The Dynamics of Cognitive Control in the Emotional Stroop Task

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ABSTRACT

Although the importance of understanding the functionality and adaptability of emotions has been underscored since the advent of evolutionary theory (Darwin, 1872), investigations of cognitive control have predominately focused on ‘cool’ tasks that feature minimal emotional engagement, as opposed to affectively laden or ‘hot’ tasks. Since cognitive control has been found to be crucial for regulating emotions, the current project was designed to explore how emotion, primarily valence regulates cognitive control through two versions of the traditional Stroop task (Stroop, 1935): a ‘cool’ Colour-Word Stroop task and a ‘hot’ Face-Word emotional Stroop task. A novel two-alternative forced-choice reach tracking experimental technique was employed to assess continuous dynamics of behaviour across 42 adult participants, to investigate whether reach tracking can be used to target processes underlying the Colour-word and the Face-Word Stroop task and the extent to which they corelate. All participants completed two versions of the task by reaching to touch two response targets on the screen. Our results demonstrated that performance on the two tasks showed significant congruency effect patterns separately. However, the size of the congruency effects observed in the tasks were not significantly correlated. Additionally, we observed a significant effect of valence in the Face-Word emotional Stroop task, with more direct hand movements observed in response to an angry face relative to a happy face. Finally, our results indicate that the patterns of effects observed in the two-alternative forced-choice Colour-Word Stroop task present a mixture of patterns observed in two other prominent congruency tasks, the Eriksen flanker task and the Simon task. This work demonstrates the promise of using reach tracking to investigate the links among cognition and emotion and provides a foundation for future research to build upon.

Keywords: Cognitive control, emotion, Stroop task, congruency effects, valence, reach tracking

DEDICATION

In the loving memory of my Grandparents. Dada and Dadi, this thesis and all the hard work that's gone into it, is dedicated to you and your legacy.

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Cognitive control is a critical human capacity that is broadly conceptualized as including the mental processes underlying the goal-directed control of thought, action, and emotion (Botvinick et al., 2001; Cromheeke & Mueller, 2014; Howieson & Lezak, 1995; Kalanthroff et al., 2015; Sullivan, 2015; Zelazo & Carlson, 2012). Cognitive control plays a crucial role in coordinating our behaviour when our prepotent or habitual response tendencies are not appropriate. Consequently, the capacity supports a wide range of daily activities such as schoolwork, cooking, and shopping (Farias et al., 2003; Sullivan, 2015).

Cognitive control is also crucial for regulating our emotions. Emotions have been found to have significant effect on cognition, physiology, and behaviour (Straub et al., 2021). Although the importance of understanding the functionality and adaptability of emotions has been underscored since the advent of evolutionary theory (Darwin, 1872), investigations of cognitive control have predominately focused on ‘cool’ tasks that feature minimal emotional engagement, as opposed to affectively laden or ‘hot’ tasks.

In the following, I will provide a brief overview of research investigating the links between cognition and emotion, highlighting the important role that advances in neuroscience methods have played in progressing our understanding. Next, I will provide an overview of research with ‘cool’ and ‘hot’ versions of the Stroop task (Stroop, 1935), including prominent models that have been developed to account for performance on the tasks. I will then discuss recent research that has used a technique called *reach tracking* to investigate how the processes underlying cognitive control in ‘cool’ tasks are reflected in unfolding hand movements (for example, Erb & Marcovitch, 2018; Erb et al., 2016). After highlighting the lack of research using this approach to study ‘hot’ tasks, I will present an experiment designed to address this gap in the literature.

Linking Cognition and Emotion

Modular versus Integrative Approaches

With the development of neuroscience methods such as electroencephalography (EEG) and functional magnetic resonance imaging (fMRI), our understanding of the links between cognition and emotion has improved greatly. This work has led to different perspectives regarding the neural underpinnings of cognition and emotion, with some researchers adopting a *modular perspective* in which cognition and emotion are considered to be separate aspects of the mind supported by dissociable neural systems. For example, Iordan et al. (2013) notes that the dorsolateral prefrontal cortex (DLPFC) is crucial for ‘cool’ cognitive control, whereas the ventromedial and orbitofrontal cortex support ‘hot’ cognitive control (Rolls, 2004), indicating that both these ‘hot’ and ‘cool’ cognitive control systems involve distinct regions of the prefrontal cortex (Sullivan, 2015).

In everyday scenarios, affectively laden and affectively neutral problems are proposed to recruit different neural systems underlying ‘hot’ or ‘cool’ cognitive control. To illustrate, planning and coordinating one’s daily commute from home to work could be a ‘cool’ cognitive control scenario and as such would be expected to recruit the DLPFC. Similarly, preparing a response in an affectively charged scenario such as a tense interpersonal social interaction would be expected to recruit the orbitofrontal cortex and amygdala (Chan et al., 2008).

In contrast to the modular perspective, contemporary research indicates that ‘cool’, higher-order cognitive processes and ‘hot’, affectively charged cognitive processes are not entirely independent of each other and draw on shared underlying neurocircuitry (Cromheeke & Mueller, 2014; Mueller, 2011; Okon-Singer et al., 2007; Pessoa, 2008; Shackman et al., 2011). Multiple studies have shown that brain regions that play a vital role in cognitive control (for example, DLPFC, the amygdala, the orbitofrontal cortex, and the anterior cingulate cortex) also have an essential role in emotional processing (Song et al., 2017) via the top-down control of emotion (Fox et al., 2005; Treadway et al., 2014; Okon-Singer et al., 2015; Straub et al., 2021). These brain areas function as central hubs that integrate cognitive and emotional stimuli (Straub et al., 2021). Such links underscore the neuroanatomical and functional connections between regulatory and affective structures such as the amygdala and DLPFC (Cromheeke & Mueller, 2014; Edgar & Fox, 2005**)**.

Further evidence of the integrative and interdependent nature of cognition and emotion is offered by research indicating that *emotional systems* can modulate cognition in a manner similar to how the *cognitive systems* modulate emotions (Okon-Singer et al., 2015). In a review by Shansky and Lipps (2013), it was highlighted that emotional systems such as the amygdala heavily influence brainstem neurotransmitters, which regulate information processing quality. It is through these systems that the amygdala assumes control over behaviour and attention while favouring fast and immediate responses over careful, slow reasoning (Arnsten, 2009). Therefore, efficient parallel processing of emotional impetuses influences the successful employment of neural regions engaged in executive control (Song et al., 2017).

Finally, it has been argued that the functional connectivity between the ventral anterior cingulate cortex (ACC) and amygdala is heightened in cognitive control tasks when emotionally incongruent stimuli (as opposed to congruent stimuli) are encountered (Kanske & Kotz, 2012). This indicates that the ACC recruits heightened cognitive control in tasks featuring conflict tied to emotionally salient stimuli. These emotionally salient stimuli are signalled by the amygdala, which leads to ACC prioritizing them and finally enhancing cognitive processing (Kanske & Kotz, 2012). In sum, neurophysiological studies widely corroborate the notion that cognitive control and emotions share a common functional backbone (Song et al., 2017; Straub et al., 2021).

Interaction between Cognition and Emotion

Much of the research investigating the links between cognition and emotion has been centred on developing 'hot' versions of classic cognitive tasks used to investigate control. This approach allows for a more direct comparison of performance on relatively 'hot' and 'cool' versions of the same task, providing a clearer picture of how emotion interacts with specific cognitive processes (Zelazo & Carlson, 2012). One such task that has been studied in 'hot' and 'cool' contexts is the Stroop task (Stroop, 1935).

In the classic Colour-Word Stroop task (Stroop, 1935), participants are instructed to identify what colour of text a colour word is presented in. Cognitive conflict is occures when the meaning of the word conflicts with the colour of text the word is presented in (for example, the word BLUE presented in red text). Researchers have adapted the task to be more affectively laden by, for example, incorporating faces with different emotional expressions or words that evoke a strong emotional response (Egner, 2007). These emotional or 'hot' Stroop tasks have played a central role in the assessment of emotional conflict in an experimental laboratory setting (Straub et al., 2021).

For instance, in the Face-Word Stroop task, participants are presented with a facial expression displaying a specific emotion (for example, a happy or angry expression) along with an emotional word (for example, the word "HAPPY" or the word "ANGRY") displayed under the face in a congruent (for example, the word "HAPPY" with a happy face) or incongruent (for example, the word "HAPPY" with an angry face) setup. An emotional conflict occurs when the emotional word and facial expression are incongruent (Zhu et al., 2010). Research with the emotional Stroop task, reviewed in detail in a subsequent section, indicates that integrating emotional and cognitive systems in an emotional conflict depends on the complexity and difficulty found across the emotional Stroop tasks and the nature of the executive task being accomplished (Song et al., 2017).

As noted above, behavioural and neuroanatomical evidence supports the notion that emotions and cognition are functionally interdependent (Dignath et al., 2020; Raz et al., 2014; Shackman et al., 2011). This interdependence of affect and cognition is captured by the interactive model proposed by Zelazo and Cunningham (2007). According to this interactive model, emotions play a crucial role in fostering the motivational facet of cognition in tasks involving, for example, goal-oriented problem solving (Li et al., 2019). Through this interactive model, Zelazo and Cunningham (2007) proposed that understanding the basics of cognition will lead to a greater understanding of emotions – especially the dynamic regulation of emotions.

Similarly, another model which captures the functional interdependence of emotion and cognition is the dual-competition framework by Pessoa (2012). According to this model, emotions and cognition collaboratively produce ongoing behaviour and influence perceptual and cognitive control competition mechanisms as they are intrinsically tied to one another in real life.

Enhancement and Impairment of Cognitive Control due to Emotions

Empirical research indicates that the presence of an emotionally significant stimulus can enhance or impair performance, depending on the task. On the one hand, for instance, the presence of emotionally laden stimuli has been observed to enhance visual processing (Pourtois et al., 2005), attentional processes (Bar-Haim et al., 2007), efficient cognitive control (Kanske, 2012; Kanske & Kotz, 2011; Pessoa, 2010), and conflict resolution in tasks relevant to understanding executive control (i.e., the participants are required to process and react to the emotionally valent stimuli to solve a task) (Kanske, 2012). Such effects have been observed for both positive and negative stimuli (Kanske & Kotz, 2011) and will be discussed in more detail in the later sections of this paper.

On the other hand, some research indicates that task-irrelevant stimuli that are emotionally valenced can be more distracting than neutral stimuli (Kalanthroff et al., 2013). It has also been argued that cognitive control can be impaired by the presence of concurrent emotions (Dolcos & McCarthy, 2006). The nature of such facilitation or impairment effects often depend on the intensity of the emotional information. To illustrate, in an emotional Stroop task, target and distractor emotional stimuli with low or mild intensity improved task-relevant behaviour by enhancing sensory representation (Pessoa et al., 2012).

To understand the enhancing or hindering effects of emotion on cognitive control, it is imperative to shed some light on the individual differences observed in participants across experimental designs (Kanske & Kotz, 2012). A key finding of a recent correlational study examining the influence of task-relevant emotional stimuli on conflict processing identified a range of individual differences including differences in sensitivity to emotional stimuli, levels of cognitive control, and in the modulation of conflict processing via emotion (for a review, see Kanske & Kotz, 2012)

Another critical finding by Kanske and Kotz (2012) was that participants with high subclinical anxiety and depression show decreased cognitive control for negatively valanced stimuli. In contrast, the temperament trait of effortful control, associated with self-regulation, correlates positively with and facilitates conflict processing stemming from emotionally laden stimuli (Gerardi-Caulton, 2000). These integrative facilitation and impairment effects also get translated to the neural underpinnings between cognition and emotions.

In sum, the individual differences aiding in either the enhancement or impairment of performance provide a glimpse of a gap in the emotion-cognition interaction literature illustrating the effect of emotions on cognitive tasks across individuals. In the next few sections, I will be focusing on the dynamics of the effects observed in ‘cool’ and ‘hot’ versions of the Stroop task (Stroop, 1935) and how performance on these tasks is accounted for by prominent theories.

THE STROOP TASK

Overview

The Stroop task has been an influential assessment tool throughout the history of cognitive psychology (Stroop, 1935). In real-life scenarios, it's necessary to reduce distractions and implement efficient decision-making and attentional control strategies to carry out an activity that requires a choice between incompatible options. The Stroop task enables researchers to investigate this mechanism of cognitive control in a more structured laboratory setting (Agusti et al., 2017). The task is traditionally used as a measure of ‘cool’ cognitive control mechanisms. Historically, the Stroop task has been considered the gold standard in assessing cognitive control due to its ability to tap into the dynamics of human behaviour which override a prepotent or automatic response with a more controlled and task-appropriate response by tapping into inhibition, attention, interference, and automatic processing (Aite et al., 2018; Saunders & Jentzsch, 2013).

As noted above, in the classic Colour-Word Stoop task, participants are presented with colour words in different font colours and are instructed to respond according to font colour regardless of the word’s meaning. The target (font colour) and distractor (word meaning) cue the same response on congruent trials (for example, the word “BLUE” in blue font). On incongruent trials, however, the target and distractor cue competing response (for example, the word “BLUE” in red font). Given that reading familiar words is an automatised response, incongruent trials place greater demands on cognitive control to ensure that the response cued by font colour is selected over the prepotent response cued by word meaning (Freund et al., 2021; Gonthier et al., 2016).

Empirical evidence supports the idea that response times (RTs henceforth) are significantly longer when the perceptual and semantic dimensions of the presented stimuli are incongruent than congruent (Haas et al., 2006). The presence of an incongruent condition leads to a cognitive conflict which decreases response accuracy and increases RTs (Kalanthroff et al., 2013; Nessler et al., 2007, as presented in Ros et al., 2021; Saunders & Jentzsch, 2013). To illustrate, on incongruent trials, the semantic and perceptual dimension of the stimuli map onto the same construct (i.e., colour) but lead to different or competing responses (i.e., "RED" semantically but in "blue ink colour" for the word appearance) (Etkin et al., 2006; Haas et al., 2006).

These two different dimensions lead to a cognitive conflict which impacts the final response selection (Etkin et al., 2006), and hence increases the RTs in incongruent trials compared to congruent trials. This is known as the *interference effect* or *congruency effec*t (Kalanthroff et al., 2013). Congruency effects are characterized as the difference in one's performance between a non- or low-conflict inducing congruent trial condition and a high-conflict inducing incongruent trial condition. This interference is an excellent measure to demonstrate the automatic nature of the processing of distracting information that takes place in the Stroop paradigm. For instance, if the participants are instructed to only focus on the ink colour of the presented word stimuli while ignoring the word altogether, the participants will still automatically read the word (Beall & Herbert, 2008; Shiffrin & Schneider, 1977).

