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INDIVIDUAL DIFFERENCES IN UNCERTAINTY RESPONSIVENESS AND STROOP
INTERFERENCE

by

JORGE ANTONIO SALAMANCA

Under the Direction of David Alan Washburn, PhD

ABSTRACT

The study of metacognition is rooted in the observation of behaviors under states of uncertainty (e.g., Smith et al., 1995). Individuals who are more responsive to uncertainty tend to show greater interference effects in a Stroop color-word naming task compared to those who are less responsive to uncertainty (Washburn, Smith, & Tagliatela, 2005). Individual differences in Stroop interference also have been shown to reflect relative differences in response competition (Washburn, 1994) and rule-maintenance ability (Kane & Engle, 2003). Why would individuals who respond to uncertainty most adaptively be characterized by the worst attention-control skills? The current study was designed to measure the individual contribution of sensitivity to response competition and rule maintenance ability to the pre-established relationship between Stroop interference and uncertainty responsiveness. Though participants performed as expected in both tasks, the previously reported relationship between Stroop interference and uncertainty responsiveness was not observed.

INDEX WORDS: Stroop interference, Uncertainty responsiveness, Attention control,
Metacognition

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JORGE ANTONIO SALAMANCA

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Arts

in the College of Arts and Sciences

Georgia State University

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Jorge Antonio Salamanca
2017

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May 2017

DEDICATION

Dedicated to my mother and father, Nashalys, Maloos, and Ty.

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Thank you to Dr. Washburn for all his kindness and patience. Thank you to Dr. Beran and Dr. Smith for all their guidance and encouragement.

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1 INTRODUCTION

Humans—and almost certainly other animals—experience doubt. The capacity to monitor and respond to the experience of uncertainty serves as a focus of the empirical investigation of metacognition in humans and in nonhuman animals (Smith et al., 1995; Smith, Shields, Schull, & Washburn, 1997; Smith, Shields, & Washburn, 2003). Metacognition is cognition about cognition, or the complex ability of an individual to monitor and to control mental states (Flavell, 1979; Nelson & Narens, 1990; Smith et al., 1995). Metacognition is said to be one of the most sophisticated abilities of human cognition (Smith, 2010). It is used to allocate and to direct cognitive resources adaptively, allowing metacognitive individuals to respond not only to the states of objects, but also to mental states in relation to objects (e.g., Smith et al., 1995; Smith et al., 1997). In human adults, metacognition is also a self-reflective mechanism that is introspective and declarative, demonstrating conscious awareness of mental states (Flavell, 1979; Koriat, 2007; Metcalfe & Schwartz, 2016).

Metacognition involves two conceptually distinct components: monitoring and control (Nelson & Narens, 1990). In monitoring, the metacognitive executive forms appraisals of mental states. In control, appraisals of mental states inform lower-level cognitive processes and guide behaviors that follow. For example, the metacognitive executive is active when we decide to reread a paragraph. Monitoring of mental states allows people to judge whether they have understood the passage to a satisfactory degree and control of cognition directs them to reread the passage with more focused attention. Metacognitive abilities are instrumental in a multitude of tasks, ranging from the contemplation of the very nature of human existence and experience to deciding whether or not to jump to a distant branch.

Metacognition has been examined through the use of several different methodologies, including confidence judgments (e.g., Kornell, Rhodes, Castel, & Tauber, 2011; Roebers, 2002; Shields, Smith, Guttmanova, & Washburn, 2005), observations of information seeking behaviors (e.g., Beran et al., 2015; Crystal & Foote, 2011; Neldner, Collier-Baker, & Nielsen, 2015), and the use of an uncertain response (e.g., Smith, et al., 1995; Smith, et al., 1997; Smith et al., 2003). With the latter paradigm, human adults (Smith et al., 1995; Smith et al., 1997), young children (Beran, Decker, Schwartz, & Smith, 2012), dolphins (Smith et al., 1995) rhesus monkeys (Shields et al., 2005; Shields, Smith, & Washburn, 1997; Smith, Beran, Redford, & Washburn, 2006; Smith, Coutinho, Church, & Beran, 2013; Smith, Redford, Beran, & Washburn, 2009; Smith et al., 1997; Washburn, Smith, & Shields, 2006; Zakrzewski et al., 2014) and some capuchin monkeys (Beran, Perdue, & Smith, 2014; Beran, Pedue, Church, & Smith, 2016; Beran et al., 2009) have demonstrated the capacity—at least under some circumstances—to respond adaptively to their own mental states.

Experiments employing the uncertain response paradigm have provided insight into the relationships between metacognition and other cognitive mechanisms, such as working memory (e.g., Coutinho et al., 2015; Smith et al., 2013) and executive attention (Washburn et al., 2005). Results from these studies serve to inform the interpretation of observed individual and species differences in responsiveness to uncertainty (Smith et al., 2003). Further investigation into the individual differences present in uncertainty responsiveness will provide additional insight into the nature of uncertainty and metacognition.

1.1 The Uncertain Response

Researchers have investigated metacognition through observations of behaviors under states of uncertainty (Smith et al., 2003; Zakrewski et al., 2014). In early psychophysical

discrimination tasks, some psychologists allowed respondents to indicate uncertainty when faced with difficult trials (e.g., George, 1917). However, these responses were believed to be psychologically distinct from the stimulus-based primary responses in which the researchers of the time were most interested (Watson, Kellogg, Kawanishi, & Lucas, 1973). Researchers worried that uncertain responses were subject to individual differences of attitude, lapses of attention, or even failure of instruction on the part of the experimenter (George, 1917). For these reasons, some researchers recommended disallowing the avoidance of difficult trials by adopting forced-choice paradigms (Brown, 1910).

For the researchers who were interested in the appraisal and response to uncertainty itself, most testing paradigms relied on participant self-report in the form of, among other things, judgments of learning or feelings of knowing (see Schwartz, 1994), or the recalling of tip-of-the-tongue experiences (Brown & McNeill, 1966; Schwartz & Metcalfe, 2011). Due to the linguistic nature of these paradigms, metacognition research was not yet sensitive to the developmental study of uncertainty monitoring (Acredolo & O'Connor, 1991) and was completely exclusionary to the comparative study of uncertainty monitoring (Smith et al., 1995). These limitations called for a new approach: the repurposing of the uncertain response.

Smith and collaborators (1995) developed a psychophysical discrimination task that allowed for individuals to use a third response to avoid loss from incorrect responses (but also forego possible maximum reward for correct responses) as a nonverbal behavioral proxy for the monitoring and responding to states of uncertainty. Maximizing reward required participants effectively to monitor and respond to uncertainty. The psychophysical uncertainty response paradigm was initially created with cross-species comparative research in mind. Among the first nonhuman animal participants was Natua, a bottlenose dolphin (Smith et al., 1995). Natua's

performance and subsequent report on his performance on the uncertainty task is credited as the introduction to the study of nonhuman animal metacognition (Smith, 2010).

Smith and his collaborators tested Natua and five human participants in an auditory threshold discrimination task (Smith et al., 1995). Each of the six participants was required to determine whether the frequency of an auditory stimulus was exactly 2,100 Hz (high tone/target-present), or less than 2,100 Hz (1,200 Hz to 2,099 Hz, low tone/target-absent). For humans, correct responses were indicated by a reward sound and a one-point increase in an on-screen “correct answer” tally. For Natua, correct responses were rewarded with a food reward and praise from a human experimenter.

Trial difficulty was modified dynamically according to response accuracy: correct responsiveness led to more difficult trials and incorrect responsiveness resulted in less difficult trials (Smith et al., 1995). Trial difficulty increased by narrowing the gap between the target-present and target-absent levels. Differences between categories became less discriminable as “target-absent” frequencies approached 2,100 Hz. Experimenters maintained response accuracy at near-chance levels with this difficulty titration, meaning that it was possible to track when Natua was unable to discriminate the tones. The dynamic modification of difficulty adapted for within-participant differences in performance across trials. These within-participant differences may include changes in motivation, effects of practice or fatigue, or even temperamental changes as warned by the early psychophysicists. If Natua, for whatever reason, was suddenly to become a more astute perceiver, trial difficulty would ramp up to accommodate his new perceptual threshold.

