-form: $RT_{ij} = \gamma_{00} + \gamma_{01}MeanAccuracy + \gamma_{10}Trial_{ij} + \gamma_{20}Invalid_{ij} + \gamma_{30}Trial_{ij} * Validity_{ij} + u_{0j} + u_{1j}Trial_{ij} + r_{ij}$

γ_{01} = model implied change in RT as a function of mean accuracy between people.
MeanAccuracy is mean-centered across participants in each experiment
All other parameters are now estimated controlling for the between-person covariate.

Model 5. Unconditional growth model WITHIN a block

Level 1: $RT_{ij} = \beta_{0j} + \beta_{1j}BlockTrial_{ij} + r_{ij}$ $\quad \boldsymbol{r}_j \sim N(\mathbf{0}, \mathbf{\Sigma})$

$$\mathbf{\Sigma}_{\boldsymbol{j}}[i, i'] = \sigma^2 \rho^{\left|time_{i'j} - time_{ij}\right|}$$

Level 2: $\beta_{0j} = \gamma_{00} + u_{0j}$ $\quad \begin{bmatrix} u_{00} \\ u_{10} \end{bmatrix} \sim N\left(\begin{bmatrix} 0, \tau_{00} \\ 0, \tau_{11} \end{bmatrix}, \begin{bmatrix} \tau_{00} & \tau_{01} \\ \tau_{10} & \tau_{11} \end{bmatrix}\right)$

$\beta_{1j} = \gamma_{10} + u_{1j}$

Reduced-form: $RT_{ij} = \gamma_{00} + \gamma_{10}BlockTrial_{ij} + u_{0j} + u_{1j}BlockTrial_{ij} + r_{ij}$

Model 6. Interaction between Validity and Time within and across Blocks

Level 1: $RT_{ij} = \beta_{0j} + \beta_{1j}BlockTrial_{ij} + \beta_{2j}Validity_{ij} + \beta_{3j}Block_{ij} + \beta_{4j}BlockTrial_{ij} * Validity_{ij} + \beta_{5j}Block_{ij} * Validity_{ij} + \beta_{6j}Block_{ij} * BlockTrial_{ij} + \beta_{7j}Block_{ij} * Validity_{ij} * BlockTrial_{ij} + r_{ij}$

$$\boldsymbol{r}_j \sim N(\mathbf{0}, \boldsymbol{\Sigma})$$

$$\boldsymbol{\Sigma_j}[i, i'] = \sigma^2 \rho^{\left|time_{i'j} - time_{ij}\right|}$$

Level 2: $\beta_{0j} = \gamma_{00} + u_{0j}$ $\qquad \begin{bmatrix} u_{00} \\ u_{10} \end{bmatrix} \sim N\left(\begin{bmatrix} 0, \tau_{00} \\ 0, \tau_{11} \end{bmatrix}, \begin{bmatrix} \tau_{00} & \tau_{01} \\ \tau_{10} & \tau_{11} \end{bmatrix}\right)$

$\beta_{1j} = \gamma_{10} + u_{1j}$ ** **Note: random slope of time ONLY retained for exp 3**
$\beta_{2j} = \gamma_{20}$
$\beta_{3j} = \gamma_{30}$
$\beta_{4j} = \gamma_{40}$
$\beta_{5j} = \gamma_{50}$
$\beta_{6j} = \gamma_{60}$
$\beta_{7j} = \gamma_{70}$

Reduced-form: $RT_{ij} = \gamma_{00} + \gamma_{10}BlockTrial_{ij} + \gamma_{20}Validity_{ij} + \gamma_{30}Block_{ij} + \gamma_{40}BlockTrial_{ij} * Validity_{ij} + \gamma_{50}Block_{ij} * Validity_{ij} + \gamma_{60}Block_{ij} * BlockTrial_{ij} + \gamma_{70}Block_{ij} * Validity_{ij} * BlockTrial_{ij} + u_{0j} + u_{1j}BlockTrial_{ij} + r_{ij}$

Valid and Block 1 are reference conditions.

Model 7. Interaction between Validity, Time, and Task

Level 1: $RT_{ij} = \beta_{0j} + \beta_{1j}Trial_{ij} + \beta_{2j}Validity_{ij} + \beta_{3j}Trial_{ij} * Validity_{ij} + r_{ij}$

$$r_j \sim N(0, \Sigma)$$

$$\Sigma_j[i, i'] = \sigma^2 \rho^{\left|time_{i'j} - time_{ij}\right|}$$

Level 2: $\beta_{0j} = \gamma_{00} + \gamma_{01}Task_j + u_{0j}$ $\qquad \begin{bmatrix} u_{00} \\ u_{10} \end{bmatrix} \sim N\left(\begin{bmatrix} 0, \tau_{00} \\ 0, \tau_{11} \end{bmatrix}, \begin{bmatrix} \tau_{00} & \tau_{01} \\ \tau_{10} & \tau_{11} \end{bmatrix}\right)$

$\beta_{1j} = \gamma_{10} + \gamma_{11}Task_j + u_{1j}$
$\beta_{2j} = \gamma_{20} + \gamma_{21}Task_j$
$\beta_{3j} = \gamma_{30} + \gamma_{31}Task_j$

Reduced-form: $RT_{ij} = \gamma_{00} + \gamma_{01}Task_j + \gamma_{10}Trial_{ij} + \gamma_{11}Task_j * Trial + \gamma_{20}Validity_{ij} + \gamma_{21}Task_j * Validity_{ij} + \gamma_{30}Trial_{ij} * Validity_{ij} + \gamma_{31}Task_j * Trial_{ij} * Validity_{ij} + u_{0j} + u_{1j}Trial_{ij} + r_{ij}$

$\gamma_{31} =$ model-implied three-way interaction between time, validity and task

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