The Colour-Word Stroop protocol has been used extensively in experimental psychology, aiding the development of various cognitive control models (Botvinick et al., 2001; Braver et al., 2007). The Stroop task has also informed our understanding of disordered processing in different psychopathologies (for example, Kerns et al., 2005). Since its introduction in 1935, the Stroop task has evolved and now has multiple variants in the mode of presentation, response, and stimuli content. Some versions of the task focus on assessing specific stimulus dimensions, including semantic, visual, and auditory dimensions, which often overlap (for example, Augusti et al., 2007; Aite et al., 2018; Basgoze et al., 2015; Beall & Herbert, 2008; Ben-Heim et al., 2016; De Gelder et al., 2000; Entel et al., 2015; Philippi et al., 2017; Fox et al., 2000; 2002; Kauschke et al., 2019; Kitayama & Ishii, 2000).

Other variants of the traditional Stroop include the Face-Word Stroop (for example, Aite et al., 2018; Zhu et al., 2010), Numerical Stroop (for example, Cohen et al., 2011), Emotional Stroop, and gender Face-Word Stroop (for example, Egner et al., 2008). Dynamics of the Face-Word Stroop task are of particular interest and will be covered in detail in the further sections of the paper. Beyond the stimulus dimensions, different studies alter the number of stimuli, facial expressions, colours of stimuli, psychopathology-specific relevant words, and the number of blocks or trials according to the task's requirements.

Congruency tasks such as the Stroop task (Stroop, 1935) have proven to be instrumental in the study of basic and applied cognitive neuroscience (Botvinick et al., 2001; Freund et al., 2021; Straub et al., 2021; Schmidt & Houwer, 2014). As noted above, congruency tasks intermittently require participants to engage cognitive control to overrule a prepotent response with a more controlled alternative response. To illustrate, after an initial conflict detection, the participant corrects or alters their response via a compensatory performance optimization process.

This is a crucial aspect of these tasks as the optimization process is recruited to drive one's performance when a response is wrong or threatens to go wrong (Duthoo et al., 2014). In a stimulus-response (S-R) forced-choice task (for example, two-alternative forced-choice Colour-Word Stroop task), stimuli and responses can have various features or dimensions (Egner, 2007). Congruency effects begin to arise when the dimensions of stimulus or responses (or both) overlap – showing a degree of perceptual, conceptual, or structural similarity (Egner, 2007).

General Models of Performance

As mentioned before, the Stroop effect, the general slow-down in response times in an incongruent trial condition relative to a congruent trial condition (Entel et al., 2014; Stroop, 1935), suggests some form of automaticity in performance. Therefore, performance on congruency tasks such as the Stroop task has long been studied to probe controlled and automatic processing (Cohen et al., 1990; 1992). The primary notion is that two different neural pathways get activated when the participant is faced with an incongruent stimulus (for example, word "BLUE" in red ink) — one for the semantic meaning (or a *reading pathway*) and one for the ink colour (or a *colour-naming pathway*) (Cohen et al., 1990).

On congruent trials, both pathways generate activations for the same response and, consequently, conflict is minimal. On incongruent pathways, however, the reading pathway automatically generates activations for the response corresponding to the meaning of the word presented, whereas the colour-naming pathway generates relatively weaker activation in favour of the response cued by the colour of the text presented. This has been characterised as an 'informational conflict' resulting from competition between two colour concepts (Levin & Tzelgov, 2014).

Following from this, more recently, evidence of performance on the Stroop task (Stroop, 1935) has reflected two pathways of processing – a direct and a control-demanding pathway (Ridderinkhof et al., 1995; Shenhav et al., 2013). These pathways have received different names, with the reading pathway sometimes referred to as a direct or an automatic pathway and the colour-naming pathway sometimes referred to as an indirect or a control-demanding pathway. The 'reading pathway' is responsible for the generation of response activation for word reading (unlike in the Ericksen flanker task where it is sensitive to the overall stimulus array), and the 'colour-naming pathway' can be used to direct attention to font colour and then bind that font colour to the appropriate response.

Several cognitive control models propose that successful conflict resolution involves a combination of dissociable processes performing different functional roles (Erb et al., 2016; Shehnav et al., 2013). These processes include a *conflict monitoring* process which registers conflict resulting from the coactivation of incompatible responses (Botvinick et al., 2001; Shehnav et al., 2013). In the Colour-Word Stroop task, this monitoring process registers conflict resulting from the coactivation of the responses cued by word meaning and font colour and is associated with the ACC (Botvinick et al., 2001; Shehnav et al., 2013).

The conflict monitoring component then engages a specification component that has been suggested to identify the appropriate task (i.e., attend to font colour and not word meaning) and engage a *threshold adjustment process* that puts a "brake" on behaviour by briefly inhibiting motor output after conflict detection (Erb et al., 2016). The threshold adjustment process has been proposed to balance speed-accuracy trade-off effects by allowing additional time for top-down control to be recruited to support a *controlled selection process* (Erb et al., 2016; Cavanagh et al., 2011). The controlled selection process directs top-down resources along the control-demanding pathway to "steer" response activations in favour of the response cued by font colour (Erb et al., 2016; Shehnav et al., 2013).

Congruency Sequence Effects in the Stroop task

In addition to the congruency effect observed in the Stroop task, a *congruency sequence effect* (CSE henceforth) is frequently observed in which the size of the congruency effect is modulated by the congruency of the previous trial, with a smaller congruency effect observed on trials preceded by an incongruent trial (iC and iI trials, where lowercase letters denote the congruency of the previous trial) relative to trials preceded by a congruent trial (cC and cI trials) (see Figure 1). Multiple studies have showcased that reaction times in incongruent trials reduce significantly if the preceding trial was incongruent (Egner, 2007; Ros et al., 2021). This gives rise to a dynamic trial-by-trial performance adjustment which is directed by the congruency in the immediately preceding trials. This trial-by-trial adjustment is also referred to as CSE or the Gratton effect (Botvinick et al., 2001; Egner, 2007). Since the CSE was first reported by Gratton et al. (1992) in the Ericksen flanker task (Eriksen & Eriksen, 1974), research on CSE has increased significantly (Duthoo et al., 2014).

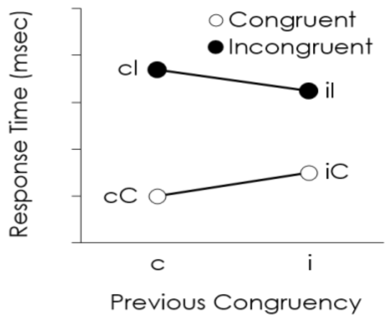

Figure 1. Illustration of Congruency Sequence Effects in congruent and incongruent trials as a function of Previous Congruency.

Despite interference-based congruency tasks being widely studied in cognitive psychology, there is currently a debate as to how the task performance needs to be interpreted (for example, see Braem et al., 2019). Erb and Marcovitch (2018) shed light on the interpretation of trial sequence effects (TSEs henceforth) – that is, understanding how the qualities of one trial effects task performance in the subsequent trial. Researchers study TSEs in order to understand and interpret the processes underlying task performance (Duthoo et al., 2014; Egner, 2007; Kerns et al., 2004; Mayr et al., 2003; Ullsperger et al., 2005). Various models of cognitive control have accounted for TSEs in the Gratton effect in congruency tasks (Erb & Marcovitch., 2018). The robust nature of the Gratton effect or the CSEs lends them to be an important observation in various congruency tasks such as the Stroop task (Stroop, 1935; for example, - Mayr et al., 2009), Ericksen flanker task (Ericksen & Ericksen, 1974), and the Simon task (Simon & Rudell, 1967).

CSEs have occupied a central role in research investigating how a specific context of a congruency task influences performance (Schmidt & Weissman, 2014). Duthoo et al. (2014) posit that the size of the congruency effect dictates the extent to which an irrelevant stimulus might take precedence in one's attentional span and hence, influence performance. It is noteworthy that the exact processes fuelling the CSE are highly controversial. The two most explored accounts in distractor interference congruency tasks are the (1) *conflict monitoring account* and (2) *feature integration account*. Both of these accounts are briefly explained in the following sections.

Conflict Monitoring Account

Botvinick et al. (2001) extended Cohen et al.'s (1990) work with their conflict monitoring model to explain the cognitive control loop. The conflict monitoring account of the CSE builds on the model of cognitive control introduced above (Botvinick et al., 2001; Duthoo et al., 2014). This model has two main components: (1) a conflict monitoring component (Botvinick et al., 2001), which evaluates the degree of conflict, and (2) a control adaptation component which adjusts cognitive resources to fulfil task demands (Dignath et al., 2020). In sum, the conflict monitoring theory posits constant and active conflict monitoring through the information processing mechanisms which detect conflict (Duthoo et al., 2014). Contingent on this conflict detection by the monitoring mechanism, there is an up-regulation or down-regulation of control based on incongruent or congruent trials, respectively (Duthoo et al., 2014).

On the one hand, it has been proposed that the level of control is low in trials that follow a congruent trial in congruency tasks (Egner, 2007). On the other hand, in trials that follow an incongruent trial, it's been proposed that there is an increase in cognitive control and reaction time, along with a decrease in response accuracy (Ros et al., 2021). Therefore, faster RTs for an incongruent trial followed by incongruent trial (iI trials) are due to reduced interference from incongruent distractors, whereas slower RTs for an incongruent trial followed by a congruent trial (iC trials) are due to reduced facilitation from congruent distractors (Egner, 2007). In sum, the central idea is rather straightforward: the CSE reflects enhanced selective attention in trials following conflict detection because the conflict monitoring and controlled selection processes were recently engaged.

Feature Integration Account

In contrast to the conflict adaptation account of the CSE, the feature integration account suggests that bottom-up associative learning mechanisms are sufficient to explain the effects observed in RTs and error rates (Duthoo et al., 2014). The feature integration account, advanced by Hommel et al. (2004), claims that CSEs result from the unequal repetitions of stimulus and response features across a range of congruence sequences (Schmidt & Weissman, 2014). This account presumes that a current trial temporarily combines stimulus and response features or dimensions into an episodic memory. In the subsequent trials, this episodic memory (referred to as an "*event file"*) will get activated with the presence of any of these features and co-activate the remaining features (Duthoo et al., 2014).

As a result, complete stimulus repetition and complete stimulus alterations lead to faster RTs, since there is an absence of undoing any previous feature binding (Duthoo et al., 2014). This has also been referred to as the repetition priming effect (Pashler & Baylis, 1991 as cited in Egner, 2007). On the other hand, RTs are slower if there is no stimulus repetition, but a similar response is required since previous feature binding will have to be undone (Egner, 2007).

In sum, complete repetition and alteration of all stimulus and response features are processed more quickly than partial repetitions (where one feature is altered but the others remain the same), which need to be processed rather slowly (Egner, 2007). Hommel et al.

(2014) extended this understanding by concluding that due to this, there is no space for any higher-order cognitive control functions such as attention in this framework.

It is noteworthy, that the CSE is a prominent finding in the literature and has been proposed to reflect several different factors. In general, the Stroop task is associated with a larger stimulus set than the Ericksen flanker or Simon task (Egner, 2007). A few of the studies exploring CSEs rule out the feature integration accounts for the Stroop task (see, Egner, 2007). Notebaert et al. (2006) performed three choice Colour-Word Stroop and thwarted feature integration effects and found that complete alternation trials produced smaller CSE relative to complete or partial repetition trials potential feature integration effects.

In the above, I introduced the Colour-Word Stroop and discussed research and theory surrounding the congruency effect and CSE observed in the task. I explored how models of cognitive control account for congruency effects via task performance and also touched on how performance on the Stroop task generates CSEs. In the following section, I will transition to focus on the emotional Stroop task and efforts to investigate the interactions of cognition and emotion with the task.

THE EMOTIONAL STROOP TASK

Overview

Emotions are central to the human experience and closely interact with our cognitions and behaviours (Crossfield & Damian, 2021). Recent research has highlighted a significant degree of functional interaction between cognitive control and emotion (Dignath et al., 2020; Pessoa, 2008; Pessoa et al., 2012). There is a bi-directional link between emotion and cognition wherein emotions act as the output as well as the input for cognitive processes. To illustrate, conflict elicits emotions, and emotions act as a learning signal for cognitive action (Dignath et al., 2020). Considering the findings which corroborate the functional and anatomical associations between emotion and cognition (Carretié, 2014; Dignath et al., 2020; Kanske, 2012; Kanske & Kotz, 2011; Lerner et al., 2021; Pessoa et al., 2005; 2008; 2010; 2012; Pourtois et al., 2013; Raz et al., 2014; Shackman et al., 2011; Zelazo & Cunningham, 2007), the emotional Stroop paradigm is a good measure of 'hot' or affectively charged cognitive control.

The emotional Stroop task has been variously described as measuring 'hot' inhibitory control abilities, attention to negative/threat-related stimuli (Chajut et al., 2010), emotional conflict (Aite et al., 2018; Hu et al., 2019), and conflict resolution (Etkin et al., 2006). Generally, in emotional Stroop tasks, participants are instructed to respond to an emotional stimulus (for example, an emotional word or an emotional facial expression), while ignoring the another simultaneously presented emotional stimuli (for example, an emotional word or an emotional facial expression). Although there are many variants of the task (described in the following section), all emotional Stroop tasks require participants to identify the target stimulus or stimulus dimension while ignoring the distracter stimulus or stimulus dimension which is displayed in a congruent or incongruent manner. Incongruent trials require the participant to avoid processing a conflicting emotional distractor (for example, an emotionally valenced word or image) (Aite et al., 2018; Chan, 2008; Ros et al., 2021; Saunders & Jentzsch, 2013).

In a traditionally 'cool' classic Stroop task, conflict monitoring and top-down control have been linked to the activation of the dorsal portion of the ACC (Bush et al., 2001; Etkin et al., 2006; Zhu et al., 2010), the lateral prefrontal cortex, and the DMPFC (Botvinick et al., 2008; Carter et al., 2007; Egner et al., 2005; 2008; Macdonald et al., 2000). Similarly, in the emotional Stroop paradigm, it has been found that cognitive control mechanisms that recruit lateral prefrontal and medial frontal regions such as the ventral ACC are required to respond to emotional stimuli (Beauregard et al., 2001; Etkin et al., 006; Haas et al., 2006; 2007; Ochsner et al., 2002). The amygdala, which responds to emotional stimuli early on, is strongly connected to this ventral ACC (Kanske & Kotz, 2011).