The critical and distinguishing feature of the uncertainty paradigm was that participants were allowed a third, non-categorical option to escape and advance any trial (Smith et al., 1995).

When selected, this third response skipped the current trial and presented a guaranteed-win trial as the next trial. To dissuade excessive use of this escape response, experimenters included a timeout period that compounded along with increased use of this escape response. Escaping several trials in a row would lead to larger and larger penalties. The optimal response pattern to maximize reward and minimize cost in the form of penalties from errors and excessive escaping would require individuals to rely on the primary discrimination as often as possible. The escape response would have to be used, but reserved for only the most difficult trials – when the individual decided that the stimulus class was indeterminable.

Natua and the human participants used the uncertain response adaptively, generally saving it for the empirically uncertain trials only (Smith et al., 1995). Researchers also took note of behavioral markers that appeared to distinguish Natua's approach to the uncertain response from the primary responses. Uncertain responses were often chosen with hesitation, wavering, and rhythmic motions such as mouth movements or swaying between response options.

Around the same time, researchers tasked human participants and two rhesus macaques with a visual analog of the auditory threshold discrimination task (Smith et al., 1997). Rhesus monkeys Abel and Baker and 14 humans were required to judge whether a frame contained either exactly 2,950 illuminated pixels (target-present/dense), or 450 to 2,949 pixels (target-absent/sparse). Correct responses by human participants were rewarded with a tone and an increase in an on-screen money counter. Incorrect responses were followed by a buzzing noise and a decrease in the money counter. Correct responses by monkeys were rewarded with food pellets and a reward tone. Incorrect responses were followed by a buzz and a timeout period. Half of the trials presented in the task were target present, 14% of the trials were set to the lowest level of target absent (450 illuminated pixels), and the remaining 36% of trials were modified

dynamically according to response accuracy in the most recent 10 trials. In a second task, Abel, Baker, and 18 undergraduate students were required to categorize pixel density as dense or sparse along a continuum. Densities from 334 to 577 pixels were to be assigned as sparse, and densities from 599 to 1,034 were to be assigned as dense. Here, density levels were randomly selected across the entire range.

In both tasks, Baker and human participants used the uncertain response adaptively when faced with difficult discriminations (Smith et al., 1997). Abel also showed a human-like pattern of responses in Experiment 1. In the second task, Abel demonstrated considerable difficulty in using the escape response optimally—but there too, his performance was mirrored by one human respondent in that same study. Results from all three species (dolphin, rhesus monkey, and human) demonstrated a remarkably similar strategic approach to avoiding difficult trials.

1.2 The Psychology of the Uncertain Response

Though early psychologists believed “doubtful” responses to be psychologically distinct from the primary categorical responses, the interpretation of the uncertain response in the psychophysical discrimination paradigm continues to be contentious (Beran, & Smith, 2014; Couchman, Coutinho, Beran, & Smith, 2010; Hampton, 2009; Kornell, 2014; Smith, Beran, Couchman, & Coutinho, 2008; Smith, Couchman, & Beran, 2014). As a result, comparative researchers have endeavored to find experimental evidence of a distinction between categorical responses and uncertain responses. Modifications to the psychophysical paradigm with human and nonhuman subjects have served to address these alternative accounts, the last decade of which are described below.

1.2.1 Generalization and Flexibility of the Uncertain Response

One behavioral distinction between uncertainty responding and primary categorical responses and their cues was found with the immediate generalization of the escape response by rhesus monkeys running multiple discrimination tasks (Washburn et al., 2006). Rhesus monkeys were presented with a familiar two-choice discrimination task. Novel stimulus pairs were randomly generated by computer software and repeated for six trials per problem. One of the two stimuli was randomly selected as the correct response, the selection of which would be positively reinforced. Because of the random generation and selection of correct answers, it was impossible for individuals to know which of the two stimuli to choose on the first trial of the six trial block. The monkeys were allowed to select an escape option that would remove the incorrect response from the screen. The participants were significantly more likely to use the escape response on the first trial of each block, when they could not perform about chance levels.

These same rhesus monkeys then completed a matching-to-sample task in which the sample and match were left-right mirror images of each other 25% of the time – a difficult task for a rhesus monkey (Washburn et al., 2006). Three of the four monkeys selected the escape response on the very first mirror-image trial, and all four animals used the uncertain response significantly more often on the mirror-image trials than on other matching-to-sample trials. The authors concluded that the instant generalization of the uncertain response provided evidence that the response is psychologically distinct from the primary response options.

Similarly, rhesus macaques quickly and flexibly used the escape response as category parameters shifted across testing sessions (Beran, Smith, Redford, & Washburn, 2006). In this experiment, participants were required to judge whether a presented array of circles was either more or less numerous than a randomly chosen center point – another fairly difficult task for the

monkeys. Participants demonstrated not only adaptive use of the escape response in the task, but also the ability to use the response flexibly while response categories were recalibrated across testing sessions. Further, the monkeys exhibited use of the uncertain response even though it was not rewarded directly through primary reinforcement, or through secondary reinforcements such as simpler subsequent trials or guaranteed-win trials.

To dissociate uncertainty responses from primary reinforcement further, researchers presented humans and rhesus macaques with a psychophysical discrimination task with deferred trial feedback (Smith et al., 2006). In these experiments, participants completed a block of trials before any feedback was given. After four trials for monkeys or eight trials for humans, feedback was arranged according to feedback type – correct response feedback was presented first, then incorrect responses. That is, if participants answered 4 trials correctly then 2 trials incorrectly then 2 trials correctly within a block, the feedback would be presented as 6 reinforcement tones (and pellets for the monkeys), then two buzzers and timeouts. The uncertain response in these tasks received no feedback. This feedback blocking and reordering made it virtually impossible for participants to track per-stimulus associations between each stimulus, the response made to it, and the specific feedback given for that response. Regardless, humans and one of the two monkeys showed adaptive use of the escape response even when its use was decoupled from its result.

Along with generalization, humans and rhesus monkeys demonstrated flexible criteria for use of the uncertain response. Zakrzewski et al. (2014) and colleagues presented human and rhesus monkey participants with a sparse-dense discrimination task requiring subjects to categorize stimuli. Correct responses for both species were rewarded with an increase on an on-screen token bank. Incorrect responses emptied this bank. Here, the third option served as a

“cash out” function that either assigned the accumulated tokens to an overall point total or delivered food pellets. The third option included a short timeout cost to discourage participants from simply claiming the earnings after every correct response. The third option did not, however, escape the current trial in any way. Thus, the utility of the uncertain response was not to avoid difficult trials, but to avoid gambling the bank’s holdings when stimuli were indiscriminable. The humans and rhesus monkeys demonstrated flexible use of the uncertain response by assessing risk dynamically according to the difficulty of the presented trial and the number of tokens gambled in the trial. For rhesus monkeys, this result served further to dissociate the uncertain response from aversion-avoidance accounts of uncertainty responding. The monkeys used the cash-out response more liberally on difficult trials when more reward was at stake. Thus, it was not enough to know the objective difficulty of the trial or the amount of reward at risk to predict uncertainty responding – one had to know *both* to make the best prediction.

1.2.2 Cognitive Dissociations from Middle Category Responses

Theorists have previously discussed the psychological distinction between middle category responses and “doubtful” responses in human psychophysics (Fernberger, 1930; George, 1917; Watson et al., 1973). To examine these differences in the context of the uncertain response, participants have been given psychophysical discrimination tasks in which the third option served as either a middle category, or an escape response.

One such behavioral dissociation of uncertain and middle category responses was observed in the first use of the uncertain response paradigm with capuchin monkeys (Beran et al., 2009). In the first task of the experiment, the monkeys were presented with a sparse-dense-uncertain task similar to the ones previously described. The escape response was met with no

direct feedback and simply advanced the task to the next trial. The experimenters encouraged the use of the escape response several ways. Experimenters increased timeout penalties for incorrect responses, increased overall difficulty by oversampling densities in the middle range of the continuum, presented trials where primary response options were disabled and only the escape response advanced to the next trial, and followed the escape response with a much simpler discrimination trial afterward. In a second task, monkeys were presented with a similar sparse-dense discrimination task, but in this case, the middle response was treated as a third category option and was rewarded when selected specifically in the presence of stimuli from the middle region of the density continuum. Task order was counterbalanced so that three of the six monkeys completed the uncertain task first, then the middle category task and vice versa. In these tasks, regardless of order, capuchin monkeys did not show adaptive use of the escape response (or much use of the escape response at all), but quickly adopted the third option when it behaved like a middle category response.

