

**THE COMPASS OF CONTROL: CONGRUENCY SEQUENCE
EFFECTS, BOUNDARIES, AND TASK SETS**

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EFFECTS, BOUNDARIES, AND TASK SETS**

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LIST OF SYMBOLS AND ABBREVIATIONS

ACC	Accuracy
CAR	Conflict Adaptation Ratio
CSE	Congruency Sequence Effect
RT	Reaction Time

SUMMARY

The congruency sequence effect literature is inconsistent when it comes to the issue of the boundaries of this phenomenon. Some have argued that control is implemented at the level of a stimulus dimension while other have claimed that control operates across dimensions and tasks. Flexible control boundaries defined by task sets might explain the inconsistent findings. Response set manipulations have been shown to influence control boundaries. Unitary response sets can produce cross-dimension congruency sequence effects but applying separate response sets to a task can lead to the absence of the congruency sequence effect on dimension switch trials. This thesis is concerned with the extension of these findings. The study applied response set manipulations to a paradigm (Stroop Trajectory Task) that has exhibited robust cross-dimension congruency sequence effects. In addition, the influence of switching routine on congruency sequence effects was tested. It was expected that separate response sets for different stimulus dimensions would eliminate the congruency sequence effect on switch trials. Switching routine was anticipated to act as a weaker boundary marker but nevertheless it was expected that systematic switching routines should have at least attenuated the congruency sequence effect on switch trials. Contrary to expectations it was found that the congruency sequence effect was present in switch trials across all conditions.

CHAPTER 1

INTRODUCTION

Congruency Sequence Effects, Boundaries, and Task Sets

Over the course of one's daily life, irrelevant stimuli must be ignored, prepotent responses must be inhibited, strategies need to be switched, and attention must be allocated between the tasks that one is performing simultaneously. In order to engage in complex behaviors attention must be modulated in a selective manner. What is it that guides this selection? Cognitive science has not yet settled on a simple answer but considerable progress has been made in the general understanding of how attentional mechanisms allow for adaptive behavior on a moment to moment basis. In recent years, numerous models of cognitive control have been proposed (Botvinick, 2007; Brown & Braver, 2005; Shenhav, Botvinick, & Cohen, 2013). These models have overcome the homunculus problem by relying on bottom up systems of components that represent particular dimensions of a task or monitor/record indices of activity in other components. The integration of a set of components through looping mechanisms leads to the emergence of task performance predictions. The field has shown a great deal of progress over the course of the past decade.

Some of the most successful models of cognitive control have focused on sequential and portion level congruency effects. The congruency sequence effect (also known as the Gratton effect, sequential modulation effect or conflict adaption) is typically found with tasks that require overcoming a prepotent response (e.g., Stroop, flanker, Simon; Akçay, Ç., & Hazeltine, E. 2008; Gratton, Coles, & Donchin, 1992;

Kerns, Cohen, MacDonald, Cho, Stenger, & Carter, 2004). For example on the Stroop task, one must respond to the color of the word (the word stimuli are written in different ink colors) and to ignore the word (the words are color words). Green written in yellow is an incongruent trial and Green written in green is a congruent trial.

Reaction times (RTs) tend to be faster on congruent trials relative to incongruent trials.

The sequential modulation effect is defined by a reduced congruency effect for trials that follow incongruent trials. Figure 1 provides an illustration of the interaction effect that defines sequential modulations. The gap between the congruent and incongruent lines in Figure 1 represents the congruency effect. The size of the congruency effect is moderated by the status of previous trial congruency. The sequential modulation effect is characterized by a smaller congruency effect for trials that occur after incongruent trials and a larger congruency effect for trials preceded by congruent trials. This effect has been demonstrated on the Stroop, flanker, and Simon tasks (Akçay & Hazeltine, 2008; Kerns et al., 2004; Gratton, Coles, & Donchin, 1992;). As stated previously, all of these tasks involve overriding a prepotent response. In the case of the flanker task, participants must respond to a centrally presented item that is flanked by distractor items. The central item is analogous to color and the flanking items are analogous to the word (color name) in the Stroop task. The Simon task involves responding to stimuli that appear in locations that are either compatible or incompatible with the location of the corresponding response (e.g. right, left).

Models of the Congruency Sequence Effect

The conflict monitoring model, a connectionist explanation of the congruency sequence effect, is one of the most cited explanations of this effect (Botvinick, Braver,

Barch, Carter, & Cohen, 2001). Connectionist networks are comprised of nodes organized in layers and are interlinked by weighted connections. Learning occurs in these models via the adjustment of weights. This model is based on the idea of response conflict, which is essentially the co-activation of incompatible responses. These responses are represented in the response layer of the model's network. The model defines conflict as simultaneous activation of mutually inhibiting units (units interconnected by inhibitory weights). Activation in the nodes of the response layer is triggered by activity in the stimulus layers which are comprised of nodes representing different stimulus features.

In their model of the Stroop effect, Botvinick and colleagues (2001) have two stimulus layers one for color and one for word, the two stimulus dimensions. Conflict is quantified and transmitted to the conflict monitor. The conflict monitor produces a conflict signal which is adjusted (nudged up or down) based on the presence of conflict in the response layer. An attention module/task demand layer will implement control by acting as a selective attention mechanism that will lead to a reduction of the influence of the irrelevant stimulus dimension and enhance the relevant stimulus dimension's impact on the response layer.

The up regulation of control is not permanent. This increase in control decays not over time (processing cycles) but over units of trials. The control signal is an exponentially weighted average of conflict on multiple preceding trials. This means that the control signal on each trial is increased or decreased based on conflict levels on the previous trial and that the shifts in control occur gradually.

According to this model congruent trials preceded by congruent trials have short RTs because the distractor dimension facilitates the response in this situation. Congruent trials that are preceded by incongruent trials will not be facilitated by the compatible features of the irrelevant dimension due to the up regulation of control. Incongruent trials preceded by congruent trials will be slow due to the interference from the irrelevant dimension but incongruent trials following incongruent trials will have shorter RTs due to the up regulation of control reducing the degree of interference from the irrelevant dimension.

Anterior cingulate cortex (ACC) has been proposed as the neural site for the conflict monitor and dorsolateral prefrontal cortex as the site that implements control (Botvinick, et al., 2001; Botvinick, Cohen, & Carter, 2004; Kerns, et al., 2004). This idea has received a fair amount of empirical support from both the functional magnetic resonance imaging (fMRI) and event related potential (ERP) research (Botvinick, Cohen, & Carter, 2004; Egner, 2007; Kerns et al., 2004; Yeung, Botvinick, & Cohen, 2004). Previous trial conflict related activation in the ACC has been shown to predict both greater prefrontal cortex activity and behavioral adjustments (Kerns et al., 2004). Conflict monitoring based simulations have been used to explain the relationship between the error related negativity (ERN) and the N2 scalp potentials to task parameters (Yeung et al., 2004). Recently research conducted on obsessive compulsive patients that were being treated with surgical lesions to ACC has shown an absence of the congruency sequence effect post-surgery (Sheth, Mian, Patel, Asaad, Williams, Bush, Dougherty, & Eskandar, 2012). Additionally, single cell recordings taken prior to the production of the lesion showed higher firing rates in ACC neurons during conflict trials (Sheth, Mian,

Patel, Asaad, Williams, Bush, Dougherty, & Eskandar, 2012). These findings provide converging evidence for ACC's role in a conflict monitoring process.

Since the initial publication of the conflict monitoring model several potential confounds and alternative models have been proposed. One potential confound involves the binding of stimulus and response features. Some researchers propose that the congruency sequence effect can be attributed to feature binding effects (Hommel, Proctor, & Vu, 2004; Mayr, Awh, & Laurey, 2003). Mayr and Hommel propose that repetition priming or episodic memory effects can produce congruency sequence effects. Hommel and colleagues (2004) suggested that the co-occurrence of stimuli and responses is dependent on the integration of features into a transient representation an "event file". Complete repetition trials (little effort needed due to feature repetition) and complete alternation trials (no feature binding to overcome) should have shorter RTs than partial repetition trials (repeat of a target but an alternation of the distractor or vice versa; previous feature binding needs to be overcome). For example in the standard letter flanker (subjects must respond to the central letter and ignore the flanking letters, the letters are either S or H) congruent trials preceded by congruent trials (CC) and incongruent trials preceded by incongruent trials (II) are always complete repetitions or complete alternations. On the other hand incongruent trials preceded by congruent trials (CI) and congruent trials preceded by incongruent trials (IC) are always partial repetitions. Initially when complete alternations were analyzed separately congruency sequence effects were not found (Mayr et al., 2003). Since this potential confound was discovered many studies have been conducted that control for feature binding effects and congruency sequence effects have still been found (Egner, 2007; Hazeltine, Lightman,

Schwarb, & Schumacher, 2011; King, Korb, & Egner, 2012; Ullsperger, Bylsma, & Botvinick, 2005; Weissman, & Carp, 2013). Feature binding accounts of the congruency sequence effect have merit but do not seem to be able to account for the congruency sequence effect alone. These accounts seem to be able to explain a portion of the effect but not the effect in its entirety.

Four choice tasks like the four color Stroop task are commonly used to control for feature binding. Yet, these tasks can potentially introduce a different kind of confound. Specifically contingency bias confounds (Schmidt, & De Houwer, 2011). Most four-choice Stroop experiments have an equal number of congruent and incongruent trials. Each word can appear in four different colors and only one color will produce a congruent trial. Words end up appearing in the congruent color more than what would be predicted by conditions of pure chance. For example in a Stroop task with four choices red, blue, green, and yellow the word red would have to appear in the color red more often than in the other 3 colors. This is because the word red is congruent on 50% of trials. Research has shown that subjects pick up on these contingencies and respond faster and with greater accuracy to high contingency trials (Schmidt, Crump, Cheesman, & Besner, 2007). Also, it has been shown that the contingency effect is larger after high contingency trials than after low contingency trials. In the case of the four-choice Stroop, congruent trials are high contingency trials and incongruent trials are low contingency trials. Predictable trial sequences elicit faster responses (Nissen & Bullemer, 1987). Schmidt and De Houwer proposed that since participants will see a sequence of any two high contingency trials more frequently than any sequence of two low contingency trials responses will be faster on sequences consisting of high contingency trials. Trial

sequences like (color word in upper case & color in lower case letters) BLUE-red → GREEN-green and GREEN-green → BLUE-red will not appear frequently. These sequences will violate participants' expectations of what should precede or follow a high contingency trial. Sequences comprised of two low contingency trials do not violate sequential trial biases since both trials appear infrequently (Schmidt and De Houwer, 2011).

The contingency bias account can make use of an executive control mechanism but contingency bias explanations in general are not dependent on such a mechanism. An attention based contingency learning explanation for the congruency sequence effect has been proposed. This version of the contingency bias account has some superficial similarities to the conflict monitoring model. Schmidt and De Houwer speculated that participants could increase attention to the word following a correct response prediction. Since the word correctly predicts the response on high contingency trials more attention is allocated to the word on the next trial and therefore the contingency effect is amplified. For low contingency trials the word does not correctly predict the response and therefore less attention is directed towards the word on the following trial. This leads to a dampening of the contingency effect (Schmidt and De Houwer, 2011).

Schmidt and De Houwer controlled for both feature binding and contingency bias and did not find congruency sequence effects (Schmidt, & De Houwer, 2011). They cited one study that controlled for both feature binding and contingency bias but this study found sequential modulation (Freitas, Bahar, Yang, & Banai, 2007). Schmidt and De Houwer's work in this area elicited many follow up experiments. Other researchers have now controlled for both contingency bias and feature binding and have found

congruency sequence effects (Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014; Freitas and Clark, 2014; Weissman, & Carp, 2013; Weissman, Jiang, & Egner, 2014). Neither the feature binding nor contingency bias accounts seem to provide a complete explanation of the congruency sequence effect. A complete explanation of the congruency sequence effect appears to require some kind of active control mechanism.