Furthermore, the dorsal and lateral portions of the ACC are interconnected even though the dorsal portion is associated more strongly with "cognitive" processing, and the ventral is associated more strongly with "affective" processing (Bush et al., 2000; Kanske & Kotz, 2011). The amygdala is sensitive to both emotionally valenced words and facial expressions (Pessoa et al., 2003), indicating that within an emotional Stroop paradigm, the amygdala plays an integral role in modulating one's task performance by identifying and processing facial affect (Etkin et al., 2006). Consistent with this view, Kanske and Kotz (2011) found that the functional connectivity between the dorsal ACC, ventral ACC, and amygdala increases on incongruent trials featuring emotionally valenced stimuli relative to neutral trials in the Stroop task.

The ventral ACC integrates emotion and cognition and prioritizes the emotional stimuli yielding facilitated processing of emotional conflict, which has been found to reduced RT conflict effects relative to conflict trials that don't feature emotionally valenced stimuli. To illustrate, Kanske and Kotz (2011) suggest that in line with the findings of previous studies, top-down regulation of amygdala activation by the ventral ACC occurs during an emotional conflict (Etkin et al., 2006) and a combined dorsal ACC activation takes place for emotional and cognitive conflict (Egner et al., 2008).

To summarise, the activation of incongruent emotional representations via facial expression and the emotional word in an emotional Stroop task leads to a competition for the same neural resources for stimulus processing. This conflict gets represented in the brain both as an emotional conflict and a response conflict (Etkin et al., 2006). The ventral ACC integrates these two conflicts by communicating with the dorsal ACC and amygdala (Kanske & Kotz, 2011). These observations reinforce the evidence reporting the influence of emotion on cognitive control in an emotional Stroop task.

Variants of the Emotional Stroop Task

The emotional Stroop task has been adapted into different variants throughout its history. All these variants showcase the Stroop effect, emotional interference, inhibitory control, attention, distraction, and cognitive control in an emotional context but vary in the degree and presentation of stimulus elements. Some studies have focused on semantics with emotionally laden words presented in different font colours, which has been referred to as the *Colour-Word emotional Stroop task*.

In a basic Colour-Word emotional Stroop task, the two presented features are mapped with different response pairings (for example, emotional word “HAPPY/JOY” with blue and “ANGRY/HEATED” with red) in either a congruent (for example, “HAPPY” paired with green colour ink) or incongruent (for example, “HAPPY” paired with blue colour ink) manner. The participants are instructed to remember the stimulus pairing and respond only to the ink colour while ignoring the emotional word by either button pressing or saying the ink colour loudly (for example, Algom et al., 2004; Chajut et al., 2010; Has et al., 2006; Song et al., 2017).

Other studies have added more elements to the paradigm such as auditory cues or prosody to examine linguistic and cultural bias within an emotional Stroop paradigm (for example, Filippi et al., 2017; De Gelder & Vroomen, 2000; Kitayama & Ishii, 2002; Paulmann & Pell, 2011; Stenberg et al., 1998; Wurm et al., 2004). Some authors implement the emotional Stroop task as an emotional distraction paradigm by instructing the participants to identify the colour of a threat-related word versus a neutral word. This specific variant of the emotional Stroop task sheds light on threat-related attentional bias and goal-conflict due to the slowed RTs in identifying the font colour of threat-related words (Phaf & Kan, 2007 as cited in Rocher & Pickering, 2017).

Face-Word Variant of the Emotional Stroop Task

Within this emotional Stroop task umbrella, the Face-Word paradigm has proven to be essential in studying emotional and cognitive conflict (Beall & Herbert, 2008; Etkin et al., 2006; Hu et al., 2019; Saunders & Jentzsch, 2013). This variant has been demonstrated to generate robust effects across a range of different languages, including Swedish (Sternberg et al., 1998), English (Haas et al., 2006; Etkin et al., 2006), Chinese (Hu et al., 2012; Zhu et al., 2010), and German (Chechko et al., 2013). In terms of the stimuli presented in the Face-Word Stroop task, many authors have integrated semantic and visual affective stimuli such as facial expressions and emotional words (for example, Aite et al., 2018; Etkin et al., 2006; Hu et al., 2019; Koizumi et al., 2007; Ros et al., 2021; Song et al., 2017; Saunders & Jetzsch, 2013).

With respect to the target stimulus, some authors choose emotional words as targets where the participants have to respond to the emotional words while ignoring the emotional expression in the presented face (for example, Sternberg et al., 1998; Haas et al., 2006; Zhu et al., 2010). Alternatively, some research focuses on emotional facial expressions as targets, where the participants have to respond to the facial expression while ignoring the emotional word presented near or on the presented face (for example, Chechko et al., 2013; Egner et al., 2008; Etkin et al., 2006; Hu et al., 2012; Zhu et al., 2010).

In a typical Face-Word Stroop task, the presented facial expressions and words differ in terms of their valence (for example, positive valence – "happy" facial expression or word and negative valence – "angry" facial expression or word; Haas et al., 2006; Hu et al., 2012; Sternberg et al., 1998). In the task, the emotional faces representing positive and negative valenced facial expressions are presented to the participant near an emotion word (for example, the word "HAPPY/ANGRY"). The participant is instructed to focus on the facial expression while ignoring the emotional word, which acts as a distracter agent in cognitive processing.

The emotional Face-Word Stroop task can be understood to mirror key elements of the Colour-Word emotional Stroop task. In the Face-Word Stroop task, an emotional conflict occurs when the relevant and irrelevant stimulus dimensions semantically and perceptually cue competing responses which leads to longer RTs (for example, the word “HAPPY” with a negative facial expression). In the Colour-Word emotional Stroop task, longer RTs for identifying the colour of the emotional word are a measure of emotional interference on cognitive control (Song et al., 2017). Compared to the Colour-Word emotional Stroop task, the semantic conflicted observed in the Face-Word Stroop has been reported to be more intense and require more effort to complete (Song et al., 2017).

Zhu et al. (2010) performed two experiments involving an emotional Face-Word Stroop variant to study the perceptual processing of emotional conflict. In the first experiment, Zhu and colleagues laid emotional words (for example, Chinese words “Yukuai”, meaning happy or “Kongju” meaning fear) written in bold red ink across 10 male and 10 female fearful and happy faces in which the emotional word and the facial expression were either congruent (“Yukuai” on a happy face) or incongruent (word “Yukuai” on a fearful face). They controlled for potential gender related generalisation confounds by keeping 10 male and 10 females faces chosen from the Chinese affective picture system and counterbalanced stimulus occurrences in a button pressing experimental design. The participants were instructed to respond as quickly and accurately as possible by pressing the response buttons corresponding to the facial expressions while ignoring the emotional word (Zhu et al., 2010). In the second experiment, the procedure remained identical to the first experiment, however the participants were instructed to respond as quickly and accurately as possible to the emotional word while ignoring the facial expression.

They assessed the electrophysiological event-related potential (ERP) of the emotional Stroop task by investigating the EEG readings of the participants throughout both experiments.

They found that when responding to the facial expressions, the incongruent conflict condition evoked a larger negative N170 component relative to the N170 component in the incongruent condition when responding to the words. This result suggests that the differentiation of emotional congruency tends to begin at an early perceptual processing stage. Their explanation for these results was that in Experiment 1, enhancement of facial processing was necessary in incongruent versus congruent trials since the face was the task-relevant stimuli. Consequently, in Experiment 2, suppression of face processing was crucial for incongruent versus congruent trials since the face was the task-irrelevant stimuli. Additionally, the results also indicated that emotional words and facial expressions interfere with each other at this early perceptual processing stage.

Emotional Stroop Effects and Valence Effects

Emotional Stroop Effects

As noted above, the emotional Stroop task generates an emotional and cognitive Stroop effect, analogous in some ways to the Stroop effect observed in the Stroop task (Entel et al., 2014; Stroop, 1935). When looking at congruency between the different stimuli within the emotional Stroop task, some studies focus on investigating the difference in performance on congruent (for example, “HAPPY” presented with happy face/word) and incongruent (for example, “HAPPY” presented with angry face/word) trials. For the purposes of this thesis, I will be referring to the emotional Stroop congruency effects as *emotional Stroop effects*. The emotional Stroop effect has been examined via different variations of the emotional Stroop task. Some have examined it with emotional pictures (Hester et al., 2006), emotionally charged words (Algom et al., 2004; Ben-Haim et al., 2014; Chajut et al., 2006), and positively or negatively valenced facial expressions (Lee et al., 2009).

Sometimes researchers use variations of the emotional Stroop task to evaluate the impact of negatively valenced words or images on performance relative to neutral words or images. For the purposes of this thesis, I will be referring to these effects as *valence effects*. The main idea is that in addition to the emotional Stroop effect, there is an additional effect of emotional valence in emotional Stroop tasks through valence effects. Studies investigating valence effects have generated conflicting findings for positive and negative valence effects in incongruent trials of the emotional Stroop tasks.

Facial stimuli, due to their emotional, social, and biological saliency are processed much more rapidly than semantic or verbal stimuli (Victor et al., 2010 as cited in Basgoze et al., 2015). Emotional stimuli have been found to increase processing load which leads to slower RTs on incongruent versus congruent trials in Face-Word Stroop tasks (Basgoze et al., 2008; Chechko et al., 2013; Egner et al., 2008; Etkin et al., 2006; Haas et al., 2006; Hu et al., 2012; Strand et al., 2013; Zhu et al., 2010). To illustrate, many studies have found that performance on incongruent trials of the emotional Face-Word Stroop task is worse when the distractor stimulus is affectively charged as opposed to neutral (for example, the word HAPPY with an angry face versus a neural face). It is proposed that negatively or positively valenced facial expression lead to an increased processing load due to the activation of cognitive-emotional interactive mechanisms versus just cognitive mechanisms.

Along with longer RTs, it has also been reported that responses are less accurate on incongruent trials than congruent trials in emotional Stroop tasks (Hu et al., 2019). These results have also been mirrored in studies where participants are instructed to respond to words in a Face-Word Stroop task (Algom et al., 2004; Ben-Haim et al., 2014; Chajut et al., 2006). These results suggest that the emotional faces in the emotional Stroop tasks interfere with the participant's cognitive processing for the emotionally charged words, in turn generating the emotional conflict Stroop effect (Hu et al., 2019). In other words, the emotional Stroop effect is due to longer naming latencies of ink colours of the emotional words versus the neutral words in a Face-Word Stroop task (Ben-Haim et al., 2016; Frings et al., 2010).

Frings et al. (2010) discuss two routes by which conflict in the emotional Face-Word Stroop task can influence performance. First, negatively valenced distractor stimuli impair one's response within the current trial by capturing the participant's attention. Second, the influence of the negative stimuli persists and leads to impairments in performance in subsequent trials due to an added cognitive load (Frings et al., 2010; McKenna & Sharma, 2004). These effects are proposed to operate similarly in the Colour-Word Stroop task as well as the Face-Word Stroop task. These two pathways have been widely associated with the "fast" (or the currently to-be-executed response) and "slow" (or the influence of the valence of previous events) interference effect, respectively (McKenna & Sharma 2004; Sullivan, 2015).

McKenna and Sharma (2004) proposed that there is a generic slowdown in performance after a negative stimulus regardless of whether the negative stimulus is the target or distractor, attributing such observations to the 'slow' effect (for example, participants would be slower responding to "ANGRY" on an angry face than "HAPPY" on a happy face). Within the slow effect, they showed that the emotional Stroop effect tends to exclusively hinge on the valence of the previous trial (i.e., slower RTs after negative stimuli). According to McKenna and Sharma (2004), this generic slowdown perhaps indicates a 'warning' system that screens the environment for threatening stimuli.

Beall and Herbert (2008) shed light on the empirical evidence which supports a rapid subcortical pathway for the 'fast and automatic' early processing of affective stimuli. Combining the evidence of rapid subcortical neural networks and behavioural evidence, it has been suggested that there is an early fast and automatic processing of emotional stimuli beyond the voluntary attentional control of emotion versus a slow and elaborative disengagement (Franken et al., 2009).

Historically, it has been found that few attentional resources are required to process the affective connotations of emotional words (Beall & Herbert, 2008; Franken et al., 2009; Zhu et al., 2010). This automatic and fast processing of words has been extended to processing the affective connotations of emotional faces too, with face processing being a skill that starts to develop in infancy (Beall & Herbert, 2008; Izard & Ansul, 1985). In sum, linking the slow and fast effects to different cognitive mechanisms reflects a more controlled generic slowdown (Algom et al., 2004; McKenna & Sharma, 2004) and a more automatic allocation of attention (Franken et al., 2009; Phaf & Kan, 2006), respectively. Though it should be noted that this discussion has been heavily debated in several cognitive and neuropsychological models of emotion, such as Lazarus (1991).

Valence Effects

As noted previous, there has been widespread debate regarding the nature of emotional Stroop effects (or congruency effects). Similarly, there has been debate regarding the effect of valence on performance in emotional Stroop tasks. Valence or the “pleasantness or unpleasantness of an emotional stimuli” (Dignath et al., 2020) has shown to play an integral role in the processing of emotions (Kauschke et al., 2019). Face processing studies investigating the perception and recognition of emotion from facial expressions indicate that these abilities engage a complex network of partially independent neural structures (Adolphs, 2002; Crossfield & Damien, 2021).

Faces provide semantic and visual information of paramount social importance (Beall & Herbert, 2008; Sternberg et al., 1998). Due to the biological and social salience of faces, it has been argued that facial expressions are processed more rapidly in an emotional Stroop task context relative to emotional word stimuli (Basgoze et al., 2015). For example, De Houwer and Hermans (1994) found that responses to pictures of faces with a positive or negative valence were much faster, more automatic, and produced more significant interference as compared to responses to words in a Face-Word Stroop task (see Basgoze et al., 2015). De Houwer and Hermans (1994) also reported that this interference was perhaps observed due to the detection of emotional saliency in the facial expressions.

In the preceding sections, I have discussed the general framework and the different variants of the emotional Stroop task. I have also outlined the patterns of emotional Stroop effects but there is yet another debate in existing research regarding the effects of valence on task performance which will be covered in the following section. This debate concerns the question of whether positively and negatively valenced stimuli are processed similarly. In the following sections, I will first focus on a subset of relevant studies reporting that negatively valenced stimuli are processed more automatically or rapidly than positively valenced stimuli. Next, I will focus on the second group of relevant studies which report that positively valenced stimuli are processed more automatically or rapidly than negatively valenced stimuli. Finally, I will briefly highlight studies that show similar processing patterns for both positively and negatively valenced stimuli.