In Experiment 2 of the study (Beran et al., 2009), researchers considered whether the capuchins simply avoided the uncertain response because of the amount of overall reinforcement received through continued primary responding – regardless of how uncertain they may have been. To balance the reinforcement landscape, experimenters modified the uncertain task to include much steeper penalties than the middle category task. Regardless, five of the six monkeys still did not use the escape response adaptively, confirming that the uncertain response was indeed being avoided specifically, unlike the middle category response.

One capuchin named Logan demonstrated use of the escape response comparable to rhesus monkeys in the very final block of his testing (Beran et al., 2009). The researchers interpreted the result cautiously as an indication that the capuchin monkeys perhaps do have the

capacity to use the escape response adaptively, but do not do so for some undetermined reason (see Beran et al., 2014; Smith et al., 2009). However, the authors concluded that the stark difference in overall use between the middle category response and the uncertain response points to a difference in the psychological nature of the responses. The middle response was a primary perceptual response on the same grounding as the sparse and dense options, whereas the uncertain response occupied a different class.

Zakrzewski and collaborators reported a similar distinction between uncertain and middle category responses in human adults (Zakrzewski et al., 2014). Human participants were randomly assigned to one of two tasks. The first, a sparse-dense discrimination task included the uncertain response as a third option. The uncertain response had no effect other than to advance to the next trial. The second task also required categorization along a density continuum, but just as the previously described experiment, the third option assigned stimuli to a middle category. That is, the second task differed from the first in that it contained three primary categorical responses instead of two categorical responses and an escape response. After a training session, all participants received two blocks of (counterbalanced) testing. In one condition, participants were bound to a 500 ms response window. The second condition was unbound by time restraint. Researchers found that uncertain responses, unlike middle category responses, were particularly sensitive to time restraints. When faced with the time limit, uncertain responses dropped significantly. These results suggest that uncertain responses require a more controlled, and therefore time consuming, decisional computation than primary categorical responses.

1.2.3 Ancillary Behaviors and Post-hoc Accounts

As previously mentioned, researchers took note of Natua's hesitation and wavering when selecting the escape response – behaviors that they did not see when Natua chose one of the two

primary response categories (Smith et. al, 1995; Smith, 2010). The researchers noted that these behaviors could potentially be used to operationalize feelings of uncertainty, though most use of the uncertainty paradigm does not involve additional behavioral observation. Generally however, humans and monkeys do not exhibit increased response latencies when choosing to escape rather than make one of the primary response options (Shields et al., 1997). In this experiment (Shields et al., 1997), one group of human participants was deliberately not instructed on how to use the escape response. Regardless, these participants demonstrated adaptive use of the escape response to avoid difficult trials. Post-experimental interviews with these individuals revealed that 23 of the 25 participants who were asked about their use of the escape response attributed it to subjective feelings of doubt, in contrast with the primary response options that were attributed to judgments of stimulus conditions. That is, the use of the uncertain response was in reaction to a mental state – not stimuli themselves. These reports also recall the intuitions of the early psychophysicists who judged “doubtful” reports as more cognitive in nature than the primary discrimination responses. The post-hoc accounts support the idea that the escape response is indeed a behavioral proxy for uncertainty, at least for humans.

1.2.4 Working Memory and the Uncertain Response

Another demonstration of the distinctly cognitive nature of the uncertain response was conducted with rhesus monkeys. Smith and collaborators presented rhesus monkeys with sparse-dense discrimination tasks that included either a middle category or an uncertain response (Smith et al., 2013). In the first two experiments, participants completed blocks of either alternating or concurrent memory tasks. In the alternating blocks, monkeys would complete a trial of a matching-to-sample (Experiment 1) or spatial memory task (Experiment 2), then a trial of the sparse-dense task. In the concurrent blocks, monkeys would be presented with a stimulus, then

would be required to hold the stimulus in memory until after the completion of a trial of the sparse-dense discrimination that included the uncertain response as a third option. In Experiment 3, monkeys were given alternating or concurrent blocks of the same matching-to-sample task, but with a middle category option instead of an uncertain response. When faced with concurrent cognitive load, uncertainty responding decreased dramatically. The primary categorical responses, however, were not affected by the concurrent memory task. Experiment 3 demonstrated that middle category responding, though slightly disturbed in one individual, was not as vulnerable to the increased demands on working memory in the concurrent blocks.

In a similar set of experiments, human participants demonstrated a comparable pattern of decreased uncertainty responsiveness under working memory load (Coutinho et al., 2015). However, after extensive training, human participants used the uncertain response as often as the middle category response. This result contrasts with the previous study, given that the rhesus monkeys were provided with a considerable number of trials to familiarize themselves with task demands. Coutinho et al. (2015) reasoned that the process of uncertainty monitoring became automatized after extended practice in humans. That is, the participants either were able to decrease the cognitive load inherent to uncertainty monitoring through practice, or were more inclined to allocate resources to monitoring once convinced of the utility of the escape response. Under this view, individuals who had less cognitive resources available to allocate, such as rhesus monkeys, would be less likely to increase uncertainty responsiveness through training.

1.2.5 Individual Differences in Uncertainty Responding

Large individual differences have been observed within and across species in uncertainty responding across psychophysical discrimination tasks (e.g., Paul, Boomer, Smith, & Ashby, 2011; Smith et. al, 1997). Thomson (1920) noted that “undecided” responses were dependent on

an individual's decision-forming habits, as opposed to actual sensitivity to stimulus conditions. Other researchers have discussed an orientation toward uncertainty as a trait of personality (Shuper et al., 2004).

Washburn et al. (2005) compared performance on a psychophysical uncertainty paradigm with a battery of assessments of personality traits, dispositional traits, and attention abilities. The authors found several correlates to more optimal use of the uncertainty response. First, they found that women used the uncertain response more than men. In addition, more optimal respondents reported fewer attention-deficit symptoms than less optimal respondents. These same relatively optimal respondents, however, reported experiencing more frequent errors of attention in a Cognitive Failures Questionnaire (Broadbent, Cooper, FitzGerald, & Parkes, 1982). Washburn et al. reasoned that the self-assessment of attention ability is a metacognitive act in itself, and that it would be reasonable to expect that individuals who are more sensitive to their attention constraints would also be more responsive to uncertainty. Optimal uncertainty responsiveness was correlated with self-reported Need for Closure (Webster & Kruglanski, 1994), and more specifically, a subscale that included items indicating a dislike for unpredictability. Similarly, more optimal respondents were also more likely to report a dislike of uncertainty in a Personal Need for Structure subscale measure (Neuberg & Newsom, 1993). However, these dispositional correlates did not ultimately account for much of the variance in uncertainty responding overall.

Beyond the self-report measures, Washburn et al. (2005) also compared performance on the psychophysical uncertainty task to three objective attention measures, including a visual search task, an attention cuing task, and a Stroop color-word task. In the visual search task, the most optimally uncertain-responding participants were more efficient in identifying targets. The

authors reported no relationship between the attention cuing task and uncertainty responding. Washburn, et al. (2005) also found that participants who responded more optimally to uncertainty tended to experience the largest interference effects from incongruent trials in the Stroop color-word task. That is, individuals who performed worse on the Stroop task tended to perform more optimally on the psychophysical discrimination task.