The feature binding, contingency bias, and conflict monitoring accounts are by no means mutually exclusive. The congruency sequence effect is probably not a process pure measure considering it can be attenuated by controlling for contingency bias and repetition priming. This investigation focused on the portion of the congruency sequence effect attributable to cognitive control processes like those described by the conflict monitoring model.

Locus of the Congruency Sequence Effect

The other major area of controversy in the congruency sequence effect literature does not involve the role of adaptive control in the congruency sequence effect but nature of its implementation. This remaining question is the level of control. That is, does it operate across tasks, within tasks, or some combination. The issue of the level of control concerns how control is directed. Item level models of control assume that control operates on specific stimulus features (Blais, Robidoux, Risko, & Besner, 2007; Verguts, & Notebaert, 2008). Control in these models adjusts weights to specific items or features (left or green). Set level control operates at the level of the stimulus dimension at which the features occur (color or location). Set level control served as the basic framework for Botvinick's conflict monitoring based models. One major strength of the item level control models is that they are able to account for the item specific proportion congruent

effect (Jacoby, Lindsay & Hessels, 2003). Item level and set level control theories possess easily defined targets of control and therefore are probably conducive to modeling. Despite these strengths set and item level models have trouble accounting for some findings in the literature. For example, item level models have difficulty explaining studies reporting sequential modulation across tasks (e.g., Freitas et al., 2007).

One example of cross-task congruency sequential modulation comes from Freitas and colleagues (2007). Across the three experiments Freitas and colleagues' (2007) had participants complete combinations of different Stroop like tasks. In all three experiments, all possible combinations of task and stimulus types were used in equal proportions and were presented in randomized orders. The first experiment used an arrow flanker task that combined vertically oriented arrow flanker trials with horizontally oriented arrow flanker trials. Switching between the two orientations occurred randomly. Subjects responded with one hand using the arrow keys located between the letter keys and the number keys on a standard keyboard. Switch trials were analyzed and the congruency sequence effect was present. This is indicative of global control since the congruency sequence effect is present across the orientation dimensions. The second experiment mixed the arrow flanker task with a two-word Stroop task (random alternation) and again the congruency sequence effect was found on switch trials thus providing additional support to the global control account. Unlike the first experiment this experiment required a vocal response (name the color & the direction of the central arrow). The third experiment mixed the flanker task with a spatial Stroop task in a randomly alternating fashion. In the spatial Stroop tasks, participants were presented with a box and an arrow. The subject had to respond by giving the direction of the box

relative to the arrow. In incongruent trials the arrow pointed away from the box and in congruent trials the arrow pointed towards the box. Subjects responded with a joystick (note: again one hand). The analysis of switch trials indicated that control was acting on a global level. The congruency sequence effect worked across the arrow box set and the simple arrow set. The modulation of cognitive control in all three paradigms transcended the stimulus set boundaries. Modulation was not contained to simple stimulus features or stimulus dimensions.

One potential problem with Freitas and colleagues (2007) results is that their studies had large sample sizes ($n = 51$, $n = 32$, $n = 52$) and small effect sizes (η_p^2 : .18, .17, .27). Therefore, one might view their results with some skepticism – that is, the results may be a statistical anomaly. Despite the relatively small effect sizes, Freitas and colleagues found the congruency sequence effect on a global level with three different experiments.

A more robust orientation switching task similar to the vertical horizontal flanker has been developed (Freitas, & Clark, 2014). The Stroop Trajectory task used in Experiment 1 of Freitas and Clark (2014) had many appealing features. On each trial in this task after a fixation period vertically or horizontally pointing black triangles were presented rapidly one after the other cumulatively yielding an array of slightly overlapping triangles. A small grey triangle pointing in the same direction as all of the others, appeared at either the top or the bottom of vertically oriented triangle arrays or at the left or right of horizontally oriented triangle arrays at the same time as the appearance of the last black triangle. The full array was kept on the screen for 146.67ms and was followed by a blank screen that was terminated by a response. The goal of the task was

to respond to the location of the small gray triangle. Congruency was based on the smaller triangle's location matching the direction that the larger triangles are pointing in and therefore matching the trajectory of the arrows' appearance (Freitas, & Clark, 2014). Vertical and horizontal trials were randomly interleaved and unlike the tasks used by Freitas and colleagues' (2007) trials were selected for presentation randomly with replacement. Considering that Freitas and Clark only analyzed switch trials this task controlled for both contingency bias and stimulus response repetitions. The task consisted of a practice block of 24 trials and of 776 real trials broken into 8 blocks of 97 trials. Participants responded with their dominant hands via the arrow keys of a standard keyboard.

The 15 undergraduate sample yielded a statistically significant previous trial congruency by current trial congruency interaction effect on switch trials thereby demonstrating global control (η_p^2 : .55 for reaction times and .39 for accuracy). This lends support to the notion that the congruency sequence effect is not merely the product of stimulus-response priming and contingency bias confounds. Also, these results provide additional evidence for global control (Freitas and Clark, 2014). Unlike the three paradigms used in Freitas and colleagues (2007) the effect sizes were not small and the sample size was fairly modest.

Freitas and his colleagues have been successful at producing evidence for global control (e.g, 2007 and 2014), however, evidence for local control is much more common in the literature (Akçay & Hazeltine, 2008; Egner, Delano, Hirsch, 2007; Funes, Lupiáñez, & Humphreys, 2010; Notebaert, & Verguts, 2008). Congruency sequence effects have been shown not to occur between a flanker task and a Simon task (Funes et

al., 2010) nor between two different versions of a Simon task (Akay & Hazeletine, 2008). Other researchers have suggested that control may be local to the type of stimulus dimension used. For example, Notebaert and Verguts (2008) found that the congruency sequence effect can cross between tasks when a relevant stimulus dimension is shared. In that study participants completed a task switching procedure comprised of randomly interleaved Simon and Spatial Numerical Association of Response Codes (SNARC) trials. The effect was present on switch trials when both tasks required that participants respond to stimulus orientation. In the other condition where the tasks did not share a relevant stimulus dimension a reversed congruency sequence effect was found. Despite the simple global vs. local dichotomy that sets the framework for most theorizing in this field research into the locus of control has yielded rather nuanced results (Akay, & Hazeletine, 2007; Hazeltine et al., 2011).

Hazeltine and colleagues (2011) charted the boundaries of control with a new procedure they called the temporal flanker task. This task is comprised of a prime and a target. The prime came from the same stimulus set as the target and appeared in the same location as the target 100 ms prior to target onset. One major strength of this task is that it allows stimuli to be manipulated along distinct modalities.

In their first experiment a letter based temporal flanker was presented in two modalities (auditory & visual) (Hazeltine et al., 2011). The letter task had four letter stimuli A, B, C, D and an overlapping response set for the two modalities (one hand). Hazeltine and colleagues used a systematic switching routine with modality switching every other trial (c.f., Rogers, & Monsell, 1995). This sequence of events for the temporal flanker was used in the other experiments they conducted as well. A large

number of trials were removed in order to control for feature repetition effects. They removed trials in which targets repeated, or flankers repeated, or flankers on the previous trial appeared as targets on the current trial, or targets on the previous trial appeared as flankers on the current trial and conceptually related stimuli (same letter different modality) were counted as repetitions. These standards lead to the removal of 52% of trials. Half of the remaining trials were incongruent and half were congruent.

Congruency sequence effects were significant on repeat trials but there was no evidence of sequential modulation on switch trials. This significant interaction between modality switch, previous trial congruency, and current trial congruency showed that modality seemed to be acting as a boundary for control. In their next experiment the focus shifted to the boundaries of sequential modulation within a modality.

In a second experiment, Hazeltine and colleagues (2011) used two sets of visual stimuli the letter task from the first study and a visuospatial task. The visuospatial task had a central fixation cross and a line comprised of dashes four in all two on each side of the fixation cross. A circle appeared over one of the dashes and participants had to ignore the prime circle and respond to the location of the target circle. These stimuli sets were systematically alternated (switched every other trial) and used an overlapping response set (one hand). Again half of the trials were congruent and half were incongruent. This task produced a significant congruency sequence effect on switch trials. Like Freitas and colleagues (2007) experiments this experiment found evidence for global control between different stimulus sets.

In a third experiment Hazeltine and colleagues (2011) replicated the second experiment with the exception of the response set. Each stimuli set was assigned to a

different hand (letter-left, visuospatial-right). On this task they found local control. The congruency sequence effect was no longer present on switch trials. The significant three way interaction between switch, previous trial congruency, and current trial congruency showed that switch status moderated the congruency sequence effect. The authors speculated that the participants' task representations were responsible for the boundary that was erected by the response set segregation. Task representations are flexible and this characteristic is what allows them to account for the inconsistencies of the locus of control literature.

Task sets are mental representations that link stimuli to the appropriate responses for a given task (Hazeltine, et al., 2011; Rogers, & Monsell, 1995). It is possible that control operates within boundaries produced by these representations. The flexible boundaries of control could be a result of subtle differences in task constraints leading to different conceptions of a task. The second experiment's overlapping response set might have lead participants to view the letter and visuospatial trials as being part of a single task. In the third experiment on the other hand the splitting of the responses could have caused subjects to view the procedure as being comprised of two different tasks. Task sets might act as the boundaries of cognitive control.

One important similarity between the experiments of Freitas and colleagues (2014 and Experiment 2 of Hazeltine and colleagues (2011) is that both used a one handed response set. Hazeltine and colleagues second experiment resulted in global control, replicating Freitas and colleagues. The separation of the response set to two hands in Hazeltine and colleagues' third experiment lead to the disappearance of sequential modulation on switch trials. Could the response set influence the participants'

conception of the task? How might the response hand manipulation erect this boundary? The task set hypothesis provides an answer that can account for the flexibility in the congruency sequence effect's boundaries. Task sets are abstract representations and if control adjustments work inside the boundaries of a task, then manipulations that change how the task is represented should influence the boundaries of control.

The Present Experiment

The results presented in the work of Freitas and colleagues supports the idea of a global cognitive control mechanism that is not bound by stimulus dimensions or low level perceptual features. Yet, this interpretation is inadequate considering that congruency sequence effects are frequently not present on stimulus set switch trials (Akçay & Hazeltine, 2008; Egner, et al., 2007; Funes, et al., 2010; Hazeltine et al., 2011; Notebaert, & Verguts, 2008). The demonstration of response set influence on the boundaries of the congruency sequence effect not to mention the general inconsistency in the literature demands a more nuanced explanation of this phenomenon (Hazeltine et al., 2011). Flexible abstract representations that bind different assemblies of stimuli, responses, and task unrelated contextual factors together could act as the locus of control.

The use of a unitary response set might be responsible for some cases of global control (Freitas & Clark, 2015; Freitas et al., 2007). In order to test the flexible task representation account of Freitas and Clark findings, the hand manipulation from Hazeltine and colleagues was applied to the Stroop trajectory task (Freitas & Clark, 2015). The application of this manipulation measured the influence of response set as a boundary for task sets and control. Additionally, Hazeltine and colleagues also showed that response set isn't sufficient to explain the boundaries of sequential modulation.

Rather, other factors can also affect how participants create/organize their task sets. One additional factor in Frietas and Clark that may have affected the boundary of control is the way that experiment switched tasks across trials. They used a random switching manipulation across trials, whereas Hazeltine and colleagues used a systematic procedure. Systematic switching routines like the classic AABBAABB system might bias participants' task perceptions. The grouping principle that defines this method might help lead to the formation of separate task sets. If switching routine acts as a task delineating signal it is probably not as salient as response set. The second Hazeltine and colleagues (2011) experiment put switching routine and response set in opposition to each other but the single response set lead to global control. This suggests that response set has a stronger effect than switching routine assuming switching routine has an effect as previously described. The switching routine might attenuate the effect of response set if the two are in opposition. For example the congruency sequence effect on switch trials for a task with a random switching routine and an overlapping response set might be more pronounced than congruency sequence effect on switch trials for a task with an overlapping response set and a systematic switching routine.