The notion of automaticity in face processing was popularised by White (1995), who examined valence (for example, happy or sad) as a significant characteristic of schematic faces (Stenberg et al., 1998). The effect of valence on the overall speed difference in processing happy and sad expressions suggested that faces were automatically categorized in terms of valence at an early or pre-attentive stage of processing (White, 1995; Stenberg et al., 1998). Early visual studies (for example, Hansen & Hansen, 1988; William et al., 2005) focused on assessing the ‘pop-out effect’ of angry faces in an array of crowded displays of faces indicated that there is a ‘pop-out’ effect of angry facial expressions as compared to simplistic neutral faces. Such preferential processing of negative stimuli versus positive stimuli has been referred to as the *negativity bias* (Kauschke et al., 2019). Such a bias has been reported in a number of studies, with angry faces appearing to be easier to detect than happy faces (Fox et al., 2000; Kauschke et al., 2019; Öhman et al., 2001).

As an extension to this, there is also evidence of angry faces influencing higher-order cognitive processes like attention (Carretié, 2014; Lerner et al., 2021; Pourtois et al., 2013). Negative emotional stimuli have also been considered to have more precedence in access to one's awareness and hence have prioritized processing (Carretié, 2014). For 'bottom-up' or 'stimulus-driven' cognitive processes, there is evidence that, as compared to neutral stimuli, affectively charged stimuli (positive and negative stimuli) are more attention-grabbing (Holtmann et al., 2014; McHugo et al., 2013; Straub et al., 2021).

It has been found that the amygdala tends to respond faster to emotional versus neutral faces, which is essential for an individual's survival as it provides means of rapid evaluation of affective stimuli in one's environment (Öhman, 2000; Straub et al., 2021; Stolicyn et al., 2017; William et al., 2004). Research on amygdala responses to emotional faces has demonstrated a priority for threatening emotional stimuli (for example, Hariri et al., 2000; Schupp et al., 2004, cited in Beall & Herbert, 2008). Therefore, it can be noted that negatively valenced facial expressions (for example, angry faces) are perhaps detected and processed more automatically than positively valenced facial expressions (for example, happy faces) due to the rapid detection of threat and potential adaptive value (Beall & Herbert, 2008; Crossfield & Damian, 2021; Fox et al., 2000; Öhman, 2001; Palermo & Rhodes, 2007; Quan et al., 2020).

A meta-analysis of the emotional Stroop task suggested that negative valence, especially negative affect, is an essential determinant of control regulation (Phaf & Kan, 2007). The reason for this is perhaps the survival-related salience of negative stimuli, which makes it difficult to disengage from negative stimuli, leading to a delay in naming the emotional word when presented with a negatively valenced face (Fox et al., 2002; Phaf & Kan, 2007).

Quan and colleagues (2020) stated that negatively valenced threatening stimuli will always induce an emotional Stroop congruency effect (Quan et al., 2020). Converging behavioural, functional, and electrophysiological evidence from past and contemporary studies in this domain corroborates the notion that threatening emotional facial expression preferentially ‘capture’ and ‘hold’ attention (Hansen & Hansen, 1994; Palermo & Rhodes, 2007; Sternberg et al., 1998). Using a variant of the emotional Stroop task, Van Honk et al. (2001) placed red, blue, green, and yellow tinted transparent foil on top of angry and neutral faces and instructed the participants to name the colour of the face while ignoring the expression in a microphone as quickly as possible. Through this variant of the emotional Stroop task, they concluded that participants took longer to name the colour of an angry face rather than a neutral face.

These and other similar studies have led some to conclude that there is more automatic processing of facial expressions which display a threat or danger at a pre-attentive level (Beall & Herbert, 2008; Öhman, 2002; Vuilleumier, 2002). These include fearful, angry, or disgusted faces, representing impending threat or aggression as there is a higher attentional bias towards processing an angry facial expressions in contrast to the ‘basic or universal’ expression of happiness (Palermo & Rhodes, 2007).

Another influential study that drives this discussion forward is Sternberg et al. (1998). They presented participants with compound stimuli consisting of words superimposed on different facial expressions in their version of the emotional Stroop task and asked the participants to assess the affective valence of the word while simultaneously disregarding the face. Results from their experiments concluded that negatively valenced words as target stimuli required faster latencies and hence more resources than positive stimuli. Overall, the speed advantage of positive words was modified due to the presentation of the faces. To illustrate, facilitation effects were observed with faster RTs in trials in which negative words were presented with a negative expression (for example, an angry face). Correspondingly, inhibition effects were observed with slower RTs in trials where negative words were presented with a positive facial expression (for example, a happy face) due to the incongruity between the two valences. The main idea is that since angry faces recruit more automatic attentional resources relative to positively valenced facial expressions therefore, individuals will be faster on congruent trials with angry faces/word than on congruent trials with happy faces/words (Sternberg et al., 1998; Van Honk et al., 2001).

In contrast to research outlined above, multiple studies have reported *enhanced* processing for positively valenced stimuli relative to negatively valenced stimuli. Similarly, some of the studies that compared fearful or angry facial expressions and other 'universal expressions' such as happiness do not provide overwhelming evidence of the automaticity of responses to negative stimuli. These researchers conclude that RTs to fearful or angry expressions are often larger than those for other expressions (for example, Batty & Taylor, 2003; Krolak-Salmon et al., 2004; Palermo & Rhodes, 2007). This calls into question the idea that angry faces are processed more rapidly. An EEG study by Batty and Taylor (2003) add that the responses to positively valenced universal facial expressions such as happiness tend to have earlier latencies in temporal regions and the amygdala.

One argument for why positively valenced stimuli might be processed more rapidly than negatively valenced stimuli is that positively valenced faces are more visually distinct as compared to negatively valenced faces and are therefore detected more rapidly (Becker et al., 2011). For instance, data from an emotional Stroop task by Lui et al. (2018) indicate the presence of fast and slow effects from positively valenced words facilitated performance on current and subsequent trials. These findings can be interpreted as positive valence leading to 'attentional reorientation' (Johnson et al., 2010).

On this view, participants detect positively valenced stimuli more rapidly following a presentation of a positively valenced stimuli which leads to a reorientation in attentional resources (for example, a happy face with the word "HAPPY" followed by a happy face with the word "HAPPY"). Response time differences for positively and negatively valenced stimuli have also been proposed to reflect a 'positivity bias' in which positive stimuli receive a processing advantage over negative stimuli (Kauschke et al., 2019). Some studies have also observed a speed advantage in decision-making tasks involving positive versus neutral or negative faces (for example, Leppänen and Hietanen, 2004 as cited in Kauschke et al., 2019).

Finally, some studies have found that positively and negatively valenced faces are processed similarly, without evidence for a negativity or positivity bias. Previous research theorizes that different types of affective stimuli (for example, faces and words) are processed automatically but on a continuum or hierarchically (Beall & Herbert, 2008). In general, happy and sad facial expressions tend to interfere more with the judgment of word valence than the interference of positive or negatively valenced words on the judgment of facial expression valence (Beall & Herbert, 2008). The same study showed that happy and angry facial expressions resulted in more significant interference effects than sad faces. These studies provide further evidence for the notion that angry and happy facial expressions are processed with similar interference effects and automaticity.

As mentioned above, Beall and Herbert's (2008) results contrasted significantly with the research concluding that potential threat stimuli via negatively valenced facial expressions are processed more automatically than positively valenced faces, and suggest that processing distinctions reflect a more complex interaction of factors than a simple positive versus negative framing would suggest. In sum, it appears that there is a gap in the literature with conflicting evidence for the automaticity of processing stimuli with positive or negative affect in an emotional Stroop paradigm. There is ongoing debate regarding the underlying processes of valence effects and how such effects impact task performance.

Congruency Sequence Effects in Emotional Stroop Task

The CSE observed in Colour-Word Stroop tasks have also been reported in emotional Stroop tasks (Chechko et al., 2014; Danfeng Li et al., 2019; Etkin et al., 2006; Saunders & Jentzsch, 2013). The emotional CSE reflects the ability of an individual to resolve an emotional conflict caused by an incongruent trial on a trial-to-trial basis. Previous research suggests that simultaneously activated affective representations in an emotional Stroop task cause an emotional conflict, which is resolved by the facilitation of executive, top-down control and by resolving the subsequent interference (Chechko et al., 2014; Danfeng Li et al., 2019; Egner et al., 2008; Etkin et al., 2006; 2011; Padmala et al., 2011; Pessoa, 2009; Saunders & Jentzsch, 2013).

Some previous studies have also confirmed that the specific valences of the target facial expressions such as anger or happiness can affect the CSE in an emotional context (Danfeng Li et al., 2019). To illustrate, Padmala et al. (2011) performed an experiment involving a gender Face-Word Stroop task (Egner et al., 2010) where the participants were instructed to identify the gender of the face stimuli (male or female) while ignoring the overlaid gender word ("MALE" or "FEMALE"). Immediately after the Face-Word Stroop trial, the participants were presented with neutral or negative images to investigate the pattern of the CSE in performance following the negative emotional stimuli. They reported that negatively valenced emotions lead to larger CSEs. Their interpretation of this result was that processing of negatively valenced emotional stimuli may have diverted or consumed resources that are needed for top-down cognitive control as outlined in the conflict monitoring account (Botvinick et al., 2001). Presentation of a negative facial stimuli in between trials led to this diversion of resources which consequently led to poorer cognitive control on the subsequent trial and larger CSEs (Padmala et al., 2011).

Egner et al. (2007) and Etkin et al. (2006) report neurological and behavioural evidence illustrating substantial CSEs within the Face-Word Stroop paradigm, interpreting the results in terms of the conflict adaptation account (Botvinick et al., 2001). Rocher and Pickering (2017) extended these findings via a Word-Face emotional Stroop task and provided further evidence for robust RT congruency effects and RT facilitation effects. To illustrate, they found reduced accuracy for incongruent trials versus neutral trials but no specific increase in accuracy for congruent trials versus neutral trials (Rocher & Pickering, 2017). In sum there is evidence for the occurrence of CSEs in emotional Stroop tasks, with the occurrence of these effects potentially impacted by valence effects.

Many authors have tried to understand how the valence of an emotional expression or word may affect the emotional-cognitive control processing and have reported conflicted findings (for example, Beall & Herbert, 2008; Chechko et al., 2014; Crossfield & Damien, 2021; Etkin et al., 2006; Egner et al., 2008; Hu et al., 2021; Haas et al., 2006; Öhman, 2002; Padmala et al., 2011; Pessoa, 2009; Vuilleumier, 2002; Zeynep et al., 2015; Zhu et al., 2010).

Developmental Trajectories in Task Performance

Another approach to understanding how emotion and cognition interact in the emotional Stroop task is to investigate how performance on the task changes across development. The effects of emotional valence on performance at different points in development are unclear, with conflicting results in the literature. The findings are contingent on the presentation of the task and the valence of the stimulus presented. A summary of the more significant findings is as follows.

The Socioemotional Selectivity Theory by Carstensen (2006) suggests that emotional regulation is reinforced with age, and because of this, older adults are especially motivated to process positive information (Agusti, 2017). Connecting this to the emotional Stroop task, Ashley and Swick (2009) compared the performance of older and younger adults in an emotional Stroop task, with presentations of “pure” blocks (all stimuli express the same emotions) versus presentations of “mixed” blocks (stimuli expressing different emotions). The authors concluded that both groups of participants had slower RTs on negative emotional words as distractor stimuli and showed an interference effect on “pure” blocks relative to positive emotional distractor stimuli. This ties back to the suggestion by Mather and Carstensen (2006) that older adults do, in fact, show a Stroop effect towards negative affective stimulus (Agusti et al., 2017).

Older adults have been found to implement emotional regulation when faced with an emotional stimulus, as in the emotional Stroop task (Mather & Carstensen, 2005). Reasons for this type of pull towards emotional regulation range from older adults’ higher vulnerability to emotional stimuli to their limited cognitive resources (Mather & Carstensen, 2005; Rosler et al., 2005). Older adults have also been found to show a higher level of interference on words with higher emotional arousal relative to younger adults (Agusti et al., 2007). Wurm et al. (2004) compared healthy young and older adults by their performance on a lexical and a Colour-Word variant of the emotional Stroop task. They concluded that older adults showcase higher interference levels on higher versus lower arousal-inducing words.

When presented with multiple stimuli and emotion regulation resources, older adults have been found to allocate more attentional resources to positive information than younger adults (Mather et al., 2005; Mather & Carstensen, 2003; 2006). This comes into play when detecting threatening faces is required (Agusti et al., 2017; Beall & Herbert, 2008; Vuilleumier, 2002). In general, younger, and older adults detect schematic threatening faces more quickly than other types of emotional stimuli. This enhanced ability to detect threatening information is mediated by the amygdala and appears to be an automatic process inaccessible to cognitive control (Anderson et al., 2003; Davis & Whalen, 2001; Öhman & Mineka, 2001). Support for this claim also comes from eye-tracking studies such as Rosler et al. (2005), who concluded that both older and younger adult's saccade to negatively valenced pictures initially, but younger adult's dwell on them longer. These findings corroborate the claim that older adults do not show an emotional Stroop effect towards negative stimuli by orienting their attention away from threatening stimuli (Mather et al., 2005; Mather & Knight, 2006).

An electrophysiological ERP study by Zhu et al. (2010) studied the physiological differences in young and older adults on an emotional Stroop task by comparing faces and words. The premise is that it would be necessary to suppress information coming from the emotional facial expression to focus on the word in an incongruent word trial and suppress information from the emotional word to focus on the face in the face trial (Zhu et al., 2010). They concluded that there is more interference on positive faces and words rather than negative faces and words for both younger and older adults when the distractor stimuli is negative. This indicates that negative words lead to a higher interference level than positive words when responding to emotional facial expressions (Agusti et al., 2017). To illustrate, if the participants were instructed to respond to a positive or negative face, a negative distractor word paired with a positive face would cause larger interference on this view.

Zhu and colleagues (2010) extended these findings to a task featuring facial expressions as target stimuli and concluded between-group differences, where older adults have higher interference levels than younger people when identifying facial expressions. Reasons for this interference could be caused by reading the word simultaneously and more automatically, greater cognitive demands with aging, or limited cognitive abilities due to aging (Agusti et al., 2017; Zhu et al., 2010). Overall, both groups revealed a greater tendency toward positive stimuli as positive affective stimuli were found to have faster responses when congruent positive stimuli were compared to congruent negative stimuli. However, older adults showed more significant results in the face-trial conditions versus the word trial condition.