1.3 Stroop Interference

The Stroop task has been referred to as the “gold-standard” of attention measures (MacLeod, 1992). Across variants, participants are asked to respond to a property of a stimulus (e.g., color, quantity, spatial location). When presented simultaneously with a conflicting and prepotent cue, such as a contrary color-word meaning, participants require more time to respond and are more prone to error (MacLeod, 1991; Stroop, 1935). The capacity quickly and accurately to resolve conflict on Stroop-like tasks has been used to indicate attention deficits and individual (and group) differences in cognitive control (Fan et al., 2002; Osimani, Alon, Berger, & Abarbanel, 1997; Washburn & Putney, 1999). Nonhuman primates exhibit Stroop interference effects (Beran, Washburn, & Rumbaugh, 2007) and demonstrate greater Stroop-like effects than do human adults (Washburn, 1994, 2016). On one account, performance on Stroop tasks requires the resolution of response competition per-trial and the sustained maintenance of task goals across trials (Kane & Engle, 2003). The contributions of these factors can be indicated through task manipulations, including changes in the semantic incongruity of per-trial stimuli (e.g., Klein, 1964; Washburn, 1994) and the ratio of congruent to incongruent trials presented in testing blocks (e.g., Hutchinson, 2011; Kane & Engle, 2003).

1.3.1 Stroop Interference and Rule Maintenance

Kane and Engle (2003) tested undergraduate volunteers on a complex span test of working memory capacity, and used performance to divide groups into high- versus low-span. They reported that low-working memory span individuals experienced greater interference in response accuracy when incongruent trials were uncommon, that is, when the proportion of congruent-Stroop trials was very high. Continued accurate and efficient responding in Stroop tasks requires participants to maintain and monitor task rules (i.e., “respond to print color, not word meaning”) throughout testing blocks. Unlike congruent or baseline trials, Kane and Engle reasoned that incongruent trials served to remind participants of task goals. When cues in the form of incongruent trials are uncommon, monitoring of task rules creates an increased demand on working memory. Low-working memory span participants were more likely to err when required actively to maintain and monitor task rules without the cuing provided by the incongruent trials. Although both low- and high-span participants experienced strong interference effects when incongruent trials were most common, low-span participants required significantly more time to respond in these blocks. High- and low-span participants did not differ in accuracy in the high-incongruent ratio blocks, where all of the incongruous trials served as objective reminders of the rules for the task.

The result was replicated in both accuracy and response times in humans (Hutchison, 2011) and monkeys (Washburn, 2016). Hutchinson (2011) compared item-specific and listwide sources of Stroop interference and working memory capacity. Results indicated that low-span individuals required more time and were more prone to error than high-span individuals when congruent trials were most common, regardless of item-specific factors. Interference effects were more likely to be observed in the form of increased response times when low-span participants

were recently reminded of the task rule with the presentation of an incongruent trial. Conversely, interference effects were more likely to be seen in response accuracy when low-span participants were not recently cued with an incongruent trial. Hutchinson concluded that the results supported Kane and Engle's (2003) account of Stroop task performance requiring participants to actively maintain task rules along with the resolution of response competition.

Similar effects also were observed with rhesus monkeys using a numerical Stroop task (Washburn, 2016). In this numerical Stroop task, participants were required to judge which of two numerical arrays was more numerous, regardless of the symbolic value of the numerical symbols composing the arrays. Humans and monkeys demonstrated Stroop interference effects when the more numerous of the two arrays was populated with symbols of lower symbolic values (Washburn, 1994; 2016). Data from both reports showed that rhesus monkeys experienced greater effects of Stroop interference than humans. Washburn (2016) reported that rhesus monkeys presented with high-congruous ratio blocks of numerical Stroop mimicked the results of low-span humans. These monkeys were unable to curb the increased interference effects when incentivized with greater rewards.

To summarize these studies, lower working memory capacity, and thus attention-control and rule-maintenance deficits, is associated with relatively larger Stroop-interference effects (Hutchison, 2011; Kane & Engle, 2003; Washburn, 2016). Moreover, increases in working memory load (which effectively decreases working-memory capacity) have been shown to reduce the use of the uncertain response in humans and rhesus monkeys (Coutinho et al., 2015; Smith et al., 2013). These results suggest that individuals who experience greater Stroop-interference effects (i.e., individuals with higher working memory capacity and rule maintenance ability) would be less responsive to uncertainty. With extended practice, humans are able to use

the uncertain response adaptively despite concurrent task demands, whereas rhesus monkeys cannot (Coutinho et al., 2015). This species differences is said to be due to the increased working memory capacity available to humans, which provides resources for metacognitive monitoring even under demanding task situations. For this reason, it can be reasonably expected that individuals within a species with access to more controlled-attention resources (i.e., individuals with higher working memory capacity and rule maintenance ability) would be more responsive to uncertainty. However, individuals who experience greater Stroop interference effects tend to be more responsive to uncertainty (Washburn et al., 2005).

This result makes sense if, for example, individuals who experience the response conflict of Stroop more vividly or more metacognitively are also those individuals most sensitive to the conflict that characterizes uncertainty in a metacognitive task. However, the pattern of results would suggest counterintuitively—and inconsistent with the results discussed above—that organisms with low working-memory capacity and rule maintenance deficits would be more responsive to uncertainty than high working-memory individuals. That is, the relationship between Stroop interference and responsiveness to uncertainty (Washburn et al., 2005) appears to be inconsistent with the remaining literature.

One potential explanation for the discrepant findings of the Washburn et al. (2005) study is found in the psychophysical discrimination task. In the individual differences report, increased responsiveness to uncertainty was calculated as the amount of escape responses chosen within the individually determined region of uncertainty (Washburn et al., 2005). The threshold task (as described by Smith et. al., 1997) presented participants with 50% dense trials (2,950 pixels), 36% probe trials, and 14% low-difficulty sparse trials (450 pixels). Probe trial difficulty titrated so that participants remained at chance accuracy in these trials. Thus, 86% of trials presented to

participants were either dense or nearly dense according to their individually determined perceptual ability, meaning participants usually remained in or near their objectively uncertain range. It seems possible that this manipulation, like the listwise manipulation of congruent-proportion in Stroop tasks previously described (e.g., Hutchison, 2011; Kane & Engle, 2002), may serve to encourage escape responses for individuals who may otherwise be less likely to monitor task goals and subjective amounts of uncertainty (e.g., rhesus monkeys). The escape response in that task was not discouraged in any way, and was only costly in the time required to select the response. The features of the difficulty sampling and of the escape response in this task may have influenced the resulting correlation between uncertainty responsiveness and Stroop interference. Specifically, participants who otherwise may have been less responsive to uncertainty were cued by the continued presentation of difficult trials. This is one hypothesis that will be tested in the proposed experiment.

1.3.2 Stroop Interference and Response Competition

Alternatively, Washburn et al. (2005) proposed that the relationship between Stroop interference and uncertainty responding could be due to a degree of response competition common to both tasks. In the psychophysical discrimination task, participants are required to categorize stimuli based on a primary perceptual property. Competition between response options increases as differences between stimulus categories are narrowed. That is, participants are presented with increasingly ambiguous stimuli, requiring constant mediation of category representations (Shields et al., 1997), thus generating greater conflict between response options. Once competition between response categories reaches an individually determined uncertainty threshold, individuals will control behavior in the form of responding 'uncertain.' Individual differences in uncertainty responsiveness are not indicative of differences of monitoring per se,

but are instead indicative of differences in the sensitivity to competition experienced between primary responses.

In the Stroop task, incongruent trials present response options in which the prepotent characteristic (e.g., color-word) conflicts with the focal response (e.g., font color). The competition between responses is responsible for generating interference within the incongruent trials (Posner & Snyder, 1975, as cited by Macleod, 1991). Resolution of this response competition is performed by a general executive-control mechanism (Engle, 2002; Kane & Engle, 2003), which is why individuals with relatively good executive-attention skills typically show less Stroop interference than those with poor capacity for executive-attention (attention control). This leads to the prediction that, if the correlation between uncertainty responding and Stroop interference is due to the response competition common to both tasks, then individual differences in sensitivity to response competition will interact with the relationship between interference effects and uncertainty responsiveness.

Stroop interference effects have been shown to be related to the degree of semantic incongruity from the relevant to the irrelevant stimulus characteristic within trials (Klein, 1964; Washburn, 1994). In numerical Stroop, for example, interference effects increase according to the symbolic difference of numerals contained within arrays (Washburn, 1994). That is, participants required significantly more time to respond and tended to make more errors when the values within the incorrect array of the incongruent trial are greater (e.g., incongruous arrays of 6s vs. 2s generate longer response latencies than arrays of 3s vs. 2s). Increased interference at higher levels of semantic incongruity is caused by differences in associative strengths. Numerical symbols of larger values such as 8s or 9s are more strongly associated with “greater” than smaller-value numerical symbols such as 3s or 4s and, thus, produce greater conflict. Efficient

resolution of incongruity at higher levels of interference requires greater control of executive attention. Consequently, both Stroop interference and the symbolic incongruity effect are amplified in rhesus monkeys when compared to humans.