The experiment used to test this hypothesis set included four conditions/groups (these terms will be used interchangeably). In two of the conditions the response set and the switching routine factors worked in the same direction. In the other two conditions these factors were in opposition. It was hypothesized that single hand conditions would produce global control while local control would be present for the two response hand conditions. In addition, it was hypothesized that a gradation of the congruency sequence effect would be observed due to the presence or absence of opposing forces.

The response set hypothesis offers an explanation for the global control observed on the Stroop trajectory task (Frietas & Clark, 2015). The overlapping responses and/or the switching procedure of the original Stroop trajectory paradigm might have caused participants to view the two orientations as one task. The random switching routine has the potential to influence how participants conceive the task. Switching every other trial is systematic and creates a clear distinction between the two sets of visual stimuli. Random switching does not clearly delineate between the two sets. If responses are segregated participants are given an additional marker that distinguishes between the two tasks. This manipulation might increase the odds of participants viewing the procedure not as one task but as two separate task sets. Unlike other control level frameworks task set based control boundaries can account for the flexibility in congruency sequence effect crossover (Hazeltine et al., 2011).

For the first condition (one hand, random switching) a previous trial congruency x current trial congruency interaction should be present on switch trials. A significant but attenuated congruency sequence effect on switch trials was the anticipated outcome for the second condition (one hand, systematic switching) due to the opposition of the routine and response set factors.

In the third condition (two hands, random switching) the congruency sequence effect was not anticipated to be significant for switch trials considering that the influence of response set seems to be stronger than that of switching routine. For the fourth condition it was expected that the magnitude of the insignificant congruency sequence effect for switch trials would be weaker than what was observed in the third condition since the switching routine and response set factors were not in opposition.

The first (one hand, random switching) and the fourth (two hands, systematic switching) conditions have the response set and switching routine factors working in the same direction. The second and third conditions are examples of the factors working in opposition. If response set is a stronger task delineator than switching routine and opposition leads to the weakening of control's boundaries then the second condition should have less robust global control relative to the first condition. Local control should be more robust for the fourth condition relative to the third condition. Essentially it was hypothesized that a gradation of the magnitude of the congruency sequence effect would be present. The first condition would sit at one extreme with global control and the fourth condition at the other with local control. The second and third conditions would yield intermediate effect sizes but it should be noted that a statistically significant congruency sequence effect was expected for the second condition but not for the third condition.

Heterogeneity

Global control and local control are typically viewed as distinct types of cognitive control arrangement. The modeling literature not to mention most of the theoretical accounts of the locus of control not derived from a computational model imply that these two terms represent distinct frameworks of control. Even if the canonical way of conceptualizing global and local control is correct these control formats can be observed with varying degrees of integrity assuming that the task representation account is sound. If control boundaries are in fact flexible and determined by task sets then it is not improbable that there will be individual differences in task representation. Situations in

which participants are exposed to mixed signals like the second and third conditions of this experiment could potentially be marked by more heterogeneity in task representation.

Task representation heterogeneity is one possible driving factor behind “weak” global or local control. Global and local control are technically typological and this conventional definition will be referred to as strict global or local control. Board global or local control will refer to a continuum of effect magnitudes in data. This empirically driven definition is associated with “weak” global or local control. Since board global and local control are of interest to this investigation individual differences were examined. Bimodality in the distributions of a subject level index of the congruency sequence effect for the mixed signal groups could be indicative of task representation heterogeneity. Therefore it was decided that the distributions of a congruency sequence effect index would be inspected in order to ensure that subtle trends that could have a bearing on the effects of interest were not being obscured. In order to get a picture of individual difference the conflict adaptation ratio (CAR) was calculated for each participant (Weldon, Mushlin, Kim, & Sohn, 2013). The CAR was originally used as a subject level measure of the congruency sequence effect in latency data. It was used to explore individual differences in the contextual regulation of control and their relationship to individual differences in working memory capacity an issue that has been difficult to study due to scaling effects (Faust, Balota, Spieler, & Ferraro, 1999; Weldon et al., 2013). The CAR is not subject to scaling effects in reaction times and this fact makes it well suited for individual differences research. It is defined as the ratio of the congruency effect for trials that followed incongruent trials to the congruency effect for

trials that followed congruent trials. CAR values were calculated for each participant's switch trial reaction time and accuracy data.

CHAPTER 2

METHODS

Participants

Forty-eight participants were recruited from the Georgia Institute of Technology's undergraduate subject pool. The participants were divided into 4 groups of equal size (12 subjects). The average age was 20.65 years and 23 of the participants were female. Written informed consent will be obtained and all participants will be required to have normal or corrected to normal vision. One participant had an accuracy level that was 3 standard deviations below the mean and another participant was run in the same condition in order to replace this performance outlier.

Stimuli and Apparatus

Stimuli were presented via Dell P1130 CRT monitors running at a 75 MHz refresh rate. Each version of the task was run on Inquisit 3. All four conditions included two segments each consisting of 776 trials (eight blocks consisting of 97 trials). Participants completed 24 practice trials at the start of each segment. Stimulus types were selected randomly with replacement. . The stimulus presentation procedure was nearly identical to that of Experiment 1 from Freitas and Clark (2014). Each trial started with a 400ms fixation period vertically or horizontally pointing black triangles were then presented rapidly (6 black triangles appearing in 26.67ms intervals and the 7th appearing with a slightly longer interval of 40ms) one after the other cumulatively yielding an array of slightly overlapping triangles. A small grey triangle pointing in the same direction as all of the others, appeared at either the top or the bottom of vertically oriented triangle

arrays or at the left or right of horizontally oriented triangle arrays at the same time as the appearance of the last black triangle. The complete set of triangles was presented for 146.67ms. If the participants did not respond during the 146.67ms stimulus period a blank screen appeared until the participants made a response. An error signal (the word “Error” written in a red) flashed on the screen after errors for 500ms. Inter-trial intervals (blank screen) ranged from 125ms to 250ms and this duration varied randomly. In all conditions participants responded with a standard keyboard. The black triangles were 83 pixels high x 27 pixels wide and the smaller grey triangle measured 24 pixels x 14 pixels. For upward pointing triangle sets the bottom triangle was located 41% of the distance from the bottom of the screen and centered horizontally. Right, downward and left pointing triangle arrays were produced by rotating the stimulus by 90°, 180°, and 270°.

Procedure

In the first condition trials switched randomly between vertical and horizontal triangle arrays. Participants in this condition responded with their dominant hand using the arrow keys. For the second condition trials switched systematically between vertical and horizontal triangle arrays. Switches occurred every other trial. Participants responded with one hand using the arrow keys on a standard keyboard. The third condition like the first condition had random switching between vertical and horizontal triangle arrays. Participants responded with two hands using one for the vertical stimuli and the other for the horizontal. The two response sets were located on opposite sides of a standard keyboard (vertical/horizontal hand assignment were counterbalanced). The “z” & “x” keys or the “.” & “/” served as response sets for the horizontal dimension. The vertical dimension was represented by the “a” & “z” keys or the “/” & “”” keys. The

fourth condition had the same systematic switching routine used in the second condition.

The response protocol was identical to the one described for the third condition.

CHAPTER 3

RESULTS

Primary Findings

The Stroop trajectory task was originally analyzed with an atypical trimming method (Freitas & Clark, 2014). For latency data all error and post error trials were removed from analysis in addition to all trials with reaction times exceeding 800ms. Accuracy data were not analyzed for post error trials. This trimming method was applied to the current data set along with a more conventional method. The conventional method removed both error and post error trials from the latency analysis. For each subject all reaction times outside a 2.5 standard deviation bound were removed from analysis not to mention post reaction time outlier trials. For accuracy data post error and post RT outlier trials were removed. Also, an arcsine transform was applied to the accuracy data. All accuracy graphs display the raw untransformed proportion of correct trials for the purpose of ensuring easy interpretation.

In addition to the primary analysis that focused on switch trials a supplemental analysis of trials across switch status (orientation switch, orientation repeat) was conducted. Unfortunately the nature of the Stroop trajectory task does not allow for complete removal of the stimulus response repetition bias on orientation repeat trials. Complete repetitions were completely removed from CC and II trials. In regards to IC and CI trials only partial repetitions with no aspect of the stimulus repeating (simply response repetitions) were kept in the analysis. Most prepotent response inhibition procedures have partial repetition trials that are comprised of target switches, response

switches, and distractor repeats or target repeats, response repeats, and distractor switches. This holds true for both the letter flanker and the arrow flanker paradigms. For example in the case of an IC trial preceded by HSH, it can either be HHH (Target: Alternation, Distractor: Repetition, Response: Alternation) or SSS (Target: Repetition, Distractor: Alternation, Response: Repetition). In the case of a CI preceded by HHH it can either be HSH (Target: Alternation, Distractor: Repetition, Response: Alternation) or SHS (Target: Alternation, Distractor: Repetition, Response: Alternation). Orientation repeat trials in the Stroop trajectory task that fall into the IC and CI categories can either be simple distractor repetition/response alternation trials or distractor alternation/response repetition trials. Distractor based partial repetitions were not included in the switch status analysis. Also, the first trial of each block was removed due to the lack of a true preceding trial type resulting from the feedback period between blocks.

Error and post error trials accounted for 13% of total trials (across segments). After the removal of post error and error trials the extraction of exact repetitions and distractor based partial repetitions resulted in the disposal of a trial number equal to 22% of the original trial total. The application of the Freitas method on the remaining trials and the removal of the first trial of each block (these trials were preceded by block level feedback and were therefore not well suited for the study of sequential effects) collectively removed a quantity of trials equal to 2% of the original trial total. In the case of the conventional trimming method the number of remaining trials removed was equal to 3% of original trial total.

A three way split plot ANOVA (Group x Trial N-1 Congruency x Trial N Congruency) was performed on switch trial data for both latencies and accuracy. When

using the Freitas method the analysis yielded for the latency data a significant main effect of current trial congruency (congruency effect), $F(1,44)=120.156, p < .001, \eta_p^2 = .732$ and a significant main effect of previous trial congruency, $F(1,44)= 10.272, p < .05, \eta_p^2 = .189$. Incongruent trials (387ms) had higher mean RT than congruent trials (351ms). The effect of previous trial congruency was weak but in accordance with what would be expected due to post conflict slowing (Ullsperger et al., 2005). The mean RT for trials following congruent trials (368ms) was faster than the mean reaction time for trials following incongruent trials (371ms). A significant congruency sequence effect was observed, $F(1,44)=141.140, p < .001, \eta_p^2 = .762$, and critical to this investigation the three way Group x N-1 Congruency x N Congruency interaction was not statistically significant, $F(3,44)= 1.067, p = .373, \eta_p^2 = .068$, thus demonstrating that the experimental manipulations did not modulate the congruency sequence effect for reaction times (Group 1 CSE=28, Group 2 CSE=25, Group 3 CSE=32, Group 4 CSE=21). In addition, there was a significant main effect for group $F(3,44)= 10.402, p < .001, \eta_p^2 = .415$. A post hoc Tukey test showed that one hand systematic switching condition differed significantly from both two hand conditions at $p < .05$ with the one hand condition faster than the two hand conditions. The one hand random switching condition RT's were faster than those for both two hand conditions and differed significantly from the two hand systematic condition $p < .05$ but did not significantly differ from the two hand random condition $p = .08$. No other effects reached statistical significance.