At the other end of the developmental spectrum, Zelazo and Carlson (2012) suggest that there is a linear pattern of development for affectively charged cognitive control abilities between childhood and early adulthood. They report that hot cognitive control abilities get increasingly more sharp and specific with age. On the other hand, in contrast to Zelazo and Carlson's (2012) model, Aite et al. (2015) hold that there is an 'U' pattern of development wherein adolescence marks a specific time window for low cognitive control abilities in affectively charged contexts (Somerville et al., 2014). Support for the later comes from interdisciplinary behavioural and neurobiological literature (for example, Casey, 2015; Fuhrmann et al., 2015), which produce new models of adolescent-specific self-control. Within these models, it's been suggested that there is a significant imbalance between the control and emotional systems, which results from the lack of top-down control of emotional responses in adolescents (Fuhrmann et al., 2015; Metcalfe & Mischel, 1999).

REACH TRACKING

Cognitive control experiments have typically focused on assessing response behaviour in congruency tasks such as the Stroop task (Stroop, 1935) with button-press measures of accuracy and response time. One drawback of this approach is that even after controlling all lexical, semantic, and visual variables, these button-press measures provide relatively little insight into how the processes underlying performance unfold over time (Chen et al., 2015 as cited in Crossfield & Damian, 2021). However, even simple motor responses such as those observed in button-press movements have been found to be updated continuously during stimulus processing and decision making (Abrams & Balota, 1991).

In more contemporary research, researchers have adopted continuous behavioural measures by using techniques such as mouse tracking (for example, Freeman & Ambady, 2010) or three-dimensional reach tracking (for example, Erb et al., 2016). In a typical mouse-tracking study (for example, Barca & Pezzulo, 2015), the mouse positions are continuously recorded. Measures such as initiation time (time interval in ms between the participant clicking on 'start' and the onset of the mouse movement), reaction time (interval in ms between stimulus presentation and response), and curvature of the mouse trajectory are computed (Crossfield & Damian, 2021). The rationale behind recording the mouse movement trajectory holds that it allows for assessing the 'attraction' towards the non-selected response and the curvature towards the incorrect response (Freeman & Ambady, 2010 as cited in Crossfield & Damian, 2021). Both reflect the competition between the simultaneously activated action plans (Crossfield & Damian, 2021).

The second type of hand tracking design is reach tracking, which has provided a more dynamic and detailed perspective on the underlying cognitive processes of decision making, relative to button pressing and mouse tracking techniques. In a typical reach tracking study, participants are instructed to reach to one of multiple targets from a designated starting location on the table in front of a computer screen. Reach tracking studies follow the same general structure as mouse tracking studies, allowing for measures of initiation times (elapsed time between stimulus and movement onset), reach curvatures (the degree to which reach movement deviates from the direct path to selected response location), movement times (elapsed time between movement onset and response completion, and response time (elapsed time between stimulus onset and response completion). It also allows for the investigation of hand movement in three spatial dimensions (Erb, 2018).

Such techniques provide new opportunities for investigating the behavioural, neural, and computational mechanisms underlying decision-making by capturing the spatial and temporal dynamics of hand movements (Erb, 2018; Song & Nakayama, 2009). Consequently, the techniques have been recruited to explore a range of psychological phenomena, including language processing, numerical cognition, social perceptions, and cognitive control (for review, see Freeman et al., 2011; Freeman & Johnson, 2016; Song, 2017; Song & Nakayama, 2009). In the cognitive control literature, hand tracking techniques have been particularly helpful for studying the dynamics of conflict detection and resolution (Erb et al., 2016; Erb et al., 2017; Erb, 2018)

Gallivan and Chapman (2014) note that one of the benefits of reach tracking is that it does not require participants to perform visuomotor transformations such as the ones needed to translate physical movements of computer mouse into the digital cursor (Erb, 2018). Hand-tracking techniques also present a more thorough account of how the underlying decision-making processes unfold over a single trial (i.e., within-trial dynamics), as well as how these cognitive processes are impacted by the salient qualities of the preceding trial (i.e., cross-trial dynamics) (Erb et al., 2018).

In a series of recent studies, Erb and colleagues (Erb & Marcovitch., 2018; Erb et al., 2016; 2017; 2018) provided evidence that initiation time and reach curvatures can be used to assess two of the processes proposed to underlie cognitive control in the Stroop task: the threshold adjustment process which temporarily puts a ‘brake’ on behaviour upon conflict detection and a controlled selection process that ‘steers’ top-down control to sway behaviour towards the appropriate target response (for example, Cavanagh et al., 2011; Erb et al., 2016; Frank, 2006; Shehnav et al., 2013. Previous work by Farmer et al. (2017) and Freeman et al. (2013) shows evidence that during hand-tracking tasks, participants often initiate movements towards a response target prior to entirely resolving the conflict cause by alternate options (Erb et al., 2016). These findings suggest that participants often exceed a response threshold before the controlled selection process has ‘steered’ attention in favour of the task-appropriate response (Erb et al., 2016).

Considering these previous findings, Erb et al. (2016) proposed that initiation times and reach curvatures can be used to target the functioning of the response threshold adjustment process and controlled response selection process, respectively. To illustrate, on incongruent trials in the Colour-Word Stroop task, conflict occurs when the font colour and the meaning of the word cue different responses. Conflict of this kind heightens the response thresholds and consequently leads to a longer period of motoric stopping (for example, Frank, 2006 as cited in Erb et al., 2019).

Initiation times reflect this threshold adjustment process by indexing how long the "brake" is put on behaviour for before a movement is started. When conflict is detected, the controlled selection process is engaged to direct attention toward the colour of font that the word is presented in. Reach curvature reflect this controlled selection process by indexing how rapidly competition between the two cued responses is resolved, with larger curvatures indicating that the controlled response selection process took longer to sway activations in favour of the task-relevant response.

To test this hypothesis, the researchers performed multiple experiments with different tasks that required participants to override a prepotent response with a more controlled response, including the Stroop task. In light of previous electrophysiology research by Sheth et al. (2012) indicating that heightened response thresholds on one trial are carried over into the next trial, Erb et al. (2016) predicted that initiation times in the Stroop task would show main effects of both the current trial's congruency and the previous trial's congruency. This meant that initiation times should be slower on incongruent (vs. congruent) trials (C < I) as well as on trials preceded by an incongruent (vs. congruent) trials (c < i). In line with these predictions, the researchers observed main effects of current and previous congruency in initiation times in a three-response version of the Stroop task, resulting in the following pattern of effects: cC < iC < cI < iI.

In contrast to the pattern of effects observed in initiation times, reach curvatures revealed a significant interaction between the congruency of the current trial and the congruency of the previous trial, resulting in the following pattern of effects: cC = iC < iI < cI (Erb et al., 2016). This pattern of effects, previously observed in an fMRI investigation of the Stroop task by Kerns et al. (2004), was interpreted to reflect the controlled selection process, with larger curvatures on cI relative to iI trials indicating that performance was enhanced on iI trials (for example, due to conflict adaptation) or impaired on cI trials (for example, due to feature integration) (Erb et al., 2016). Taken together, the distinct patterns of effects observed in initiation time and curvature by Erb et al. (2016) and in subsequent studies with the Stroop and Ericksen flanker tasks (Erb & Marcovitch, 2018; Erb et al., 2019) indicate that hand tracking techniques can be used to target the functioning of dissociable processes underlying cognitive control.

The Present Study

In the preceding sections, I highlighted the considerable disagreement in the literature on the emotional Stroop task regarding the effects of positively and negatively valenced stimuli on task performance. I further discussed how researchers have recently begun to use a technique known a reach tracking to target how two dissociable processes underlying cognitive control – a threshold adjustment process involving the inhibition of motor output and a controlled selection process involving the recruitment of top-down control – function.

The current study was designed to investigate three central questions. First, can reach tracking be used to target the threshold adjustment process and controlled selection process in the Face-Word Stroop task? Second, does the positive or negative valence of the facial stimuli presented in the emotional Stroop task have an effect on performance? Third, is performance on the Face-Word Stroop task related to performance on the classic Colour-Word Stroop task? Additionally, a secondary question of interest concerned the extent to which the cross-trial dynamics observed in the Face-Word and Colour-Word Stroop tasks would mirror those observed in previous hand-tracking research with the Ericksen flanker task (for example, Erb & Marcovitch., 2018) or those observed in previous hand-tracking research with the Simon task (for example, Erb & Marcovitch., 2019).

For the current study, one experiment with two tasks were conducted wherein two variants of a forced choice two alternative Stroop task (Stroop, 1935) – the classic Colour-Word Stroop task and the Face-Word Stroop task (Egner et al., 2008; Etkin et al., 2006) – were adapted for use with reach tracking. The classic Colour-Word Stroop task featured two colour words (RED and BLUE) that appeared in either a congruent font colour ("RED" in red font) or an incongruent font colour ("BLUE" in red font). In order to keep consistency and to draw direct comparisons between performance on the two tasks, Face-Word Stroop task also featured two faces (a happy expression and an angry expression) that were paired with either a congruent distractor (for example, the word "HAPPY" presented with a happy face) or and incongruent distractor (for example, the word "HAPPY" presented with an angry face).

The trial conditions remained the same for the emotional Stroop task. The emotional words were presented underneath the facial expression in black font for both incongruent and congruent trials. In the Face-Word Stroop task, participants were asked to identify the emotional expression on the faces as quickly and accurately as possible while ignoring the emotional word underneath them. Historically, the emotional Stroop paradigm has been used to measure performance with multiple facial and emotional stimuli (Edger, 2006; Zhu et al., 2010). However, in the current study, our overarching aim was to identify the dynamics of the two alternative forced choice Face-Word Stroop task by establishing links to the two alternative forced choice Colour-Word Stroop task in a reach-tracking experimental design.

METHODOLOGY

Participants

The final sample consisted of 42 participants between 18 and 28 years of age (*M* = 21.8 years, *SD* = 3.1). Twenty-five of the participants identified as female, 16 identified as male, and one participant preferred not to provide a response concerning their gender identity. Sixteen of the participants identified as Asian, 16 identified as New Zealand European, two identified as Pacific, two preferred not to respond, and two identified as "other". The remaining participants identified as African (1), European (1), Latin American (1), and Middle Eastern (1). All participants were right-handed with normal or corrected-to-normal visual acuity, understood English, were capable of normal reaching behaviour, and were not formally diagnosed with a social or cognitive impairment.

All participants also reported normal colour vision. Four additional individuals participated but were excluded from the final sample. One participant was excluded due to equipment failure, two participants were excluded due to experimenter error, and one participant was excluded due extreme difficulty performing one of the tasks, resulting in an error rate above 15%. Participants received either course credit or a $15 NZD supermarket voucher participating in the hour-long session. The protocol was approved by the University of Auckland Human Participants Ethics Committee (UAHPEC).

Materials

The experiment was conducted using a rear-mounted projector to display the task on a Plexiglass screen (for example, Erb et al., 2016; Moher & Song, 2013). The projector, screen, and an electromagnetic source were affixed to a wooden board that was mounted to a 89.5 cm by 150 cm table. The projected display on the Plexiglass screen was 30.5 cm by 53.5 cm. A 2 cm by 2 cm square marker was placed 27 cm in front of the screen (see Figure 2A).

The square marker served as a starting marker from which participants initiated their movements. Reach movements and response selections were measured at a rate of approximately 155 Hz with an electromagnetic position and orientation recording system (Liberty, Polhemus). A small motion-tracking sensor was secured to participants' right index finger with a Velcro strap. The sensor was 2.26 cm long, 1.27 cm wide, and 1.14 cm high, and weighed 3.7 grams. The task was programmed in MATLAB (Mathworks).

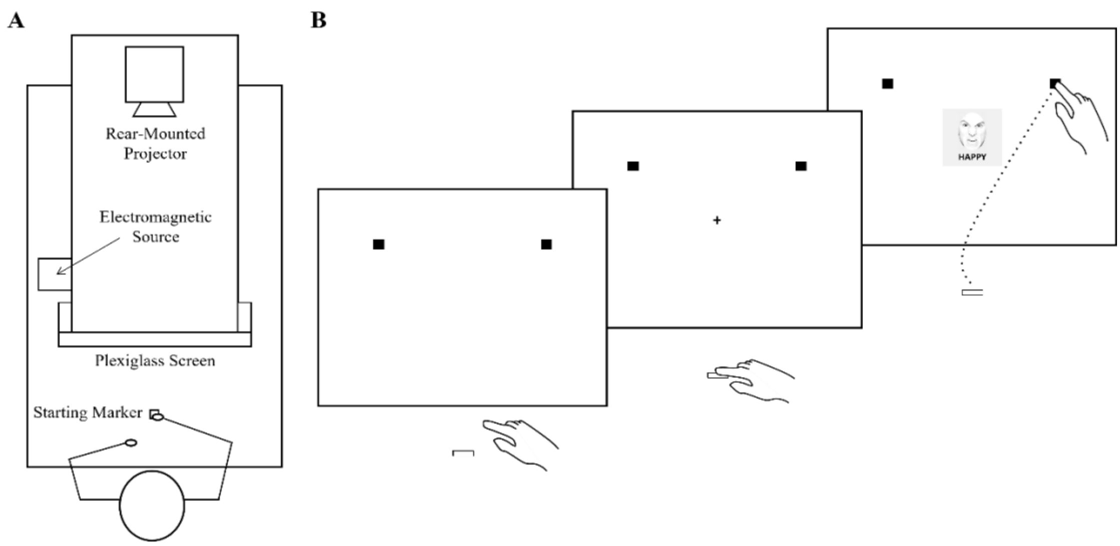

Figure 2. ***(A)*** Diagram of the experimental setup from a top-down view. The task was displayed on a Plexiglas screen mounted upright on the table in front of the participant. All movements were initiated from a starting marker mounted on the table 27 cm in front of the screen. ***(B)*** Illustration of an incongruent trial in the Face-Word Stroop task (an ANGRY facial expression with the word HAPPY presented in text) from the perspective of the participant.

Procedure

Half of the participants completed the Colour-Word Stroop task before the Face-Word Stroop task, whereas the other half of participants completed the tasks in the opposite order. Before each task, participants completed a nine-point calibration sequence followed by 16 baseline trials that required reaching to a square that appeared alone at the top left or right of the screen. In each of the experimental tasks, participants completed a practice block consisting of 10 trials, followed by four blocks of 56 trials. Each block consisted of 28 congruent trials and 28 incongruent trials. Within each block, trial presentation was fully randomised, and the correct response was evenly divided between the two response locations.