2 EXPERIMENT

Individuals who experience more Stroop interference effects are more responsive to uncertainty (Washburn et al., 2005). This result appears to be inconsistent with the previously summarized literature. One account of the Stroop effect attributes interference to the requirement of per-trial resolution of response competition and across-trial maintenance of task goals or rule (Kane & Engle, 2003). The purpose of the current study was to determine the contribution of individual differences in sensitivity to response competition and rule maintenance ability to the previously reported relation between Stroop interference and uncertainty responsiveness. Section heading

2.1 Method

2.1.1 *Participants*

Three groups of undergraduate participants (total $n = 209$) were recruited and completed a numerical Stroop task and a psychophysical uncertainty task. Demographic data were not collected for these volunteers, but it seems likely that the sample reflected the typical distribution of the undergraduate participant pool (approximately 59% female and 41% male, 40.8% African American, 28.8% White, 11.6% Asian, and 9.3% Hispanic/Latino). The groups are described below. Participants were assigned class credit for taking part in the study.

2.1.2 *Stroop Task*

Participants completed 400 trials of a computerized numerical Stroop task similar to the one described by Washburn (1994). Participants were required to perform a trial-initiation response at the start of every trial. A cursor was presented below the center of the screen with a circle icon directly above it. Participants pressed the up arrow key to place the cursor over the circle to begin the trial. In each test trial, two arrays of characters were presented on the screen,

one array to the right and one to the left of the cursor located at the center. Each array was composed of one to seven characters. Participants were instructed to select as quickly and as accurately as possible the array of stimuli that contained the largest number of items. Participants chose arrays by using the arrow keys to move the cursor over one of the two arrays. Baseline trials were comprised of arrays containing letters (A, B, C, or D). The other two trial types used Arabic numerals instead of letters in the array. Congruent trials consisted of larger arrays containing numerals with greater value and smaller arrays containing numerals with lesser value (e.g., five 3s vs. two 0s). Incongruent trials consisted of larger arrays containing numerals with lesser value and smaller arrays containing numerals with greater value (e.g., seven 1s vs. six 2s. Numerical-symbol differences (the difference between the numerals contained in each array) ranged from 1 to 5. Array size differences (the difference between the number of items in each array) also ranged from 1 to 5. Correct responses were indicated by a tone. Incorrect responses were indicated by a buzz and a 2-second timeout.

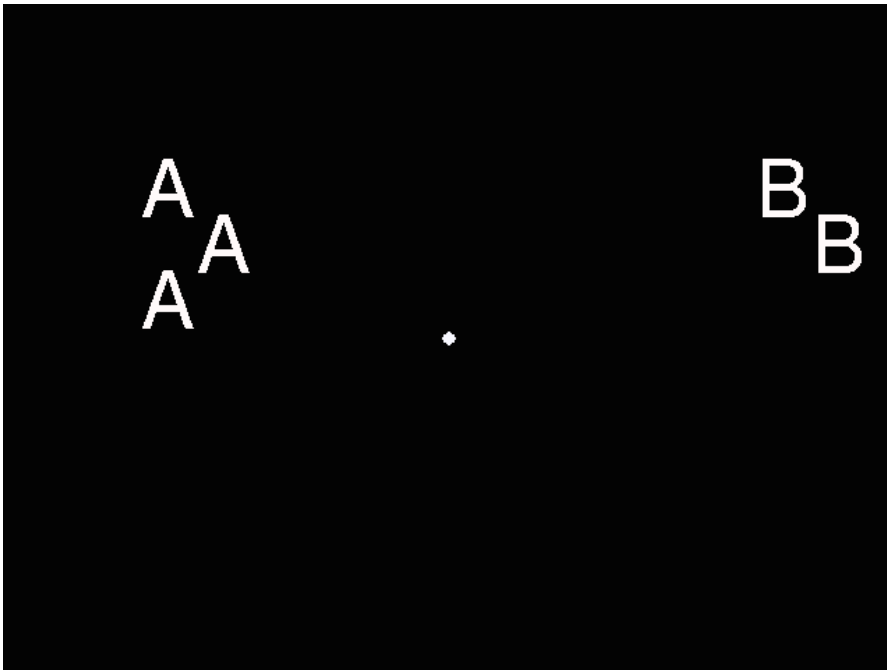


Figure 1 Sample Baseline Numerical Stroop Trial

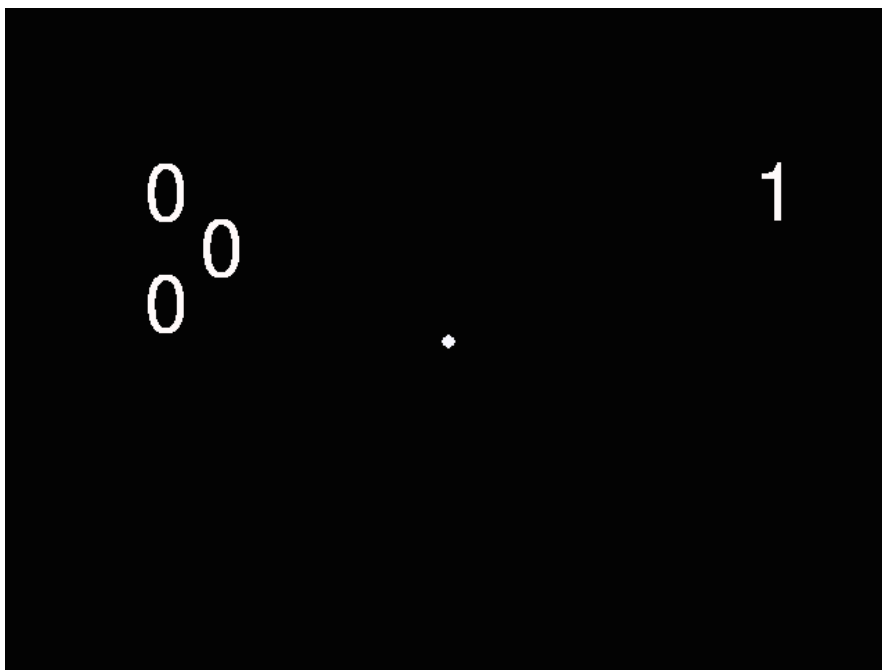


Figure 2 Sample Incongruent Numerical Stroop Trial

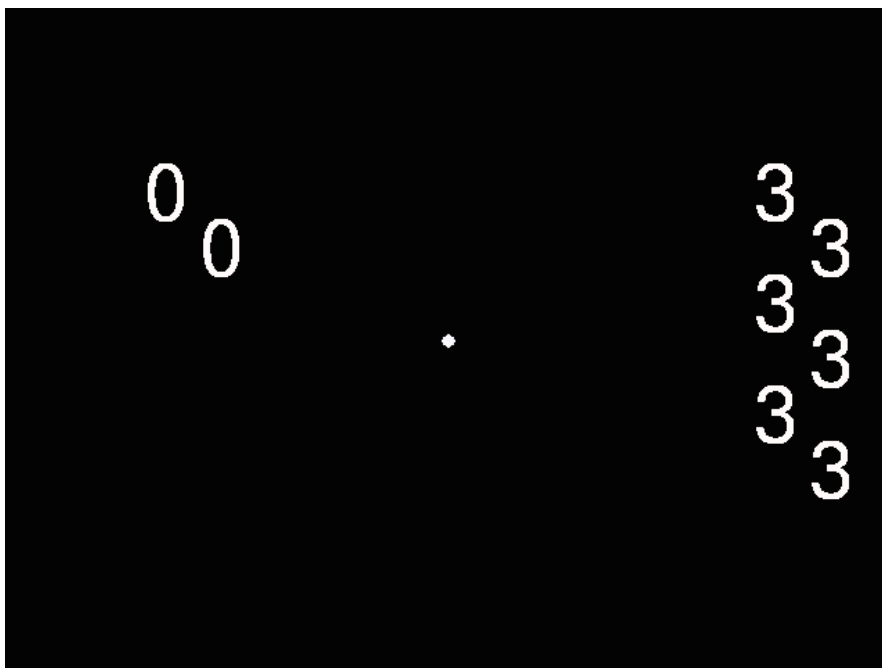


Figure 3 Sample Congruent Numerical Stroop Trial

The Stroop task was divided into two counterbalanced blocks. In one block, participants were presented with 250 trials of 80% congruent trials and 20% incongruent trials, resulting in about 200 congruent trials and 50 incongruent trials. In the other block, Stroop trial types were randomized for 150 trials, resulting in about 50 congruent trials, 50 incongruent trials, and 50 baseline trials. Symbolic incongruity differences were randomized.