An arcsine transformation (Sheskin, 2003) was applied to the accuracy data to account for the non-normal distribution of the accuracy data. An ANOVA was conducted on the transformed data. The ANOVA yielded a significant main effect of

current trial congruency (congruency effect), $F(1,44)= 115.494, p < .001, \eta_p^2 = .724$ and a significant main effect of previous trial congruency, $F(1,44)= 39.983, p < .001, \eta_p^2 = .476$. The proportion of trials responded to correctly was greater on congruent trials (97%) relative to incongruent trials (89%). Accuracy was better on trials following incongruent trials (94%) relative to those following congruent trials (92%). The post incongruent trial slowdown and increase in accuracy suggests that participants traded speed for accuracy after incongruent trials. As with the reaction time data a significant congruency sequence effect was observed, $F(1,44)= 46.230, p < .001, \eta_p^2 = .512$, and critical to this investigation the three way Group x N-1 Congruency x N Congruency interaction was not statistically significant, $F(3,44)= 2.578, p = .066, \eta_p^2 = .149$ (One Hand/Random CSE=.054, One Hand/Systematic CSE=.087, Two Hand/Random CSE=.049, Two Hand/Systematic CSE=.024). In addition, there was a statistically significant Group x N Congruency interaction $F(3,44)= 3.968, p < .05, \eta_p^2 = .213$. This interaction was defined by a stronger congruency effect in the one hand systematic switching group.

The conventional standard deviation trimming method produced results extremely similar to those found with the Freitas method considering that the pattern of significant effects did not change. For the latency data a significant main effect of current trial congruency (congruency effect), $F(1,44)= 128.862, p < .001, \eta_p^2 = .745$ and a significant main effect of previous trial congruency, $F(1,44)= 12.340, p = .001, \eta_p^2 = .219$. Congruent trials (351ms) exhibited a lower mean reaction time than incongruent trials (387ms). The mean of trials following incongruent trials (370ms) was slower than the mean for trials following congruent trials (367ms). A robust and significant congruency

sequence effect was observed, $F(1,44)= 101.431, p < .001, \eta_p^2 = .697$, and critical to this investigation the three way Group x N-1 Congruency x N Congruency interaction (see figures 3-6) was not statistically significant, $F(3,44)= 2.065, p = .119, \eta_p^2 = .123$ (One Hand/Random CSE=25, One Hand/Systematic CSE=25, Two Hand/Random CSE=30, Two Hand/Systematic CSE=15). A significant effect of group, $F(3,44)= 9.182, p < .001, \eta_p^2 = .385$, was found as well. A post hoc Tukey test showed that one hand systematic switching condition differed significantly from both two hand conditions at $p < .05$ with the one hand condition being faster than the two hand conditions. The one hand random switching condition reaction times were faster than those for both two hand conditions and differed significantly from the two hand systematic condition $p < .05$ but did not significantly differ from the two hand random condition $p = .11$.

This trend continued for the accuracy data. A significant main effect of current trial congruency (congruency effect), $F(1,44)= 115.746, p < .001, \eta_p^2 = .725$ and a significant main effect of previous trial congruency, $F(1,44)= 37.019, p < .001, \eta_p^2 = .457$ were found. The mean percentage of trials responded to correctly was higher for congruent (97%) trials than for incongruent trials (89%). Accuracy was superior on trials preceded by incongruent trials (94%) relative to trials preceded by congruent trials (92%). Also, a significant congruency sequence effect was observed, $F(1,44)= 46.181, p < .001, \eta_p^2 = .512$, and critical to this investigation the three way Group x N-1 Congruency x N Congruency interaction (see figures 7-10) was not statistically significant, $F(3,44)= 2.579, p = .066, \eta_p^2 = .150$ (One Hand/Random CSE=.059, One Hand/Systematic CSE=.091, Two Hand/Random CSE=.049, Two Hand/Systematic CSE=.024). In addition, there was a statistically significant Group x N Congruency

interaction $F(3,44)= 3.979, p < .05, \eta_p^2 = .213$. Due to the similarity of the results obtained under the two trimming methods all subsequent analyses will be performed on data trimmed with the conventional method.

The Influence of Orientation Switching

In order to gain insights into the effects of switching and the influence of group membership on switching a four way split plot ANOVA (Group x Switch Status x N-1 Congruency x N Congruency) was conducted on both latency and accuracy data. The aforementioned procedure was applied to the repeat trials in order to mitigate the influence of previously established feature bindings. The analysis of the latencies uncovered a weak but statistically significant main effect of switch status, $F(1,44)= 4.344, p < .05, \eta_p^2 = .090$. In addition to a significant congruency effect, $F(1,44)= 161.038, p < .001, \eta_p^2 = .785$, and a significant main effect of previous trial congruency, $F(1,44)= 8.927, p < .05, \eta_p^2 = .169$, a significant main effect of group, $F(3,44)= 98.811, p < .001, \eta_p^2 = .375$ was observed. Interaction effects that passed the threshold of statistical significance included a weak interaction of switch status and congruency, $F(1,44)= 4.676, p < .05, \eta_p^2 = .096$, a robust N-1 Congruency x N Congruency interaction, $F(1,44)= 139.744, p < .001, \eta_p^2 = .761$, and a Switch Status x N-1 Congruency x N Congruency interaction, $F(1,44)= 70.126, p < .001, \eta_p^2 = .614$. The four way interaction of group membership, switch status, previous trial congruency, and current trial congruency was not statistically significant, $F(3,44)= 1.224, p = .312, \eta_p^2 = .077$, thus indicating that group does not modulate the interaction of switch status and the congruency sequence effect in regards to reaction times (see figures 11-14 for repeat trial latency congruency sequence effects by group).

For the accuracy data the four way ANOVA yielded a significant main effect of congruency, $F(1,44)= 136.658, p < .001, \eta_p^2 = .756$, and significant a main effect of previous trial congruency, $F(1,44)= 76.856, p < .05 \eta_p^2 = .636$. No additional main effects reached significance. The Switch Status x N-1 Congruency interaction, $F(1,44)= 9.868, p < .001, \eta_p^2 = .183$, the Group x N Congruency interaction, $F(3,44)= 3.715, p < .05, \eta_p^2 = .202$, and the Group x N-1 Congruency x N Congruency interaction, $F(3,44)= 3.640, p < .05, \eta_p^2 = .199$ were all statistically significant. The Group x N-1 Congruency x N Congruency interaction is somewhat interesting but it should be noted that this pertains to the modulation of congruency sequence effect by group across switch status. The interaction of previous trial and current trial congruency that defines the congruency sequence effect was statistically significant, $F(1,44)= 152.822, p < .001, \eta_p^2 = .776$, as was the Switch Status x N-1 Congruency x N Congruency interaction, $F(1,44)= 81.319, p < .001, \eta_p^2 = .649$. The four way interaction of group, switch status, previous trial congruency, and current trial congruency was statistically significant as well, $F(3,44)= 3.074, p < .05, \eta_p^2 = .173$. No other effects were significant (see figures 15-18 for repeat trial accuracy congruency sequence effects by group). When it comes to the 4 way interaction simple visual inspection of Appendix B makes it rather clear that the magnitudes of the congruency sequence effects do not follow the predicted pattern.

CAR Heterogeneity

Unfortunately sample size restrictions prevented a truly adequate analysis of individual differences in the congruency sequence effect in each group. Evidence for bimodality was not found and the topic will not be elaborated on any further. Yet, it

would have been borderline irresponsible not to examine subject level effects since theoretically important trends in individual differences might be masked by aggregation¹.

¹ Based upon visual examination of histograms of the CAR it was apparent that bimodality was not present for any of the groups. In regards to latency CAR values the one hand random group and the two hand random group contained congruency sequence effect outliers. The former had a participant with a reversed congruency sequence effect (CAR = 1.94) and the latter group possessed a participant with an extremely strong congruency sequence effect (CAR = -1.62) a clear example of overshooting. Extreme over and under modulation were not uncommon in the error rate CAR distributions.

CHAPTER 4

DISCUSSION

Summary of Findings

On the surface the lack of a modulator effect of group on the switch trial congruency sequence effect not to mention the lack of influence group membership has on switch status' modulation of the congruency sequence effect for reaction times seems to support the global control model proposed by Freitas and colleagues. Item level control theories predict that control modulations are specific to particular items and set level control predicts modulations are specific to stimulus dimensions. The presence of a significant congruency sequence effect on switch trials runs against the predictions of these models. Despite the evidence they have presented for global control Freitas and Clark accept that task representation might be responsible for their observations of global control and on other experiments they demonstrated that conflict type can act as a congruency sequence effect boundary (Freitas & Clark, 2015). It is unlikely that a parsimonious answer will adequately resolve the inconsistent findings. The outcome of this experiment by no means falsifies the task representation account of the locus of control. Based on past research one could expect response set segregation to erect a control boundary but response set is not an essential marker of task categorization.

The Nature of Orientation Repeats

In regards to switch status's impact on the congruency sequence effect in the Stroop trajectory task, congruency sequence effects on RT across all groups were stronger in orientation repeat trials relative to orientation switch trials. This outcome

might be the result of similarity modulating the impact of the congruency sequence effect. Similarity could influence control boundaries on its own and/or through task set integrity. The task set parameters might be better maintained with greater stimuli similarity.

The degree of similarity, both in terms of basic features and in a more abstract conceptual sense, between two dimensions/tasks might inform control at the level of implementation. Similarity between the previous and the current trial can act as a signal to something akin to Botvinick's task demand layer. Similarity beyond some threshold would indicate that the two trials belong to the same series and conflict from the previous trial should be used to update control parameters for current trial (Botvinick et al., 2001). Task sets can be thought of as the product of a classification process informed by the degree of similarity between task subcomponents/trial types.

Unfortunately partial repetitions could not be completely eliminated (Hommel et al., 2004). It was decided that distractor based partial repetitions would be removed from analysis. This path was taken since partial repetitions on letter and arrow flanker tasks are not defined by partial repetitions solely based on the repetition of the response. Conventional letter and arrow flanker paradigms have partial repetitions based on distractor alternations, response repetitions, and target repetitions or distractor repetitions, response alternations, and target alternations. Including distractor based partial repetitions in the analysis instead of response based partial repetitions did not lead to a change of statistical significance for any of the effects in 4 way analysis of the latency data other than the effect of switch status being statistically insignificant and a significant switch status congruency interaction was not present. The trial type RT means for the

different groups were very similar to those found when removing response based partial repetitions. The only differences in the pattern of significant effects observed in the analysis of accuracy data was a significant main effect of switch status a nonsignificant interaction of group and congruency, the absence of the modulation of the congruency sequence effect by group, and a lack of a 4 way interaction. The data were analyzed with no repetition trial removal and the pattern of significance was the same as what was found for the analysis conducted with the removal of distractor based partial repetitions.

A feature integration explanation can explain the outcome of the supplemental 4 way analysis but a similarity based modulation of cognitive control is capable of explaining these results as well. The partial repetition issue is insurmountable given the structure of the Stroop trajectory task. Future research will have to attempt to replicate this effect with a paradigm that lacks feature integration confounds on stimulus set repeat trials.

The Role of Stimulus Set Similarity

Global control still remains a rarity in the literature but in recent years it has been observed with greater frequency (Weissman, Colter, Drake, & Morgan, 2015; Weissman et al., 2014). It has been proposed that response mode (e.g., same hand) on consecutive trials might act as an insurmountable boundary for control (Kim & Cho 2014).

Weissman and colleagues found evidence against this claim with two paradigms similar to the Stroop trajectory task (Weissman et al., 2015). Two experiments one based on a prime-probe task that controlled for both stimulus response repetition and contingency bias confounds and the other with a flanker like paradigm that did not have a temporal disconnect between the distractor and the target that also controlled for both confounds

were conducted. Each task included two stimulus sets and a block was devoted to each of the tasks. In both experiments a response mode (one hand or stimulus sets segregated by hand) condition was assigned to a given task for each subject (counterbalanced) and this resulted in participants being exposed to both response modes but the that order of exposure was counterbalanced. The authors argued that associating split or unsegregated response modes to different tasks would prevent task representation interference a factor that was a major concern in the study that is the topic of this thesis. In both experiments Weissman and colleagues found that the congruency sequence effect was present in both conditions thus demonstrating global control (Weissman et al., 2015). Like both the Stroop trajectory task and the temporal flanker task used by Hazeltine and colleagues the paradigm used in the first experiment made use of a prepotent response paradigm with a temporal disconnect between distractor presentation and target presentation (Freitas and Clark, 2014; Hazeltine et al., 2011; Weissman et al., 2014). Some have argued that the congruency sequence effect when mitigating the influence of confounds, as was done with both the Stroop trajectory task and the prime-probe paradigm, is more robust when the distractor precedes the target compared to confound minimized paradigms with simultaneous presentation of the distractor and the target (Weissman et al., 2014).