Each trial in both tasks followed the same general sequence of events. To initiate each trial, participants had to rest their finger on the starting marker on the table in front them for 500 ms. Next, a fixation cross measuring 0.6 cm by 0.6 cm was presented in the centre of the display for 1,000 ms. If the participant's hand moved from the starting marker before the imperative stimulus appeared, the task was paused and did not resume until the participant returned their hand to the starting block for 1 second. Following the fixation cross, the imperative stimulus appeared in the centre of the screen, replacing the fixation cross.

Participants had up to 2 seconds to respond following stimulus onset by reaching to touch one of two response targets that remained on the screen throughout the task. The response targets were black squares that measured 1 cm by 1 cm (see Figure 2B). The centre of each response target was 6 cm from the top of the projected display, with one response target located 12.5 cm in from the left side of the projected display and the other square located 12.5 cm in from the right side. A high tone sounded for correct responses provided in the allotted time (600 Hz for 200 milliseconds), and a low tone sounded for incorrect responses or responses that exceeded the allotted time (300 Hz for 200 milliseconds).

Face-Word Stroop

Participants were presented with a two-alternative forced-choice (2AFC henceforth) version of a Face-Word Stroop modelled of the task used by Aïte et al. (2018). On each trial, a 6.8 cm by 6.8 cm grey (RGB: 128, 128, 128) square appeared in the centre of the projected display. One of two facial expression images were presented in an oval measuring 4.6 cm in height and 3 cm in width. Both images featured a black and white image of a male face, with one face presenting a happy expression and the other presenting an angry expression. The words "HAPPY" and "ANGRY" were presented under the oval in capital, black letters and measured .7 cm in height and varied in width from 3.1 cm (“HAPPY”) to 3.3 cm (“ANGRY”) (see Figure 3A). Participants were instructed to respond according to the facial expression presented regardless of the word’s meaning by touching one of two response targets, with half of the participants mapping happy facial expressions to the left and angry facial expressions to the right, and half of the participants receiving the inverse mapping. These mappings remained constant across the experiment for each participant. Participants were told the mappings for each response target multiple times and were asked to recall the mappings before the block of practice trials. Before each experimental block, participants were reminded to respond as quickly and accurately as possible.

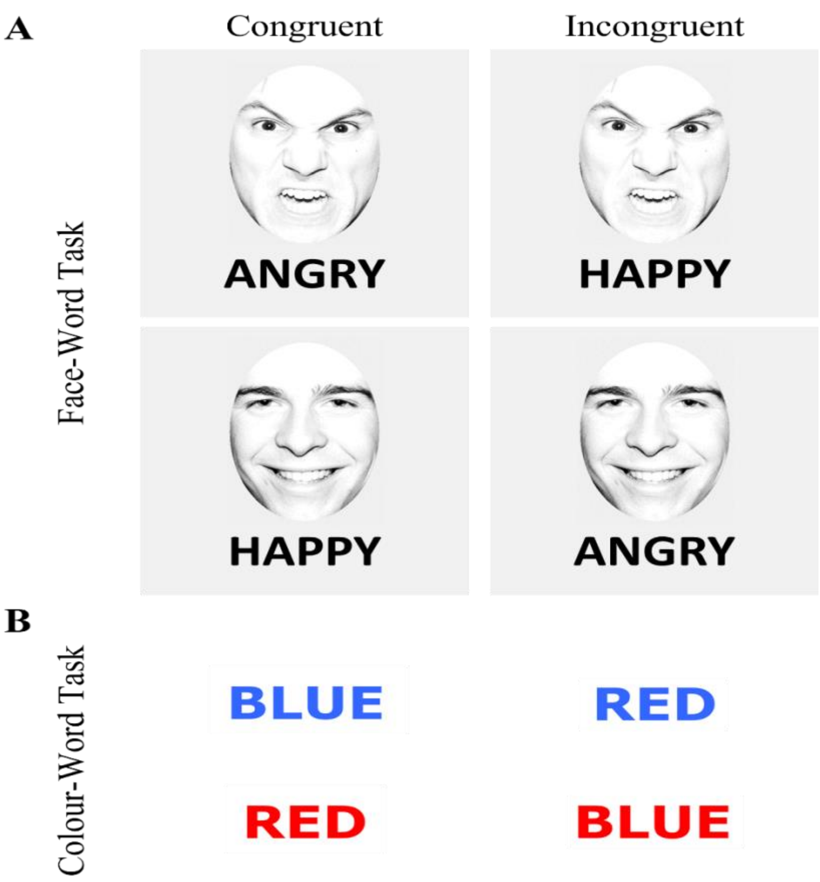

Figure 3. (A) Illustrations of the congruent and the incongruent stimuli of the Face-Word Stroop task. ***(B)*** Illustrations of the congruent and the incongruent stimuli of the Colour-Word Stroop task.

Colour-Word Stroop

Participants were presented with a 2AFC version of the Stroop task in which the word "RED" or "BLUE" was presented in the either red (RGB values: 185, 58, 58) or blue (RGB: 51, 102, 255) text in the centre of the display following a fixation cross (see Figure 3B). The word "RED" measured 0.9 cm in height and 2.5 cm in width. The word "BLUE" measured 0.9 cm in height and 3.1 cm in width. Participants were instructed to respond according to the colour of text that the word was presented in regardless of the word's meaning by touching one of two response targets, with half of the participants mapping red text to the left and blue text to the right, and half of the participants receiving the inverse mapping. These mappings remained constant across the experiment for each participant. Participants were told the mappings for each response target multiple times and were asked to recall the mappings before the block of practice trials. Before each experimental block, participants were reminded to respond as quickly and accurately as possible.

Data processing

The processing procedures used in the current study were largely adapted from Moher and Song (2013). Three-dimensional resultant speed scalars were created for each trial using a differentiation procedure in MATLAB. These scalars were then submitted to a second order, low-pass Butterworth filter with a cut-off of 10 Hz. Movement onset was calculated as the first point on each trial after stimulus onset at which hand movement speed exceeded 10 cm/s. Each individual trial was visually inspected as in previous work (for example, Song & Nakayama, 2007); for trials in which the default threshold clearly missed part of the movement or included substantial movement back to the starting point, thresholds were adjusted manually. Such adjustments were rare, occurring on fewer than 1% of trials.

Initiation time (IT) was calculated as the time elapsed between stimulus onset and movement onset, whereas movement time (MT) was calculated as the time elapsed between movement onset and response completion. Trajectories for calculating curvature (CURV) were measured in two-dimensional xy space by calculating a line from the start to the end point of the movement and measuring the orthogonal deviation of the actual movement from that line at each sample. Curvature was defined as the maximum point of deviation in centimetres divided by the length of the line from the start to the end points of the movement in centimetres (following Desmurget et al., 1997; Moher & Song, 2013).

RESULTS

Average error rates were extremely low for both tasks (Face-Word Stroop: *M* = 0.7%, *SE* = 0.2%; Colour-Word Stroop: *M* = 0.6%, *SE* = 0.1%) and, consequently, were not analysed further. Low error rates are commonly observed in hand-tracking tasks because participants make online adjustments when movements initially approach the incorrect response (for example, Erb & Marcovitch, 2019). To control for post-error performance adjustments (for example, Danielmeier & Ullsperger, 2011), the subsequent analysis of response times, initiation times, movement times, and curvatures was restricted to trials featuring accurate responses preceded by an accurate response.

Face-Word Stroop

Preliminary analyses were conducted to ensure that there were no unanticipated effects of mapping condition (i.e., whether happy expressions were mapped to the left response and angry expressions were mapped to the right response, or vice versa) or task order (i.e., whether participants completed the Face-Word Stroop task before or after the Colour-Word Stroop task), with alpha set to .01 given the large number of factors being evaluated. A series of mixed ANOVAs featuring a between-subjects factor of mapping condition (A vs. B) and within-subjects factors of current congruency (C vs. I), previous congruency (c vs. i), and response repetition type (response repeat vs. response switch) revealed no significant effects (main or interaction) of mapping condition on any of the dependent measures.

Similar analyses evaluating the between-subjects factor of task order failed to reveal significant effects of task order (main or interaction) on any of the dependent measures. These preliminary analyses indicate that performance was not driven by task order effects or pre-existing associations between emotions and spatial locations (for example, participants did not appear to preferentially associate "happy" with the left or the right response). Consequently, the effects of current congruency, previous congruency, and response repetition type were evaluated in a series of repeated-measures ANOVAs. In the following, the Holm-Bonferroni method is adopted to account for family-wise error rates resulting from multiple hypothesis tests, with the target alpha level for each ANOVA set to .05.

Initiation Times.

In light of previous hand-tracking research (for example, Erb & Marcovitch, 2018, 2019; Erb et al., 2019; Erb et al., 2016), we predicted that initiation times in the Face-Word Stroop would reveal significant main effects of current congruency and previous congruency. The results revealed a main effect of current congruency, $F(1, 41) = 20.82$, $p < .001$ (Holm-Bonferroni adjusted *p*-value = .025), $\eta_p^2 = .34$, with faster initiation times on congruent trial (*M* = 504 ms, *SE* = 14 ms) than incongruent trials (*M* = 519 ms, *SE* = 15 ms), and a main effect of previous congruency, $F(1, 41) = 14.34$, $p < .001$ (Holm-Bonferroni adjusted *p*-value = .05), $\eta_p^2 = .26$, with faster initiation times on trials preceded by a congruent trial (*M* = 508 ms, *SE* = 14 ms) relative to those preceded by an incongruent trial (*M* = 515 ms, *SE* = 15 ms) (see Figure 4A). No other main effects or interaction effects approached significance.

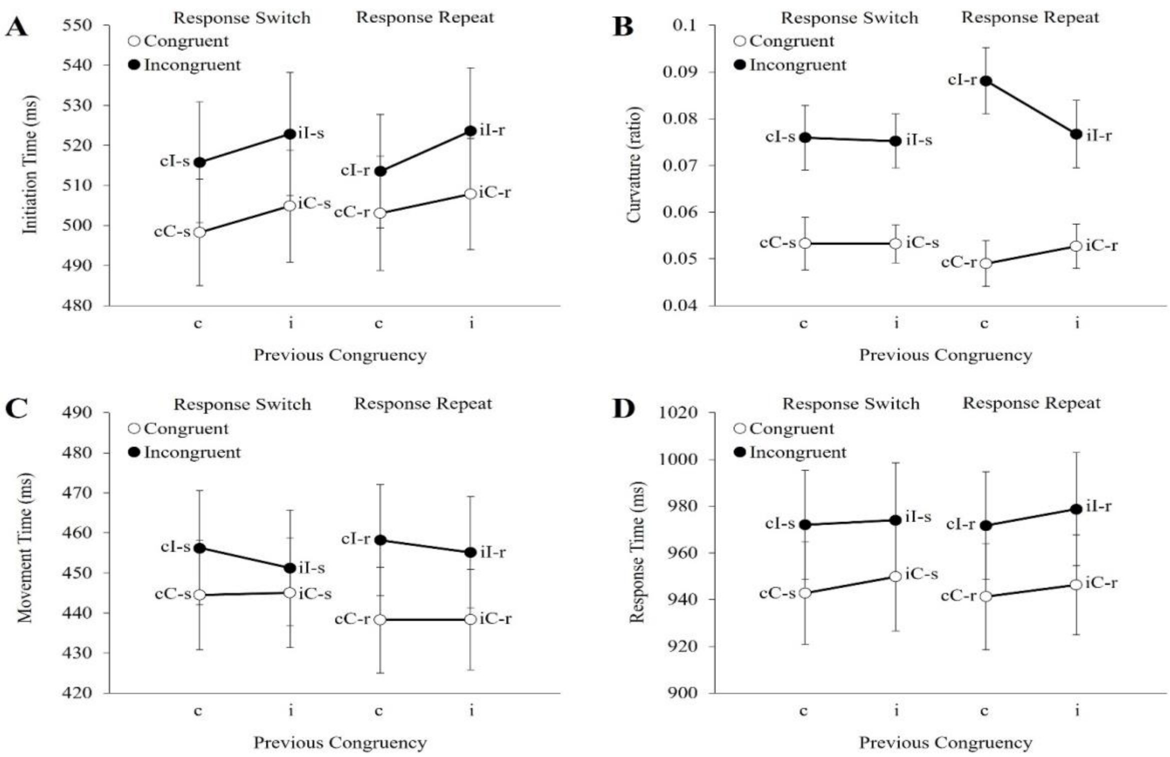

Figure 4. Average ***(A)*** initiation times**,** ***(B)*** reach curvatures**,** ***(C)*** movement times, and **(*D*)** response times as function of Previous Congruency, Current Congruency, and Response Type for all participants in the Face-Word Stroop task. Error bars denote standard errors.

Curvatures.

With regard to movement curvatures, our main question of interest concerned the extent to which the effect of current congruency interacted with the remaining factors to generate trial sequence effects such as the CSE. We therefore evaluated four effects of interest: the main effect of current congruency; the interaction of current and previous congruency; the interaction of current congruency and response repetition type; and the interaction of current congruency, previous congruency, and response repetition type. A main effect of current congruency was observed, $F(1, 41) = 58.61$, $p < .001$ (Holm-Bonferroni adjusted *p*-value = .0125), $\eta_p^2 = .59$, with more direct movements on congruent trials ($M = .052$, $SE = .004$) than incongruent trials ($M = .079$, $SE = .006$). The interaction between current congruency and response repetition type approached but did not reach significance, $F(1, 41) = 5.77$, $p = .021$

(Holm-Bonferroni adjusted *p*-value = .0167) (see Figure 4B). The interaction between current congruency and previous congruency was not significant, $F(1, 41) = 2.43$, $p = .13$, nor was the three-way interaction between response repetition type, current congruency, and previous congruency also failed to reach significance, $F(1, 41) = 2.82$, $p = .10$.

Movement Times.

Movement times generally present patterns of effects similar to those observed in reach curvatures. Movement times revealed a significant main effect of current congruency, $F(1, 41) = 32.11$, $p < .001$ (Holm-Bonferroni adjusted *p*-value = .0125), $\eta_p^2 = .43$, with faster movement times on congruent ($M = 442$ ms, $SE = 13$ ms) than incongruent trials ($M = 455$ ms, $SE = 14$ ms). A significant interaction between current congruency and response repetition type was observed, $F(1, 41) = 11.61$, $p = .001$ (Holm-Bonferroni adjusted *p*-value = .0167), $\eta_p^2 = .22$. Follow-up analyses demonstrated that the effect of current congruency was significantly larger on response repeat trials ($M = 18.4$ ms, $SE = 2.9$ ms) than response switch trials ($M = 8.7$ ms, $SE = 2.7$ ms), $F(1, 41) = 12.34$, $p = .001$, $\eta_p^2 = .23$ (see Figure 4C). The interaction between current congruency and previous congruency was not significant, $F(1, 41) = 1.16$, $p = .27$. The three-way interaction between response repetition type, current congruency, and previous congruency failed to reach significance, $F(1, 41) = 0.18$, $p = .67$.