The testing software recorded the trial type and difference between numerical arrays per trial. Participant accuracy and response times were recorded. Response times were filtered according to *a priori* assumptions of task performance; Responses under 200 *ms* and over 2000 *ms* were removed as being either too fast or too slow to indicate a valid trial attempt.

Note that the previous correlational study (Washburn et al., 2005) used a classic color-word Stroop task, whereas the numerical Stroop task was employed here to allow for a relatively simple, linear tracking of degrees of interference presented by the stimuli in each trial. That is, every incongruous Stroop trial generates response competition between cues, but the degree of competition is likely not equivalent across incongruous trials. Symbolic differences between arrays in a numerical Stroop task are more easily quantifiable than perceptual differences between colors and color-words on incongruous Stroop trials. For example, four 7s versus five 2s is a symbolic distance of 5, whereas four 7s versus five 6s is a symbolic distance of 1; however, it is unclear how to measure the relative differences of BLUE printed in red compared to GREEN printed in red. Thus, the numerical Stroop task yielded predictions and analyses that were more straightforward.

2.1.3 Uncertainty Task

Participants completed 500 trials of a psychophysical discrimination task similar to the original continuous-stimuli uncertainty task described by Smith et al. (1997), but using updated

parameters (e.g., Coutinho et al., 2015). Though the Washburn et al. (2005) correlational study used a psychophysical threshold task, the symmetrical-category discrimination method was employed here to allow for a more modest oversampling of the difficult range.

Participants were required to perform a trial initiation response at the start of each trial. A cursor was presented below the center of the screen with a 200 x 100 pixel space at the center of the screen. The frame was filled with a variable number of illuminated pixels scattered randomly within this space. Participants pressed the up arrow key to touch the cursor to the frame to begin the trial. The number of illuminated pixels spanned across 42 levels of trial difficulty, with each level containing 1.8% more illuminated pixels than the last. Pixel densities were calculated using the following formula, rounded to the nearest whole number: $1,066 \times 1.018^t$ where t is equal to the trial step variable. Level 1, for example, consisted of 1,085 illuminated pixels. Level 42 contained 2,255 pixels.

Participants were required to respond “sparse” on trial densities 1 through 21 by using the arrow keys to move the cursor to an “S” symbol, and “dense” from trial densities 22 through 42 using the arrow keys to move the cursor to a “D” symbol. Participants were allowed to respond “uncertain” at any time by using the arrow keys to move the cursor to a question mark (“?”) symbol. Correct responses were indicated by a 0.5s ascending tone, and a 1-point increase in a counter displayed on-screen. Incorrect responses were indicated by a buzzer, a point penalty in the on-screen counter, and a timeout.

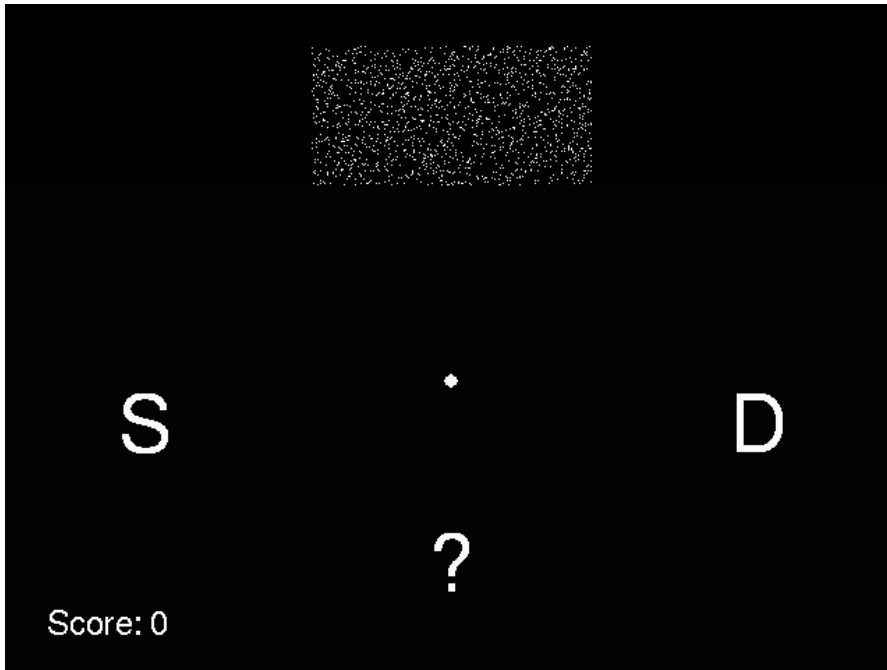


Figure 4 Sample Uncertainty Task Trial

As noted above, three groups of volunteers were tested. Participants in Group 1 ($n = 77$) received a 1-point decrease and a 1-second timeout per incorrect response on the Uncertainty task. Participants in Group 2 ($n = 58$) received a 3-point decrease and a 3-second timeout per incorrect response. Participants in Group 3 ($n = 80$) received a 3-point decrease and an 8-second timeout per incorrect response. Irrespective of group, uncertain responses cleared the current trial and advanced to the next trial without points or penalty. Each trial level was chosen randomly from the density range regardless of response on the previous trial.

2.2 Statistical Analysis

Five scores were computed for each individual participant. Uncertainty responsiveness was calculated as the number of escape responses chosen within the center density range divided by the number of trials the individual completed within that range. Although participants may not have been equally uncertain within this density range, overall responsiveness to uncertainty

was captured within these middle density levels. Stroop interference was calculated as the difference between baseline trials from the randomized ratio block and incongruent response times in both the randomized and ratio blocks. A ratio difference score was computed as the difference between incongruent response time difference scores across blocks. A response competition score was computed for individuals as the difference in mean response times from high interference (arrays with a numerical difference of 5) to low (arrays with a numerical difference of 1).

Initial analyses of each group's data produced similar patterns of results for Group 2 and Group 3. These results closely resembled previously reported results for uncertainty responsiveness; consequently, Group 2 and Group 3 were combined for the results reported here.

3 RESULTS

Means for response time on the Stroop task and escape ratio on the Uncertainty task are presented in Table 1. The numerical Stroop task produced Stroop-like interference: Participants required significantly more time to respond to incongruent trials than to baseline trials, $t(133) = 4.76, p < .001$. Incongruent trials with high numerical differences across arrays required significantly longer response times than those with low numerical differences, $t(132) = 3.15, p < .01$. Finally, incongruent trials in the high-congruent-ratio block (with incongruent trials appearing less frequently) generated longer response times than those in the equal incongruent trial distribution block, $t(133) = 2.14, p < .05$.