A mixed design was used in the current study in order to avoid the problem of sticky task representations. Weissman feared that being exposed to both response modes might have broadened his participants' subjective task boundaries to include both response modes once they were made aware of the second response mode midpoint of the experiment (Weissman et al., 2015). The authors addressed this issue by conducting a separate analysis that made use of the first half of each subject's data (the period when a

participant was only exposed to one of the response modes). This analysis with response mode acting as a between subjects factor did not yield a significant modulation of the congruency sequence effect by response mode and thereby supports the global control account (Weissman et al., 2015). Considering these findings future research on congruency sequence effect boundaries should make use of the general framework employed by employed in Weissman et al (2015) in order to avoid the use of between subjects factors.

Weissman and colleagues did mention that their stimulus sets were similar and that this factor might have lead subjects to use a single task representation despite being exposed to a split response set in cases. This is relevant when considering both the study presented in this thesis and the Weissman study in the context of the task representation account (Hazeltine et al., 2011). The first experiment in Hazeltine et al (2011) involved a letter task alternating between the auditory and visual modality. It is not unreasonable to assume that modality is a stronger delineating factor than spatial orientation and especially digit/letter set. More importantly experiments two and three made use of a paradigm that alternates between a letter task and a visuospatial task that involved responding to a circle based upon a dashed line it appeared above. Despite being in the same sensory modality these tasks are fairly different in terms of appearance. The objective and the procedure of each task are similar but the concepts connected to the different stimuli sets are rather different. The Stroop trajectory task makes use of triangles in both the vertical and the horizontal trial types. The impact of hand might depend upon the relationship between the stimuli sets that comprise the paradigm. Recent research including the results of this study demand further exploration of the

relationship between the impact of response set on control boundaries and the similarity of the stimuli sets that one is trying to segregate with a split response manipulation. The impact of response set on task representation might interact with stimulus set similarity. If stimulus sets are very similar common response sets might have little influence on task boundaries. This probably holds true for the other extreme as well considering that in the first experiment conducted by Hazeltine and colleagues a common response set did not break down the boundary imposed by modality (Hazeltine et al., 2011). A certain degree of stimulus set dissimilarity could mark a maximum point of response set influence. An inverted U shaped relationship between stimulus set similarity and influence of response set on task boundaries is plausible explanation given past research (Freitas & Clark 2015; Hazeltine et al., 2011; Kim & Cho 2015; Weissman et al., 2015).

In their fourth experiment Hazeltine and colleagues produced their most dramatic demonstration of the nuanced nature of sequential modulation boundaries. They showed that the congruency sequence effect can cross modalities under certain conditions (Hazeltine et al., 2011). Participants completed a paradigm that switched from the auditory to the visual modality and it switched between a letter task and an animal task. These two tasks made use of a single response set. The modality was varied pseudorandomly and the tasks alternating every other trial. Despite the different presentation modalities the congruency sequence effect was found on switch trials. The complexity of the paradigm was believed to have taken away from the salience of modality (Hazeltine et al., 2011). If the manipulation of salience can break the boundaries associated with modality it is not improbable that response set is vulnerable to such effects. The Stroop trajectory task in addition to the tasks used by Weissman and

colleagues lacked the complexity of the modality switch letter-animal paradigm but stimuli orientation switches relative to the switches used in the temporal flanker paradigms seem unremarkable in terms of the saliency (Hazeltine et al., 2011; Weissman et al., 2015).

What might be of the utmost importance is the interaction between the response set and the degree of stimulus set similarity. This interaction can and should be analyzed in future research endeavors but this is easier said than done. One can devise some kind of a priori means of modulating similarity between different stimuli sets but assuming that similarity does act as both a moderator of response set's influence on control boundaries and as a control boundary delimiting factor the real marker of similarity lies in the subjects' perception. In addition, stimuli sets can be similar or dissimilar in both the concrete/feature sense or in an abstract/conceptual sense and it is not yet clear how these dimensions of similarity interact or the kind of weight each has on tasks boundary formation. Future research should modulate the procedural complexity of a task but experimental design faces some of the same challenges that similarity modulation designs will have to overcome.

Another important area for future research concerns comparing the hybrid event file account and the task representation model (Hazeltine et al., 2011; Hommel et al., 2004). A simple episodic account that does not incorporate a cognitive control mechanism is not a complete explanation of the congruency sequence effect, especially in regards to dimension switching paradigms, but a hybrid account that incorporates not only stimulus-response features but contextual factors, and control parameters into an event file could explain cross-dimensional congruency sequence effects as long as some

sort of contextual link is present between the two dimensions (Spapé, & Hommel, 2008). The broad view of “event files” has basically rendered this concept to be almost synonymous to task sets.

The task representation account is fairly similar to the hybrid event file account that incorporates a cognitive control information into the episode. Task sets are essentially a broader version of an event file. They are associative webs comprised not of a single event but of multiple events. The extreme inconsistency in the locus of control literature is best explained by the task representation theory. The persistent global control found on the Stroop trajectory task is not a threat to the task representation school but rather an example of the subtle nature of the interplay of factors that inform task set formation. The challenge going forward is to gain a better understanding of how contextual factors like stimulus orientation contribute to task set formation.

The event file model can explain the stronger congruency sequence effect in the orientation repeat trials. As stated before the feature integration accounts and the control accounts of the congruency sequence effect are not mutually exclusive and the congruency sequence effect is very likely not process pure but we cannot say for certain that the greater magnitude congruency sequence effect for orientation repeat trials in the Stroop trajectory task represents a modulation of cognitive control boundaries. It cannot be ruled out that the three way interaction is not simply the result of feature integration factors producing a stronger congruency sequence effect on orientation repeat trials.

Future studies should make use of new paradigms with larger response sets for each task/stimulus set. This course of action could resolve the stimulus response repetition confound issue but careful thought would have to be given to preventing

contingency bias when designing these paradigms. In addition, methods of manipulating the similarity between stimulus sets should be developed. For example a new Stroop trajectory task could be created with not only orientation separating each set but color (red to vertical, blue to horizontal or vice versa), different target shapes (a star for vertical, a circle for horizontal) or possibly contextual factors unrelated to the task could be used to make the sets less similar. The switch trial congruency sequence effects for tasks with similar stimuli sets can be compared with those for tasks with dissimilar stimuli sets. Also, the work of Weissman and colleagues shows that it might be advantageous to use two switching tasks as opposed to one. If you are using two different procedures within a participant then prior exposure to something like the hand manipulation might not bias task representation (Weissman et al., 2015). One would be able to look at the hand manipulation within participants. Also, factors like training participants on each stimulus set separately might bias task representation in favor of the use of two task sets as opposed to one.

A key goal of those that support the task representation account must be the formulation of a comprehensive set of predictions for conditions that determine when it is optimal to use a unitary task set. Does the complexity of a paradigm induce enough cognitive load that it makes the maintenance of multiple tasks too costly in terms of cognitive resources? If so how does one measure the complexity of a paradigm? Additionally, how and in what situations might the use of multiple as opposed to a unitary task set be advantageous to the participant?

From an ecological perspective it is hard to believe that control is allocated in a simple manner. In a world that is relentless becoming more complex humans need to be

able to multi-task, plan, and rapidly adapt. People encounter abstract problems that might require control being applied in ways that can't be simply defined by stimulus features and dimensions. Items and dimensions might be part of a bigger picture one that involves abstract representations, goal information, and episodic memories. Control needs a compass, a driving force that directs the adjustment of weights that manifests the behavioral effects that modelers simulate. Models of control that are capable of acting in a truly flexible fashion need some kind of process for determining what weights to adjust (item weights, dimension weights, abstract representation weights, etc...). The flexibility of sequential modulation's boundaries is hard to account for without the use of some kind of task representation. Representations are fluid just like the boundaries of sequential adjustments in control. The congruency sequence effect might just be one of many markers of control's task set imposed borders. Task sets are a possible alternative to the rigid systems that have defined the general thinking about how control is directed. In order for task sets to be better incorporated into theories of control a firmer empirical understanding of their impact on cognitive adjustments must be reached.

APPENDIX A

Table 1: One Hand/Random Switch Trials

Trial n Congruency		Trial $n - 1$ Congruency	
		Congruent	Incongruent
Congruent	RT	331 (38)	344 (32)
Incongruent	RT	376 (26)	364 (24)
Congruent	ACC	0.979 (0.02)	0.970 (0.03)
Incongruent	ACC	0.873 (0.10)	0.923 (0.07)

SD in parentheses, $N = 12$

Table 2: One Hand/Systematic Switch Trials

Trial n Congruency		Trial $n - 1$ Congruency	
		Congruent	Incongruent
Congruent	RT	306 (21)	322 (21)
Incongruent	RT	365 (24)	356 (25)
Congruent	ACC	0.979 (0.01)	0.965 (0.03)
Incongruent	ACC	0.823 (0.09)	0.900 (0.06)

SD in parentheses, $N = 12$

Table 3: Two Hand/Random Switch Trials

Trial n Congruency		Trial $n - 1$ Congruency	
		Congruent	Incongruent
Congruent	RT	359 (42)	378 (41)
Incongruent	RT	406 (30)	395 (37)
Congruent	ACC	0.952 (0.03)	0.948 (0.03)
Incongruent	ACC	0.882 (0.06)	0.927 (0.04)

SD in parentheses, $N = 12$

Table 4: Two Hand/Systematic Switch Trials

Trial n Congruency		Trial $n - 1$ Congruency	
		Congruent	Incongruent
Congruent	RT	377 (51)	388 (46)
Incongruent	RT	420 (40)	416 (43)
Congruent	ACC	0.968 (0.02)	0.964 (0.03)
Incongruent	ACC	0.889 (0.07)	0.909 (0.07)

SD in parentheses, $N = 12$

Table 5: One Hand/Random Repeat Trials

Trial n Congruency		Trial $n - 1$ Congruency	
		Congruent	Incongruent
Congruent	RT	326 (35)	363 (37)
Incongruent	RT	395 (28)	369 (26)
Congruent	ACC	0.986 (0.02)	0.975 (0.02)
Incongruent	ACC	0.857 (0.13)	0.950 (0.05)

SD in parentheses, $N = 12$

Table 6: One Hand/Systematic Repeat Trials

Trial n Congruency		Trial $n - 1$ Congruency	
		Congruent	Incongruent
Congruent	RT	294 (19)	343 (21)
Incongruent	RT	392 (29)	344 (21)
Congruent	ACC	0.993 (0.01)	0.946 (0.04)
Incongruent	ACC	0.769 (0.10)	0.949 (0.04)

SD in parentheses, $N = 12$

Table 7: Two Hand/Random Repeat Trials

Trial n Congruency		Trial $n - 1$ Congruency	
		Congruent	Incongruent
Congruent	RT	337 (31)	392 (69)
Incongruent	RT	426 (38)	384 (38)
Congruent	ACC	0.968 (0.03)	0.933 (0.03)
Incongruent	ACC	0.840 (0.07)	0.947 (0.03)

SD in parentheses, $N = 12$

Table 8: Two Hand/Systematic Repeat Trials

Trial n Congruency		Trial $n - 1$ Congruency	
		Congruent	Incongruent
Congruent	RT	361 (37)	397 (41)
Incongruent	RT	436 (35)	403 (30)
Congruent	ACC	0.970 (0.03)	0.960 (0.04)
Incongruent	ACC	0.809 (0.11)	0.952 (0.04)