Response Times.

Response times revealed a main effect of current congruency, $F(1, 41) = 51.40$, $p < .001$ (Holm-Bonferroni adjusted *p*-value = .0125), $\eta_p^2 = .56$, with faster response times on congruent trials ($M = 945$ ms, $SE = 22$ ms) than incongruent trials ($M = 974$ ms, $SE = 24$ ms). The effect of previous congruency observed in initiation times was not significant in response times, $F(1, 41) = 4.27$, $p = .045$ (Holm-Bonferroni adjusted *p*-value = .0167), $\eta_p^2 = .09$, though response times were descriptively faster on trials preceded by a congruent trial ($M = 957$ ms, *SE* = 22 ms) than those preceded by an incongruent trial (*M* = 962 ms, *SE* = 23 ms) (see Figure 4D). No other main effects or interaction effects were observed in response times, including the interaction between current congruency and response repetition type observed in movement times, $F(1, 41) = 0.73$, $p = .40$.

Valence.

To evaluate the effect of facial expression valence on initiation times and curvatures, we ran a series of repeated-measures ANOVAs featuring current congruency (C vs. I) and valence (happy vs. angry). The main effect of valence and the interaction between valence and current congruency were of specific relevance. Initiation times did not reveal a main effect of expression valence, $F(1, 41) = 0.17$, $p = .68$, with positive (*M* = 510 ms, *SE* = 14 ms) and negative (*M* = 512 ms, *SE* = 15 ms) facial expressions generating similar initiation times. The interaction between valence and current congruency also failed to reach significance, $F(1, 41) = 0.39$, $p = .54$ (see Figure 5A).

Curvatures, however, did reveal a significant effect of expression valence, $F(1, 41) = 5.54$, $p = .023$ (Holm-Bonferroni adjusted *p*-value = .025), $\eta_p^2 = .12$, with more direct movements in response to the negatively valanced (angry) face, (*M* = .054, *SE* = .007) than the positively valanced (happy) face (*M* = .077, *SE* = .007) (see Figure 5B). The interaction between valence and current congruency was not significant in curvatures, $F(1, 41) = 0.67$, $p = .42$. Exploratory analyses evaluating the effect of valence on movement times and response times did not reveal main effects of valence or significant interactions between valence and current congruency.

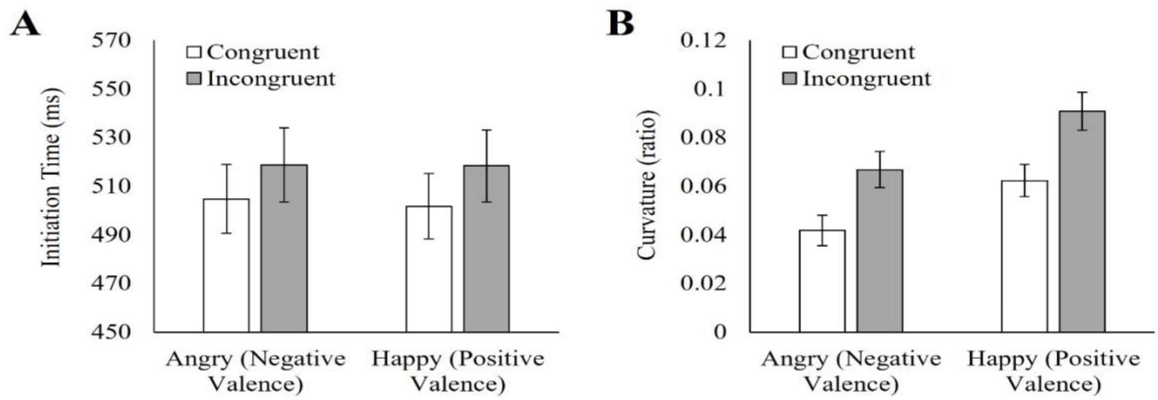

Figure 5. Average ***(A)*** initiation times and **(*B*)** reach curvatures as a function of Valence (negative versus positive) and Current Congruency (congruent versus incongruent) across trials. Error bars denotes standard errors.

Colour-Word Stroop

As with the Face-Word Stroop task, preliminary analyses were conducted to ensure that there were no unanticipated effects of mapping condition (i.e., whether red text colour was mapped to the left response and blue text colour was mapped to the right response, or vice versa) or task order (i.e., whether participants completed the Face-Word Stroop task before or after the Colour-Word Stroop task), with alpha set to .01. None of the measures revealed a significant interaction effect with mapping condition aside from initiation time, which is discussed in detail below. None of the measures revealed a significant interaction effect with task order.

Initiation Times.

Initiation times revealed a significant four-way interaction among current congruency, previous congruency, response repetition type, and mapping condition, $F(1, 40) = 7.68$, $p = .008$, $\eta_p^2 = .16$. Follow-up analyses evaluating each mapping condition separately revealed a main effect of current congruency alone in the Mapping A condition (blue mapped to the left, red to the right), $F(1, 20) = 9.00$, $p = .007$, $\eta_p^2 = .31$, with faster initiation times on congruent trials (M = 443 ms, SE = 17 ms) than incongruent trials (M = 459 ms, SE = 20 ms) (see Figure 6A). The Mapping B condition (red mapped to the left, blue to the right) revealed a significant interaction between current congruency, previous congruency, and response repetition type, $F(1, 40) = 7.91$, $p = .011$, $\eta_p^2 = .28$ (see Figure 6B).

Subsequent analyses evaluating response repetition and response alternation trials separately in the Mapping B condition revealed a significant interaction between current congruency and previous congruency in response repetition trials, $F(1, 20) = 9.24$, $p = .006$, $\eta_p^2 = .32$. A main effect of current congruency in trials preceded by a congruent trial was also observed, $F(1, 20) = 9.26$, $p = .006$, $\eta_p^2 = .32$, with faster initiation times on congruent trials (M = 425 ms, SE = 12 ms) than incongruent trials (M = 444 ms, SE = 16 ms). The effect of current congruency was not significant on trials preceded by an incongruent trial when a response repetition occurred in the Mapping B condition, $F(1, 20) = 0.73$, $p = .40$. No significant main effects or interaction effects were observed in response alternation trials in the Mapping B condition, p-values > .14.

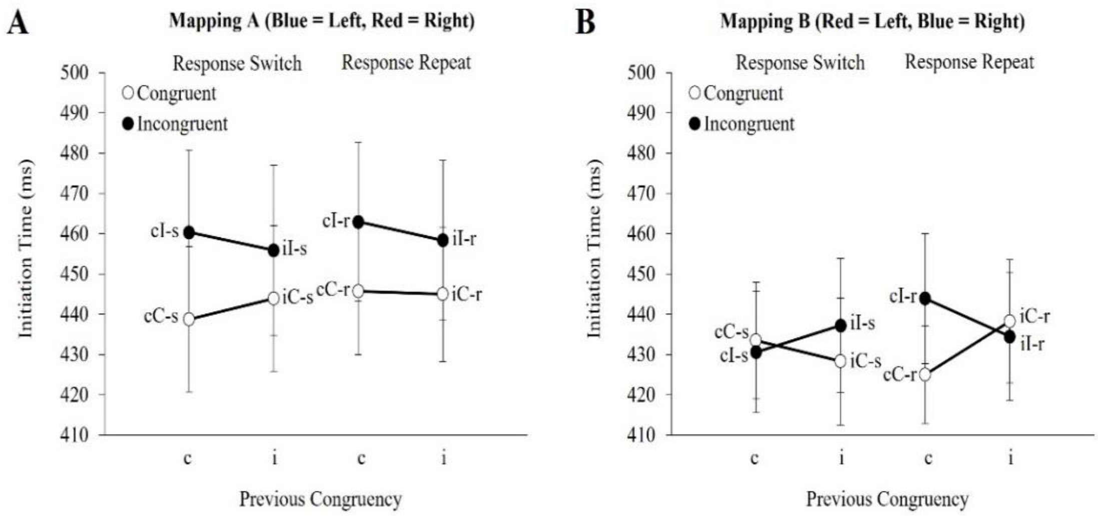

Figure 6. Average initiation times as function of Current Congruency, Previous Congruency, and Response Type for the ***(A)*** Mapping A condition and the ***(B)*** Mapping B condition in the Colour-Word Stroop task. Error bars display standard errors.

In sum, initiation times revealed an unanticipated effect of the mapping condition. Neither mapping condition showed the predicted pattern of effects (main effects of both current congruency and previous congruency). Instead, the Mapping A condition revealed a main effect of current congruency alone. In contrast, the Mapping B condition revealed a congruency sequence effect on response repetition trials and no significant main or interaction effects on response alternation trials.

Curvatures.

As in the Face-Word Stroop, our main question of interest with regard to movement curvatures in the Colour-Word Stroop concerned the extent to which the effect of current congruency interacted with the remaining factors to generate trial sequence effects such as the CSE. We had four effects of interest: the main effect of current congruency; the interaction of current and previous congruency; the interaction of current congruency and response repetition type; and the interaction of current congruency, previous congruency, and response repetition type.

Curvatures revealed a significant main effect of current congruency, $F(1, 41) = 36.94$, $p < .001$ (Holm-Bonferroni adjusted *p*-value = .0125), $\eta_p^2 = .47$, with more direct movements on congruent trials ($M = .046$, $SE = .004$) than incongruent trials ($M = .064$, $SE = .005$), and significant interactions between current congruency and response repetition type, $F(1, 41) = 13.69$, $p < .001$ (Holm-Bonferroni adjusted *p*-value = .0167), $\eta_p^2 = .25$, between current congruency and previous congruency, $F(1, 41) = 13.55$, $p < .001$ (Holm-Bonferroni adjusted *p*-value = .025), $\eta_p^2 = .25$, and between previous congruency and response repetition type, $F(1, 41) = 7.29$, $p = .010$ (Holm-Bonferroni adjusted *p*-value = .05), $\eta_p^2 = .15$.

Follow-up analyses evaluating the interaction between current congruency and previous congruency revealed no effect of previous congruency on congruent trials, $F(1, 41) =$

0.34, $p = .56$. A significant effect of previous congruency was observed on incongruent trials, however, $F(1, 41) = 14.62$, $p < .001$, $\eta_p^2 = .26$, with larger curvatures on cI trials (*M* = .073, *SE* = .006) than on iI trials (*M* = .057, *SE* = .004) (see Figure 7A). Follow-up analyses evaluating the interaction between current congruency and response repetition type revealed a larger congruency effect in response repetition trials, $F(1, 41) = 43.02$, $p < .001$, $\eta_p^2 = .51$ (*M* = .027, *SE* = .001), than in response alternation trials, $F(1, 41) = 9.98$, $p = .003$, $\eta_p^2 = .20$ (*M* = .010, *SE* = .0002).

Finally, follow-up analyses evaluating the interaction between previous congruency and response repetition type revealed a significant effect of response repetition type on trials preceded by a congruent trial, $F(1, 41) = 11.47$, $p = .002$, $\eta_p^2 = .22$, with larger curvatures on response repeat trials (*M* = .062, *SE* = .005) than response alternation trials (*M* = .050, *SE* = .004). The effect of response repetition type on trials preceded by an incongruent trial was not significant, $F(1, 41) = 1.89$, $p = .18$.

Movement Times.

Movement time results revealed a significant main effect of current congruency, $F(1, 41) = 14.91$, $p < .001$ (Holm-Bonferroni adjusted *p*-value = .0125), $\eta_p^2 = .26$, with faster movements on congruent trials (*M* = 436 ms, *SE* = 13 ms) than incongruent trials (*M* = 445 ms, *SE* = 14 ms) (see Figure 7B). The interaction between current and previous congruency did not reach significance in movement times, $F(1, 41) = 4.58$, $p = .038$ (Holm-Bonferroni adjusted *p*-value = .0167), $\eta_p^2 = .10$, in contrast to the effect observed in curvatures.

Response Times.

Response times revealed a significant main effect of current congruency, $F(1, 41) = 21.51$, $p < .001$ (Holm-Bonferroni adjusted *p*-value = .0125), $\eta_p^2 = .34$, with faster responses on congruent trials (*M* = 873 ms, *SE* = 21 ms) than incongruent trials (*M* = 893 ms, *SE* = 22 ms). A significant interaction between current and previous congruency was also observed, *F*(1, 41) = 10.79, *p* = .002 (Holm-Bonferroni adjusted *p*-value = .0167), η_p^2 = .21 (see Figure 7C). Follow-up analyses revealed no effect of previous congruency on congruent trials, *F*(1, 41) = 0.77, *p* = .384. However, a significant effect of previous congruency was observed on incongruent trials, *F*(1, 41) = 8.84, *p* = .005, η_p^2 = .18, with slower reaction times on cI trials (*M* = 898 ms, *SE* = 23) than iI trials (*M* = 888 ms, *SE* = 23 ms).