Table 1 Numerical Stroop Task Means

	Baseline	Incongruent	Low Difference	High Difference	Rule Maintenance Ratio
Group 1	602.29ms, sd = 111.88	613.97ms, sd = 111.78	610.74 ms, sd = 109.35	627.11m s, sd = 131.35	617.51ms , sd = 128.89
Group 2	615.20ms, sd = 93.38	630.89ms, sd = 96.05	626.70 ms, sd = 94.51	646.53m s, sd = 122.06	636.40ms , sd = 119.23
Group 3	596.29ms, sd = 98.04	615.91ms, sd = 98.79	612.32 ms, sd = 99.45	630.13m s, sd = 106.53	638.89ms , sd = 150.66
Group 2 &	604.5ms,	622.4ms,	618.5m	637.2ms	637.8ms,

3	sd = 96.15	sd = 97.53	s, sd = 97.24	, sd = 113.29	sd = 137.46
Total	603.68ms, sd = 101.91	619.32ms, sd = 102.78	616.70 ms, sd = 101.64	633.48m s, sd = 120.01	630.41ms , sd = 134.44

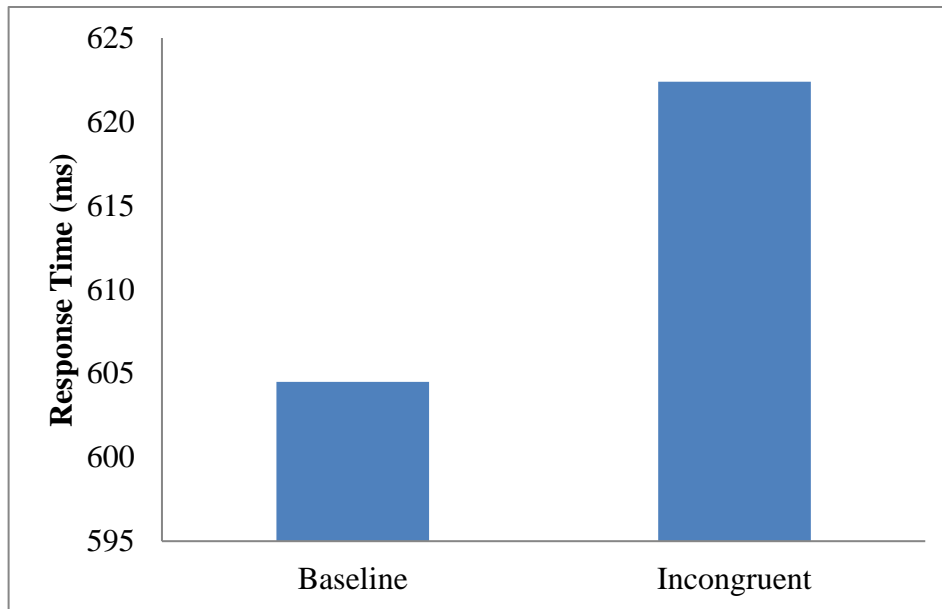


Figure 5 Numerical Stroop Interference Effect

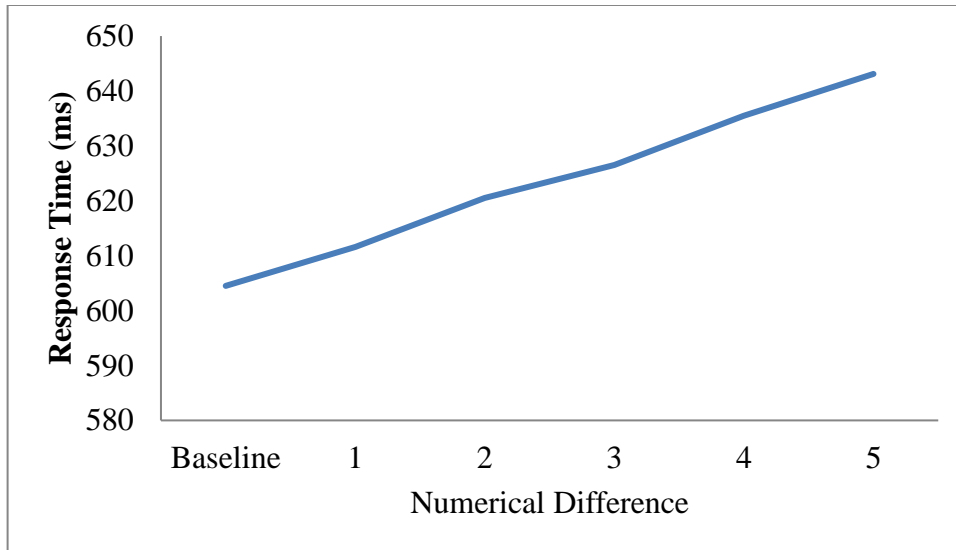


Figure 6 Stroop Interference by Numerical Difference

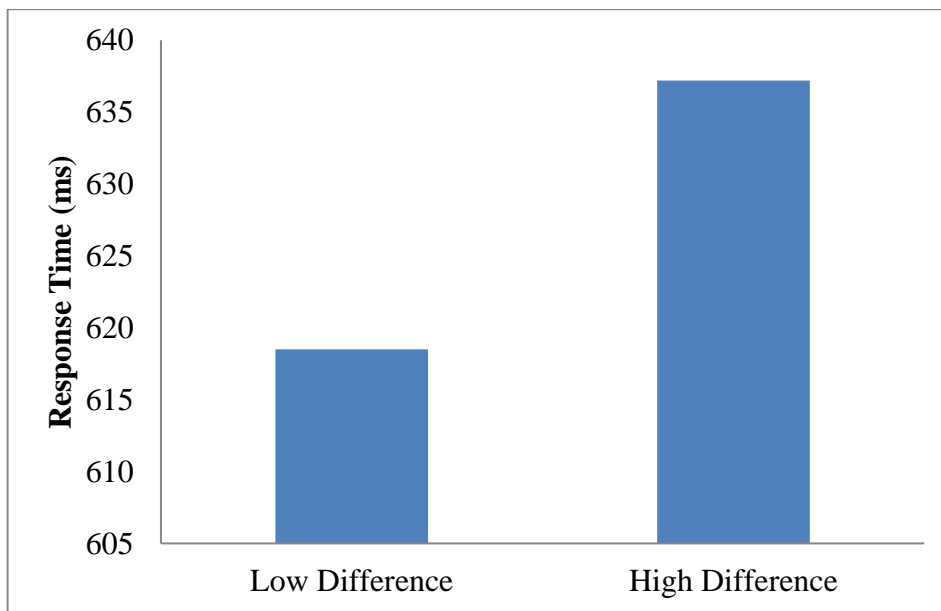


Figure 7 Stroop Interference by Difference Level

The uncertainty task produced similar response rates to those reported in Washburn et al. (2005). Responsiveness ratios (i.e., the proportion of uncertain responses to total trials within the center-density levels) ranged from 0.00 to 0.83. The mean responsiveness ratio was 0.27 with a standard deviation of 0.23. In Washburn et al. (2005) the optimality of responsiveness to

uncertainty [ORU] measure ranged from 0.00 to 0.80, with a mean of 0.23 and a standard deviation of 0.21. However, the correlation between Stroop interference and uncertainty responsiveness that was reported by Washburn et al. (2005) was not replicated in the present study. There was no significant relation between Stroop interference and uncertainty responsiveness, $r(129) = 0.13$, $p = .14$. Additionally, extreme-groups analysis using a tertile split on the basis of Stroop performance did not show a difference in uncertainty responsiveness between the best (difference score $M = 0.21$ ms) and worst (difference score $M = 0.26$ ms) performing participants in the Stroop task, $t(78) = 1.02$, $p = 0.31$.

Table 2 Uncertainty Task Descriptives

	Min	Max	Mean	Standard Deviation
Group 1	0.00	0.53	0.11	0.13
Group 2	0.00	0.83	0.23	0.24
Group 3	0.00	0.79	0.31	0.23
Group 2 & 3	0.00	0.83	0.27	0.23
Total	0.00	0.83	0.21	0.22