SD in parentheses, $N = 12$

APPENDIX B

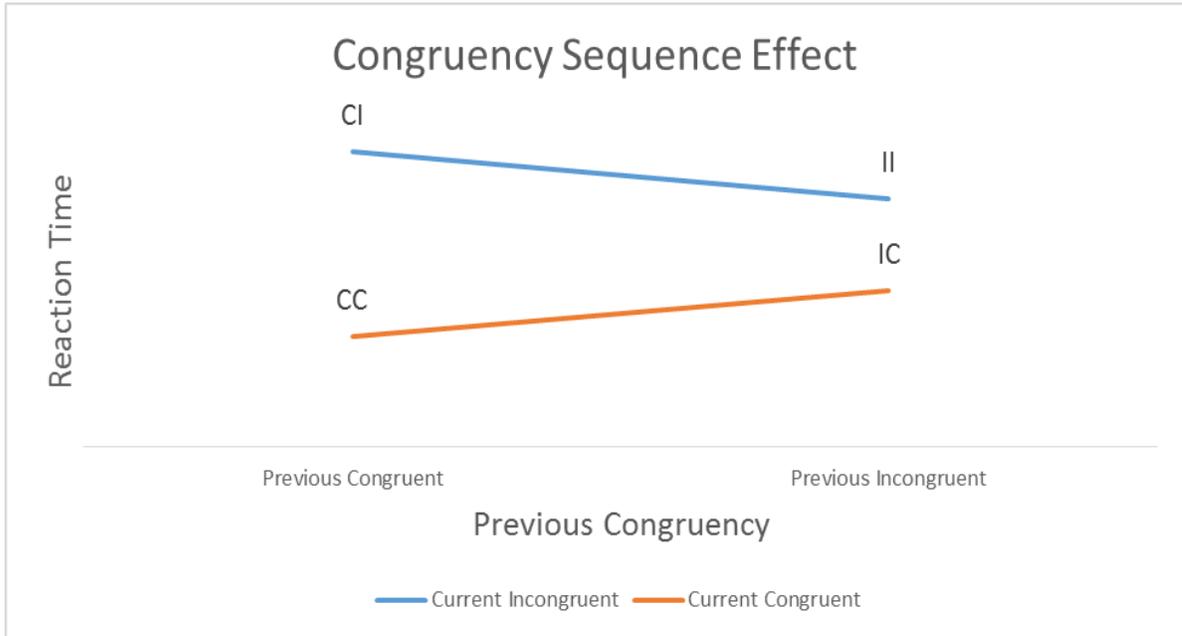
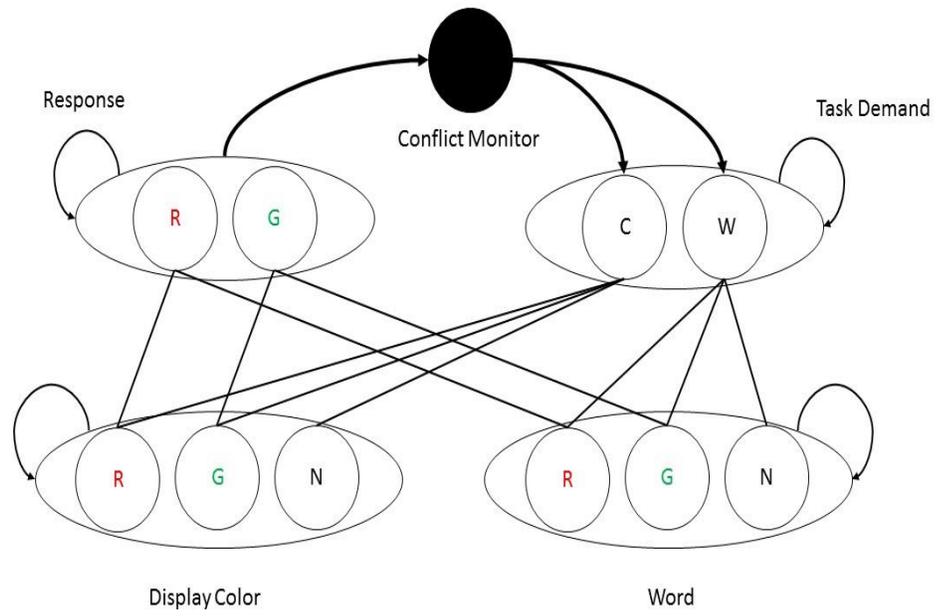


Figure 1: Reaction time is on the y axis and previous trial congruency on the x axis. The congruency effect (difference between CC and CI) for trials that are preceded by a congruent trial are large relative to the congruency effect for trials that are preceded by an incongruent trial (difference between IC and II).



Stroop Task Model

Figure 2: An example of the conflict monitoring architecture used to model the Stroop effect.

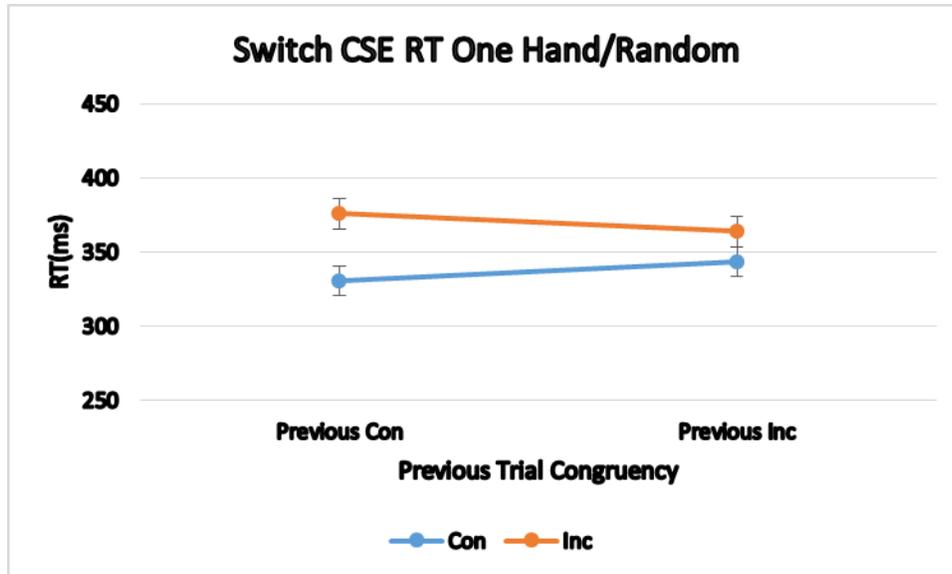


Figure 3: Reaction time(ms) congruency sequence effect (conventional trim) for switch trials in the one hand response/random switching routine condition. The errors bars represent the within subject standard error.

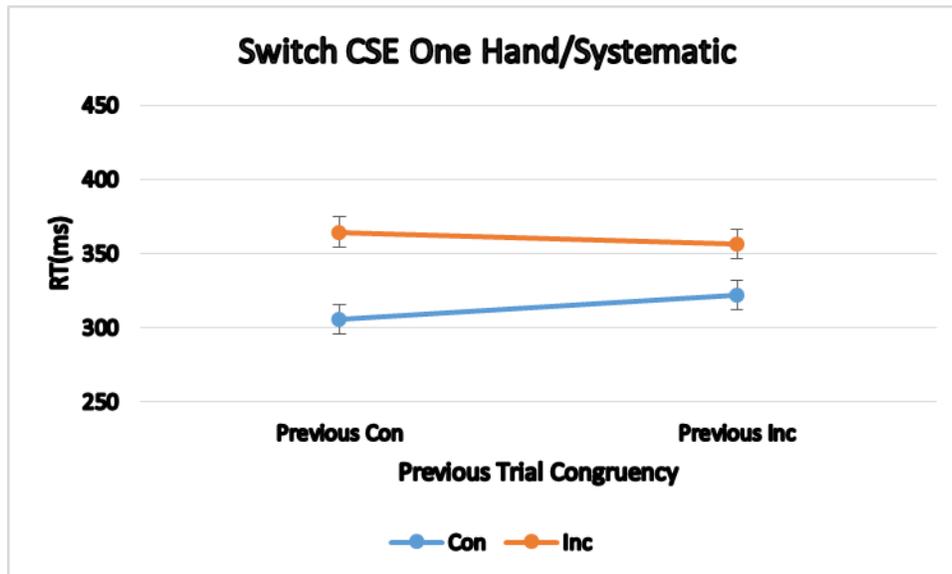


Figure 4: Reaction time(ms) congruency sequence effect (conventional trim) for switch trials in the one hand response/systematic switching routine condition. The errors bars represent the within subject standard error.

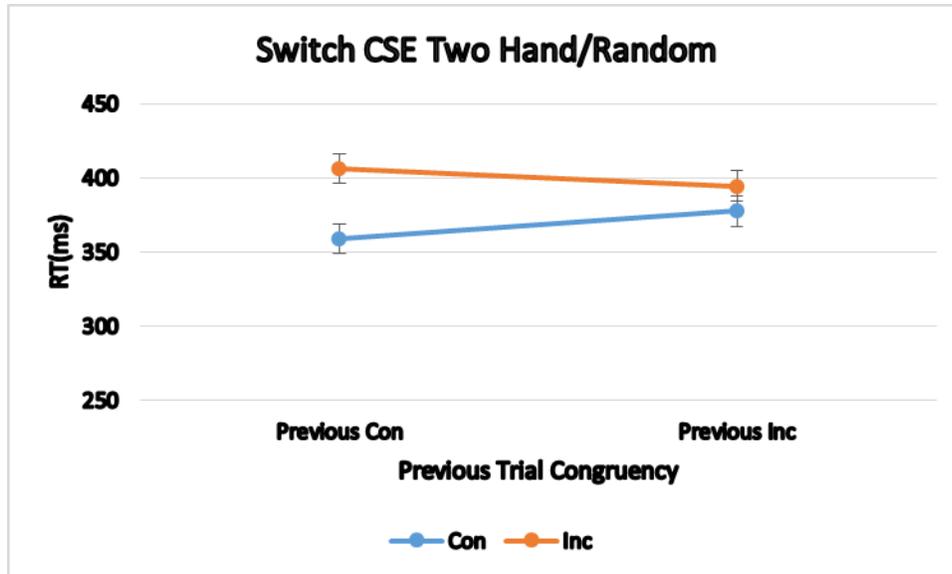


Figure 5: Reaction time(ms) congruency sequence effect (conventional trim) for switch trials in the two hand response/random switching routine condition. The errors bars represent the within subject standard error.

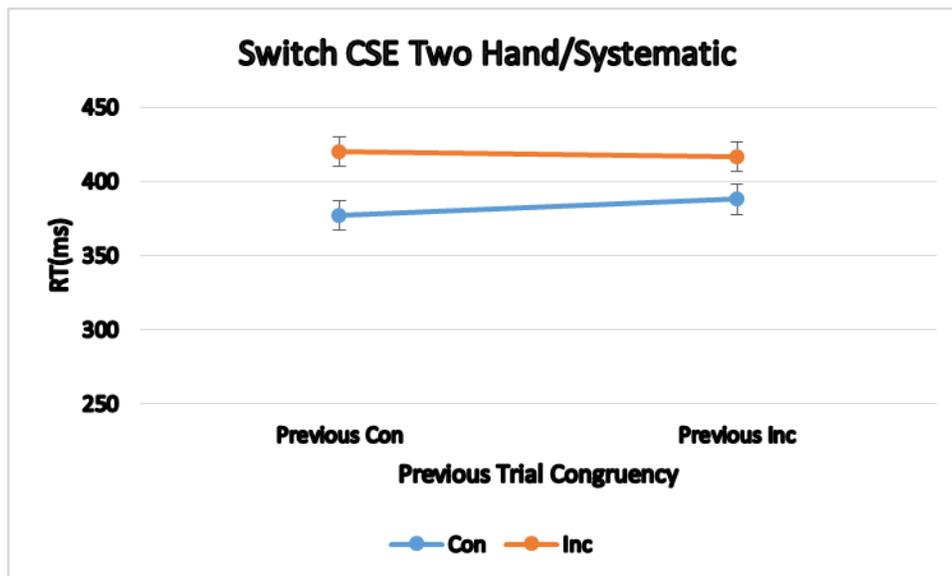


Figure 6: Reaction time(ms) congruency sequence effect (conventional trim) for switch trials in the two hand response/systematic switching routine condition. The errors bars represent the within subject standard error.

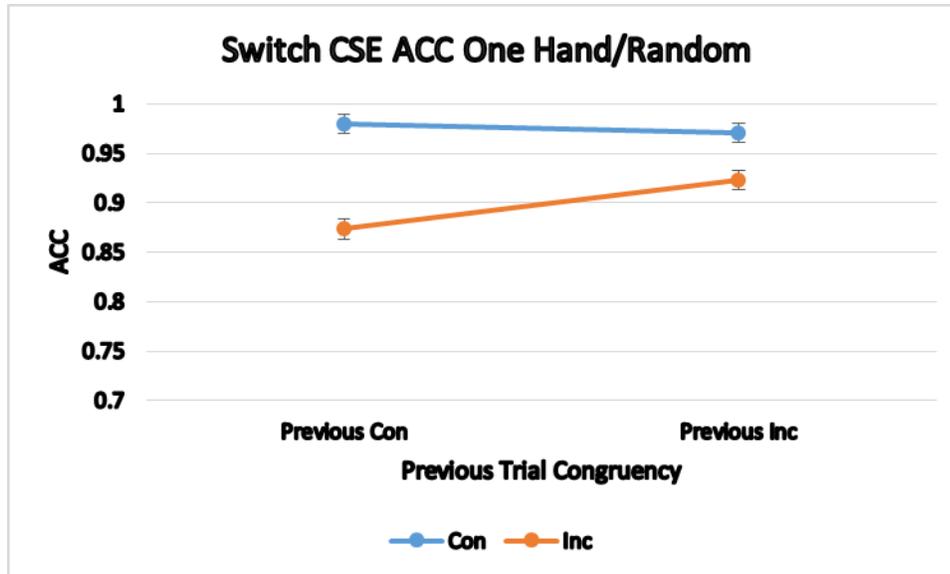


Figure 7: Accuracy (proportion correct) congruency sequence effect (conventional trim) for switch trials in the one hand response/random switching routine condition. The errors bars represent the within subject standard error.

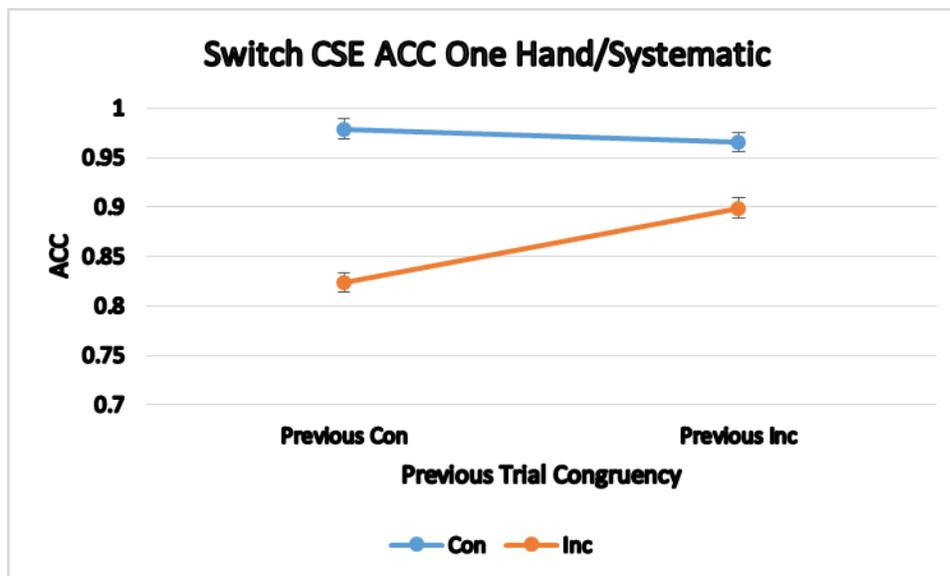


Figure 8: Accuracy (proportion correct) congruency sequence effect (conventional trim) for switch trials in the one hand response/systematic switching routine condition. The errors bars represent the within subject standard error.

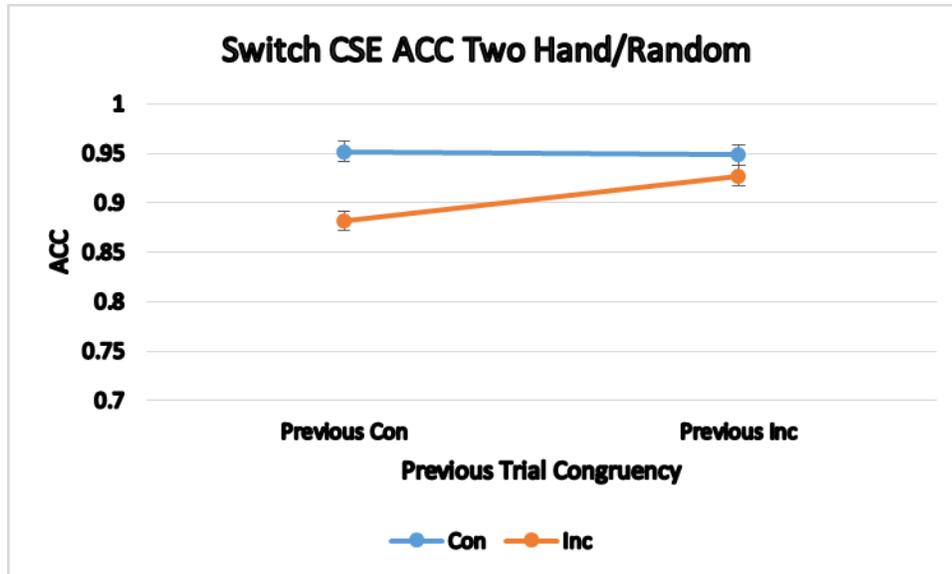


Figure 9: Accuracy (proportion correct) congruency sequence effect (conventional trim) for switch trials in the two hand response/random switching routine condition. The errors bars represent the within subject standard error.

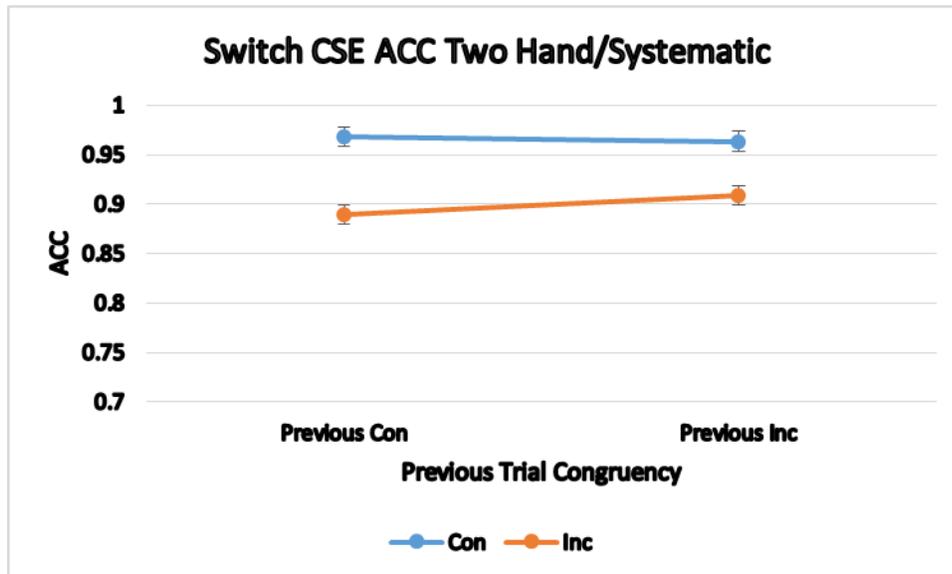


Figure 10: Accuracy (proportion correct) congruency sequence effect (conventional trim) for switch trials in the two hand response/systematic switching routine condition. The errors bars represent the within subject standard error.

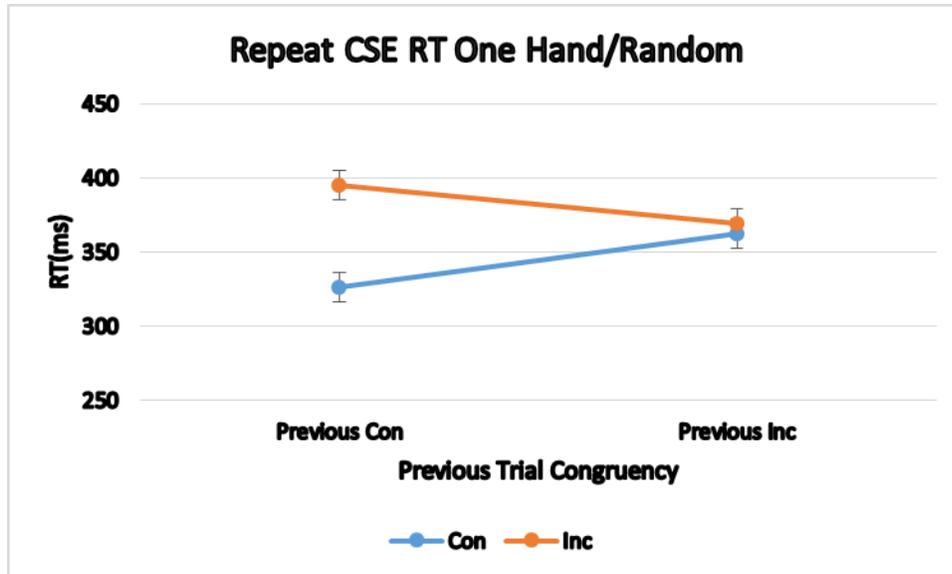


Figure 11: Reaction time(ms) congruency sequence effect (conventional trim) for repeat trials in the one hand response/random switching routine condition. The errors bars represent the within subject standard error.

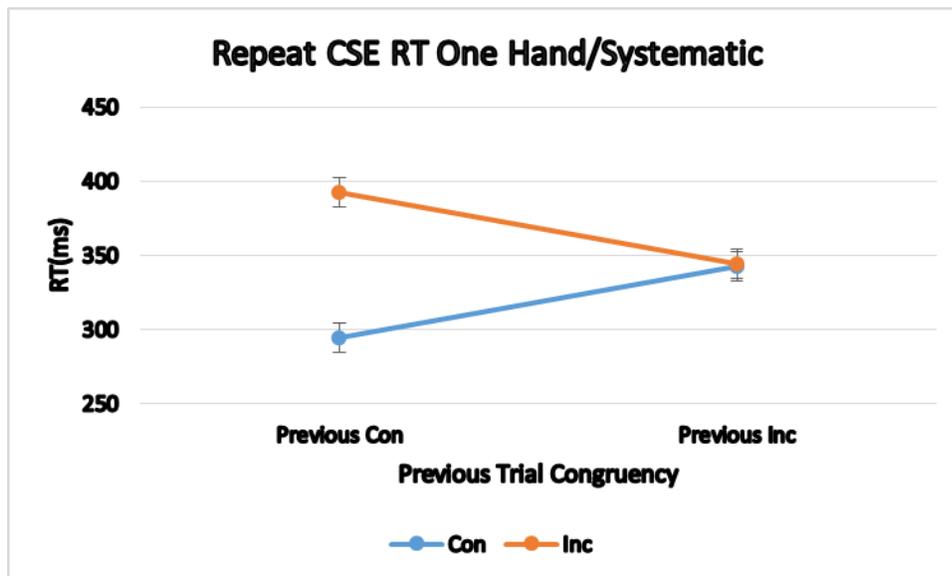


Figure 12: Reaction time(ms) congruency sequence effect (conventional trim) for repeat trials in the one hand response/systematic switching routine condition. The errors bars represent the within subject standard error.