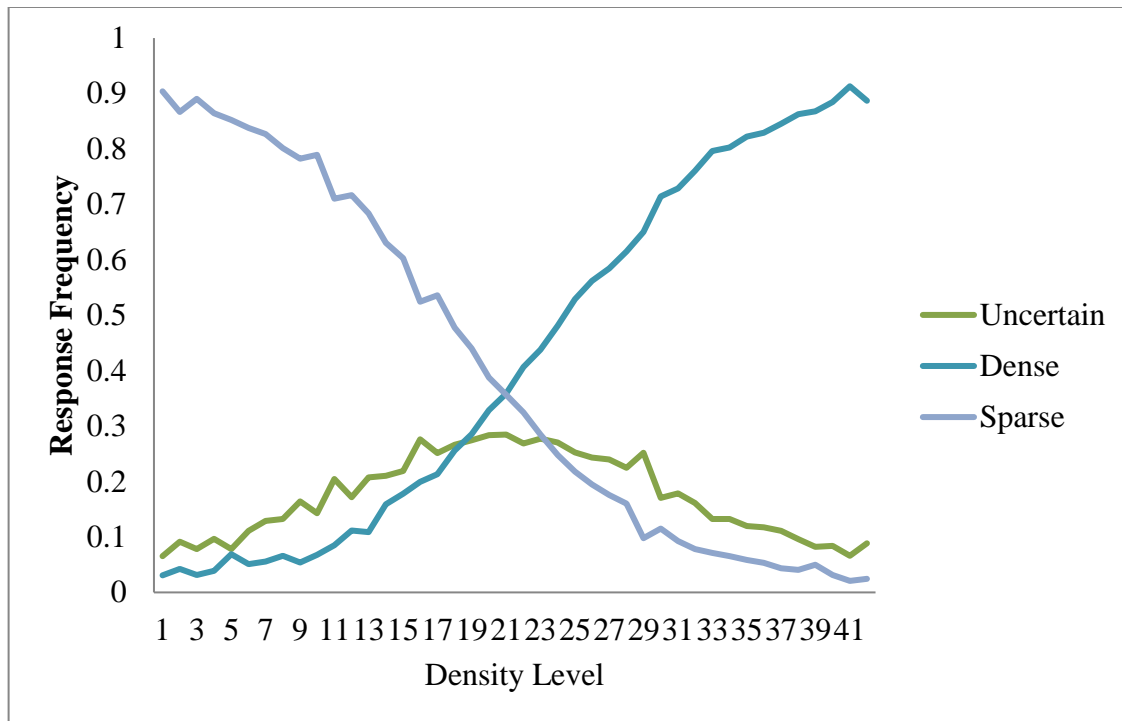


Figure 8 Uncertainty Task Responses by Density Level

Given the absence of a significant correlation between performance on the Stroop and Uncertainty tasks, there was no mediation effect of response competition or rule maintenance on the relation between Stroop interference and responsiveness to uncertainty. Further, extreme-groups analyses again failed to reveal significant differences: Participants who were more sensitive to differences in response competition were not more responsive to uncertainty than those who were less sensitive ($M = 0.30$ and $M = 0.25$ respectively), $t(83) = 0.80$, $p = 0.43$. Participants who were more capable of rule maintenance were not more responsive to uncertainty than those who were less capable ($M = 0.25$ and $M = 0.23$ respectively), $t(85) = 0.46$, $p = 0.64$.

4 CONCLUSIONS

The results from this study were as expected in several important ways. The numerical Stroop task successfully reproduced a Stroop-like interference effect. Participants required significantly more time to respond to incongruent trials than to baseline trials. Higher levels of incongruence (larger symbolic differences across numerical arrays) also produced longer response times, as had been predicted. This suggests that variations in the level of response competition contributed to the amount of interference on each response. The ratio of congruent to incongruent trials also drove interference, such that participants required more time to respond to incongruent trials when they were presented less often. Additionally, the uncertainty task and analysis produced results similar to those reported in Washburn et al. (2005), in that participants used the uncertain response option appropriately (i.e., on those trials in which they were demonstrably uncertain). Despite these results that were consistent with hypotheses and with prior findings, the result of primary interest for this study was surprising and disappointing. No significant relation was found in this study between the Stroop interference and responsiveness to uncertainty. The present study was designed to explicate the finding reported by Washburn et al. (2005) that individuals who experienced greater levels of interference were also more likely to respond to uncertainty; however, this finding was not replicated, and thus not explained, in the current study.

At least two explanations may be offered to account for the failure to replicate the previously reported relationship between Stroop interference and uncertainty responsiveness. First, a different Stroop task was used in the present study than by Washburn and collaborators (2005). If different variations of Stroop-like tasks all measure the common cognitive-control processes, as is typically assumed, then this change should not have affected the present findings;

however, it might have. Although the numerical Stroop task is capable of producing a Stroop-like interference effect, as shown here, different tasks that generate Stroop-like interference tend not to intercorrelate highly (Salamanca & Washburn, in preparation). That is, individuals who perform well on the Stroop color-word task do not necessarily perform well on the numerical Stroop task. The previously reported relationship between Stroop interference and responsiveness to uncertainty (Washburn et. al, 2005) may, in fact, be only a relation between Stroop color-word interference and responsiveness to uncertainty. The Stroop color-word task, like the psychophysical discrimination task, is inherently a categorization task that requires participants to sort stimuli according to a primary perceptual property. The participants who were most impacted by interference in the Stroop color-word categorization trials were more responsive to uncertainty in the psychophysical categorization trials. This commonality may be central to the interpretation of the current result. In contrast, the numerical Stroop task involves a comparison between two sets. The relation with uncertainty may be lost by a Stroop-like task that involves comparison of two sets (vs. competition between two features—color and meaning—of a single word). This relationship would therefore not be apparent in the numerical Stroop task. A follow-up study would be required to determine whether uncertainty monitoring is uniquely correlated with some but not all Stroop-like tests.

Second, it is possible that the difference in the overall difficulty of the uncertainty task promoted uncertain responses from a group of individuals distinct from that of the psychophysical threshold task previously used (Washburn et. al, 2005). To date, there is no existing research comparing individual uncertainty responsiveness in the continuous and threshold tasks. It may be that, like the inter-task differences in Stroop interference, different uncertainty tasks produce different levels of uncertainty responsiveness within individuals. If so,

the relationship between Stroop interference and uncertainty responsiveness may be related specifically to the difficulty of the uncertainty task used. This recalls one of the suggestions by Washburn and collaborators (2005) who speculated that the relationship may be due to the amount of uncertainty experienced due to associative strengths developed throughout the task. If participants begin to find the primary categorical options less favorable due to their being more greatly associated with penalties, they may be further encouraged to use the escape response on difficult trials beyond the difficulty of the primary discrimination. In other words, responses to trials of the same difficulty will be moderated by their associated likelihood of penalty. Because difficult trials were more frequent in the threshold task, participants were more likely to respond incorrectly and to face penalties. A similar effect was seen in the present data: Participants were more likely to use the uncertain response when the associated penalties were more aversive. The increase of task difficulty by increasing the amount of difficult trials has been previously used to encourage the use of the uncertain response (e.g., Beran et al., 2009). However, this does not suggest that the uncertain response is a conditioned response in itself. As previously discussed, several studies demonstrate the difference between the uncertain response and the primary categorical responses (e.g., Zakrzewski et al., 2014). This was also demonstrated in the current study where, despite differences in penalties, at least one participant in each group did not use the uncertain response at all. A future study could seek to increase the aversion to the primary response categories by increasing risk of incorrect answers with greater penalties.

One of the limitations on the interpretability of the results is that the current study manipulated both tasks used. If, for instance, there was no relationship between a color-word Stroop task (the task originally used; Washburn et. al, 2005) and the uncertainty task with continuous stimuli, it could be assumed that the previously reported relationship was due to a

factor specific to the threshold uncertainty task. If there was no relationship between the numerical Stroop task and a threshold uncertainty task (the task originally used; Washburn et. al, 2005), it could be assumed that the previously reported relationship was due to a factor specific to the color-word Stroop task. However, because both tasks were altered, it is not possible to determine which of the two tasks produced the discrepancy.

Also inherent in these speculations is the possibility that the present results capture the real independence of uncertainty responsiveness and Stroop interference, and that the Washburn et al. (2005) results were spurious. However, the failure to replicate the previously reported relation in the current study is not sufficient to determine whether there truly is no relation between the two variables. Future research into the relationship between Stroop interference and uncertainty responsiveness should continue to examine the contribution of both response competition and rule maintenance ability in both tasks. Like the present study, manipulations in the amount of conflict experienced in both the Stroop task can be used to quantify sensitivity to response competition, with the added manipulation of increased task difficulty in the uncertainty task to measure the potential effects of this sensitivity across tasks. For rule maintenance, future investigations could include other measures of the capacity, including operation-span or other measures of working memory.

The current study was designed to replicate a previously reported relation between Stroop interference and uncertainty responsiveness. Although this was unsuccessful, the results produced in the current study provide guidance for future investigations into individual differences in metacognitive task performance.

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