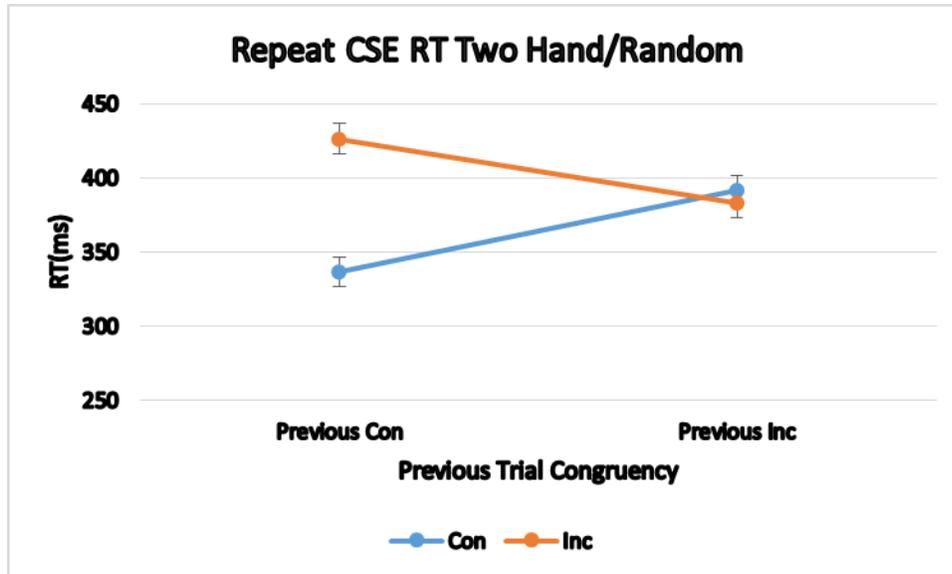


Figure 13: Reaction time(ms) congruency sequence effect (conventional trim) for repeat trials in the two hand response/random switching routine condition. The errors bars represent the within subject standard error.

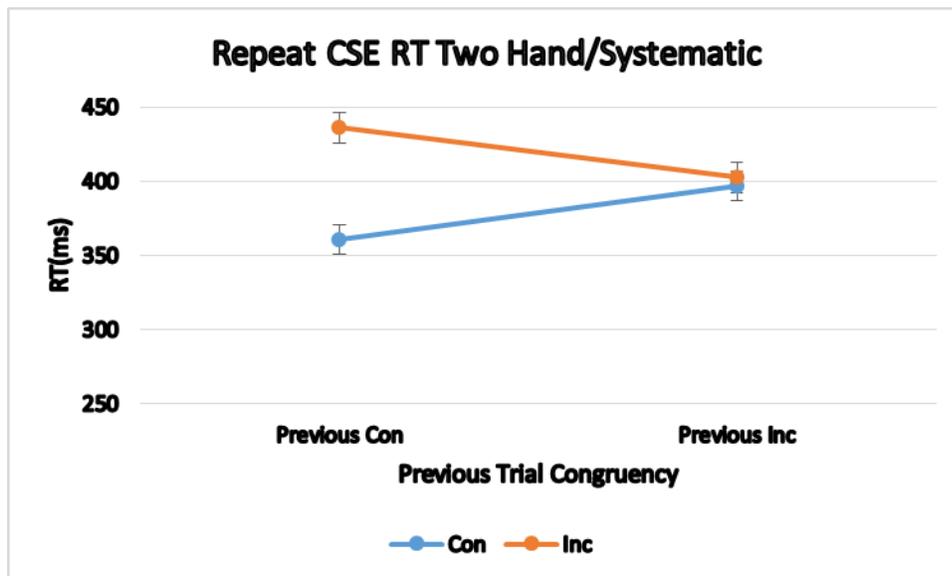


Figure 14: Reaction time(ms) congruency sequence effect (conventional trim) for repeat trials in the two hand response/systematic switching routine condition. The errors bars represent the within subject standard error.

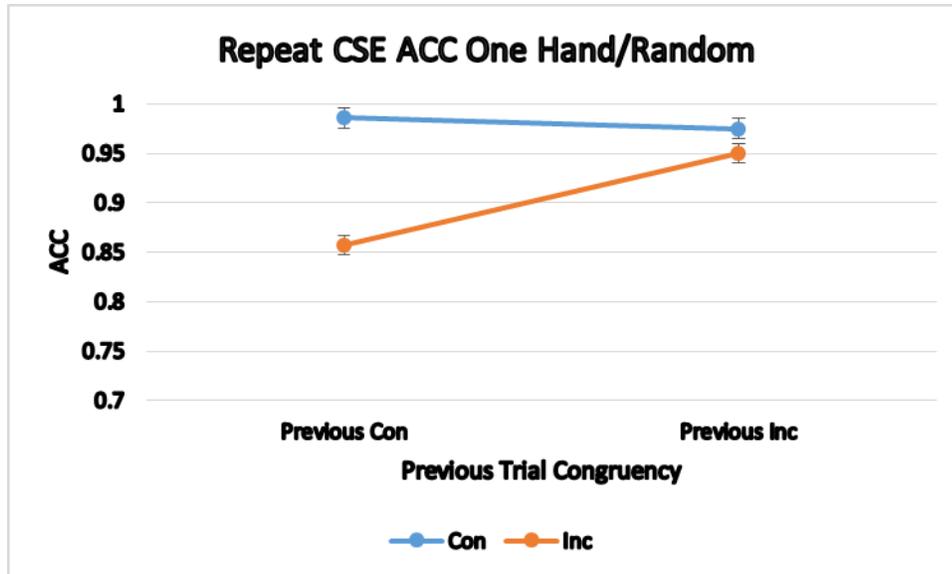


Figure 15: Accuracy (proportion correct) congruency sequence effect (conventional trim) for repeat trials in the one hand response/random switching routine condition. The errors bars represent the within subject standard error.

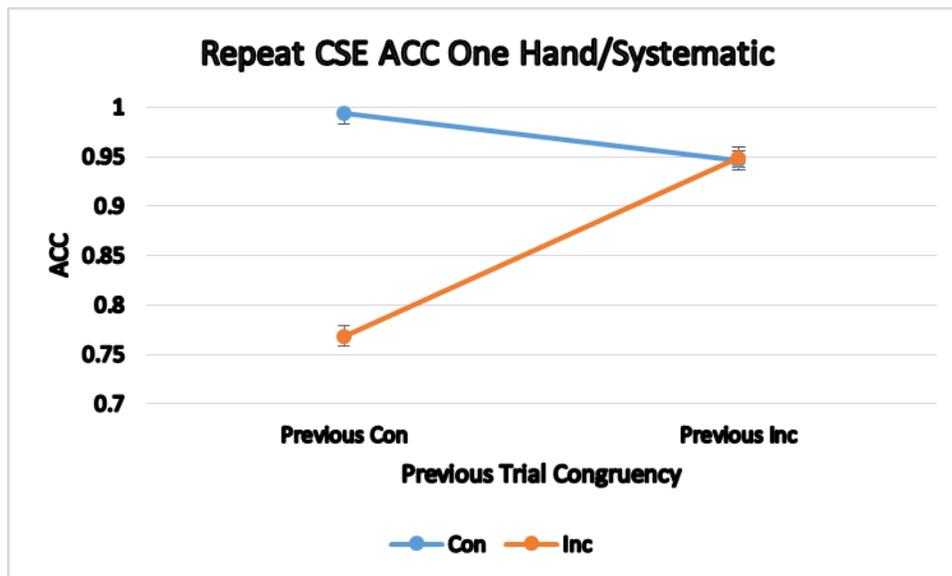


Figure 16: Accuracy (proportion correct) congruency sequence effect (conventional trim) for repeat trials in the one hand response/systematic switching routine condition. The errors bars represent the within subject standard error.

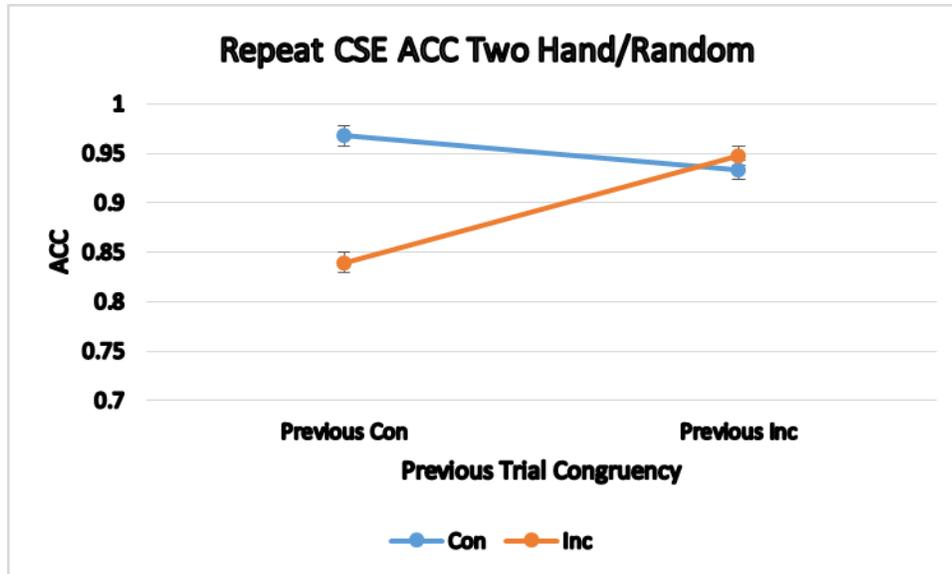


Figure 17: Accuracy (proportion correct) congruency sequence effect (conventional trim) for repeat trials in the two hand response/random switching routine condition. The errors bars represent the within subject standard error.

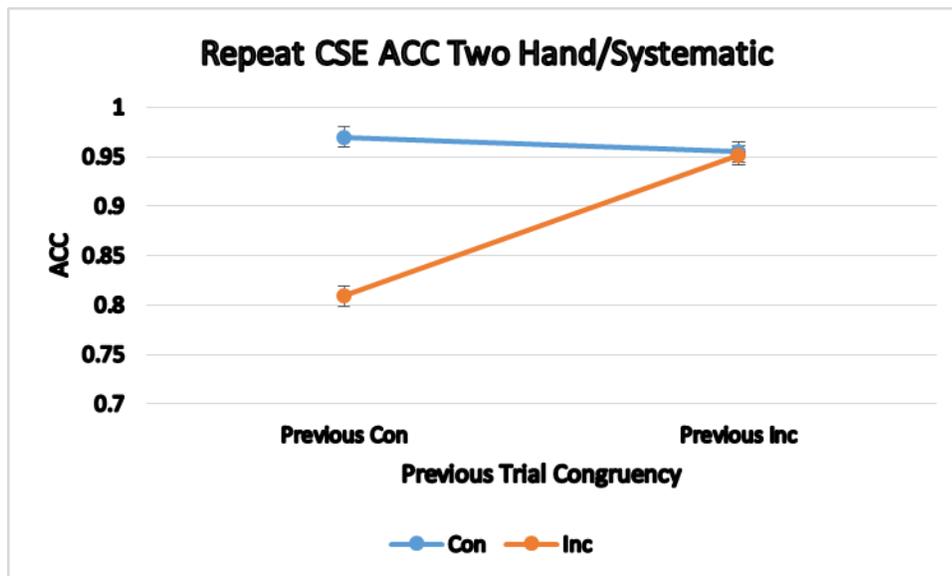


Figure 18: Accuracy (proportion correct) congruency sequence effect (conventional trim) for repeat trials in the two hand response/systematic switching routine condition. The errors bars represent the within subject standard error.

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