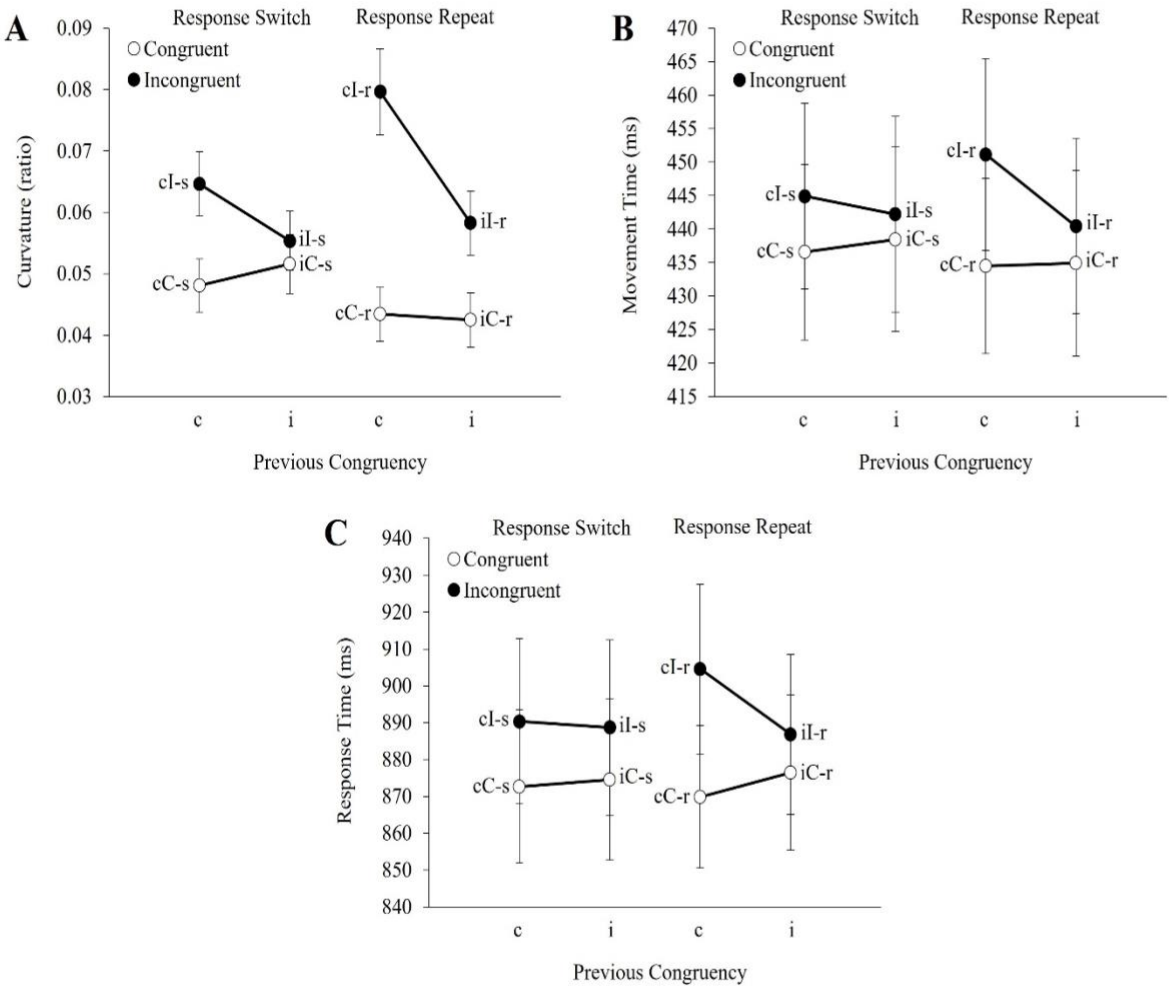

Figure 7. Average ***(A)*** reach curvatures, ***(B)*** movement times, and **(*C)*** response times as function of Previous Congruency, Current Congruency, and Response Type in the Colour-Word Stroop task. Error bars denote standard errors.

Correlation between Face-Word and Colour-Word Stroop Effects

To evaluate whether performance on the Face-Word and Colour-Word Stroop tasks was correlated, the correlation between the size of the congruency effect observed in each task was assessed for the measures of initiation time and curvature. Initiation times revealed a significant correlation effect, $r(1, 40) = .488$, $p = .001$. Inspection of a scatter plot (see Figure 8) indicated that this correlation was driven by an outlier. When this outlier was removed, the correlation was no longer significant, $r(1, 39) = .286$, $p = .070$. The congruency effects observed in curvatures were not significantly correlated, $r(1, 40) = -.054$, $p = .736$.

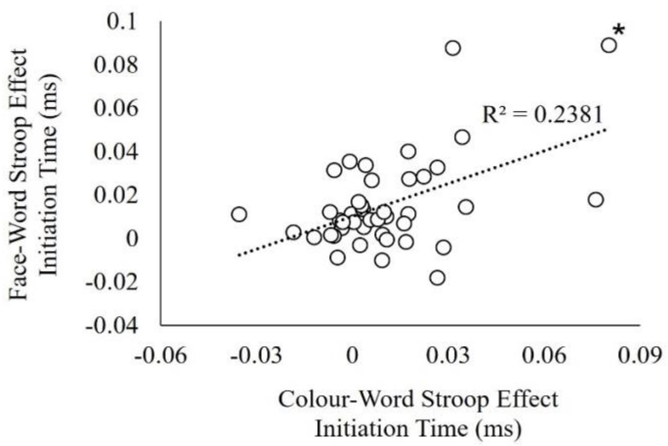

Figure 8. Scatter plot for the average initiation times congruency effects observed in the Face-Word Stroop and Colour-Word Stroop effects. Outlier denoted by asterisk.

DISCUSSION

Cognitive control is a critical human capacity that is broadly conceptualized as including the mental processes underlying the goal-directed control of thought, action, and emotion (Botvinick et al., 2001; Cromheeke & Mueller, 2014; Howieson & Lezak, 1995; Kalanthroff et al., 2015; Sullivan, 2015; Zelazo & Carlson, 2012). Emotions are central to the human experience and closely interact with our cognitions and behaviours (Crossfield & Damian, 2021). Research on cognitive control has predominately focused on performance of 'cool' tasks that feature minimal emotional engagement, as opposed to affectively laden or 'hot' tasks. The modular or traditional approach considers emotion and cognition as separate entities functioning independently, however, evidence from recent studies highlights a significant degree of functional interaction between cognitive control and affect or emotion (Dignath et al., 2020; Pessoa, 2008; Pessoa et al., 2012). Due to these interactions, there have been increased efforts to study the links between cognitive control and emotion using 'hot' or affectively laden and 'cool' or affectively neutral cognitive tasks.

The Stroop task (Stroop, 1935) has been used to understand cognitive control and, more contemporarily, the dynamics of cognition and emotions, making it a prime example of a congruency task that can tap into both neutral and affectively charged cognitive control processes. Hence, the Stroop task is an excellent task to investigate the interactive nature of cognition and emotions. Hand-tracking techniques such as reach-tracking have helped to inform our understanding of how continuous processes underlying cognitive control unfold over time (Erb, 2016). Reach tracking has been used to understand the underlying processes of the Stroop task (for example, Erb et al., 2018). However, reach-tracking techniques have not been used to the same extent to investigate the links between cognition and emotion in an emotional Stroop task.

The current study built on previous work investigating the links between cognition and emotion in the Stroop task by developing reaching tracking versions of a 2AFC 'cool' Colour-Word Stroop task and a 2AFC 'hot' Face-Word Stroop task. The study sought to address three primary questions. First, to what extent can the threshold adjustment process and controlled selection process be targeted behaviourally in the Face-Word Stroop task with measures of initiation time and reach curvature? If these processes supported performance in 'hot' versions of the task in the same manner as in 'cool' versions, we would expect to see distinct patterns of effects in initiation time and reach curvature corresponding to those observed in previous hand-tracking investigations of the Stroop task (for example, Erb et al., 2019; Erb et al., 2016). Second, to what extent does the valence of a facial expression impact performance in the Face-Word Stroop task? Finally, to what extent is performance on ‘hot’ and ‘cool’ versions of the Stroop task correlated? The aim for this question was to investigate whether the ‘hot’ and ‘cool’ versions of the Stroop task draw on shared cognitive resources that are stable within individuals. Although one may expect that performance on the tasks would tap into similar underlying capacities that are stable within individuals (for example, individual differences in conflict detection and resolution), multiple studies have failed to observe significant correlations between the congruency effects observed in ‘hot’ and ‘cool’ tasks (for example, Aite et al., 2015).

Face-Word Stroop Task

For the first question, our aim was to explore whether we could observe patterns of effects in initiation times and curvatures in the emotional Stroop task that have been linked to threshold adjustment process and controlled selection process in previous reach tracking research (Erb et al., 2016; Erb & Marcovitch, 2018). If initiation times in the emotional Stroop task reflected the threshold adjustment process, we predicted that initiation times would reveal significant main effects of current congruency and previous congruency. Consistent with these predictions, we observed faster initiation times on congruent than incongruent trials and faster initiation times on trials preceded by a congruent trial relative to those preceded by an incongruent trial. These findings indicate that the conflict generated on incongruent trials in the Face-Word version of the Stroop task impacts performance in much the same way as conflict in other congruency tasks, including the Colour-Word Stroop task, the Ericksen flanker task, and the Simon task (Erb & Marcovitch, 2018; 2019; Erb et al., 2019; Erb et al., 2016).

With regard to curvatures, we were particularly interested in interactions between the congruency of the current trial, the congruency of the previous trial, and the response repetition type of the current trial. Although the interaction between current congruency and response repetition type did not reach significance after we accounted for testing multiple effects of interest (p = .021, with a Holm-Bonferroni adjusted p-value = .0167), the congruency effect observed in response repeat trials was descriptively larger than the congruency effect observed in response switch trials.

This trend is consistent with previous hand-tracking research with the Ericksen flanker task indicating that the congruency effects observed in curvatures are larger on response repeat trials than response switch trials (for example, Erb & Marcovitch, 2018). Consequently, our findings provide some preliminary evidence that reach curvatures in the Face-Word Stroop task index the controlled selection task in a manner similar to other congruency tasks. However, additional research with a larger sample size would be required to make strong conclusions. It is also important to note that the interaction between current congruency and response repetition type was significant in movement times, adding further support to the idea that hand movements can be used to index the controlled selection process in the Face-Word Stroop task.

Response times in the Face-Word Stroop task showed a main effect of current congruency alone, with faster response times on congruent trials than incongruent trials. Interestingly, response times in the task did not show evidence of a CSEs, unlike previous research with the Face-Word Stroop task by (Egner & Hirsch, 2005; Egner et al., 2007). Egner and Hirsch (2005a) performed a Face-Word Stroop task with six facial stimulus values paired with three famous politician names and three famous actor names. In two versions of the same task, participants were instructed to categorise either the face or the name dimension of the stimuli as belonging to either the politician or the actor (Egner & Hirsch, 2005a). The researchers controlled for potential feature integration effects across both response repeat and response switch trials and observed substantial CSEs. Egner et al. (2006) have replicated a similar Face-Word paradigm and observed robust congruency sequence effects (Egner et al., 2007). Consequently, further research is needed to determine the conditions under which CSEs are observed in the Face-Word Stroop task.

Valence

Our second research question concerned the effect of valence on task performance in the Face-Word Stroop. Although some studies have found that negatively valenced faces are processed more rapidly than neutral or positively valenced faces (for example, Crossfield & Damian, 2021; Hansen & Hansen, 1994; Holtmann et al., 2014; Fox et al., 2000; Phaf & Kan, 2007; Öhman, 2001; Quan et al., 2020; Sternberg et al., 1998; Straub et al., 2021; Van Honk et al., 2001), others have reported that negatively valenced faces impair performance by, for example, increasing processing demands (for example, Batty & Taylor, 2003; Krolak-Salmon et al., 2004; Johnson et al., 2010; Lui et al. 2018; Palermo & Rhodes, 2007). Further, some studies have failed to observe differences in responses to positively or negatively valenced stimuli (for example, Beall & Herbert, 2008). The underlying question here was whether one valence of face was processed more rapidly than the other. Hence, to see how these dynamics interact with the threshold adjustment and control selection process, we assessed the effects of valence and congruency on initiation times and curvatures.

In terms of initiation times, one possibility was that negative stimuli would be registered as a type of conflict signal and lead to higher response thresholds and, consequently, longer initiation times for negative relative to positive stimuli. Our results show no effect of expression valence, with positive and negative facial expressions generating similar initiation times. In terms of curvatures, it was unclear whether positively valenced faces would be processed more rapidly than negatively valenced faces, negatively valenced faces would be processed more rapidly than positively valenced faces, or would the two would be processed at similar speeds. Our results suggested that the negatively valenced (angry) faces were processed more rapidly, with curvatures revealing that movements were significantly more direct on trials featuring the negatively valenced face than the positively valenced face, regardless of the trial's congruency.

There appears to be a gap in the valence effect literature in the emotional Stroop domain with extensive research on the comparison between positive and negative valence. On the one hand, many researchers believe that positively valenced facial expressions lead to a 'positivity bias' and enhance performance (for example, Batty & Taylor, 2003; Krolak-Salmon et al., 2004; Palermo & Rhodes, 2007). On the other hand, evidence from previous research (for example, Fox et al., 2000; Hansen & Hansen, 1988; Kauschke et al., 2019; Öhman et al., 2001; William et al., 2005) shows a 'pop' out effect of angry faces compared to happy faces due to a possible threat detection bias or increased cognitive processing (Beall & Herbert, 2008; Crossfield & Damian, 2021; Palermo & Rhodes, 2007; Öhman et al., 2001; Quan et al., 2020). Our curvature results appear to support this second collection of findings, with participants generating more direct hand movements when presented with the angry face.

Using a Face-Word Stroop task, Van Honk et al. (2001) presented participants with images of five male and five female faces showing neutral or negative facial expressions over led by red, green, blue and yellow coloured translucent foil. The participants were instructed to name the colour of the image while ignoring the facial expression and concluded that participants took longer to name the colour of an angry face rather than a neutral face. Our results mirror the same however provide additional evidence from a Face-Word Stroop task in a reach tracking experimental design.

Further exploratory analyses evaluating the effect of valence on movement times and response times did not reveal main effects of valence or significant interactions between valence and current congruency, highlight the value of assessing both the temporal and spatial components of responses, as the effect of valence would not have been observed in the current study if the spatial characteristics of reaching behaviour were not assessed.

Face-Word versus Colour-Word Stroop Task

Our third research question concerned the relation between performance on the Colour-Word Stroop task and the Face-Word emotional Stroop task. This question was addressed in three parts. First, we observed that overall error rates were very low on both tasks. Second, we evaluated the extent to which cognitive control, as indexed by the congruency effect, was related across the tasks. The results of our correlational analyses revealed some evidence of a link between the size of the congruency effect observed in initiation times in each task. However, this correlation was not significant after an outlier was excluded from analysis. Additionally, none of the congruency effects observed in our other measures approached significance in our correlational analyses. Consequently, the current study revealed weak evidence of a link between performance on 'hot' and 'cool' versions of the Stroop task, consistent with previous work by Aite et al. (2015).

Finally, we evaluated the extent to which the two tasks generated similar patterns of effects in initiation times and curvatures. However, comparison of performance on the two tasks was somewhat complicated by the presence of unanticipated mapping effects in the Colour-Word Stroop task. For the initiation times in the classic Stroop task, we predicted that initiation times in the Colour-Word Stroop task would reveal main effects of current congruency and previous congruency. Preliminary analyses evaluating the effect of mapping condition revealed a significant four-way interaction among current congruency, previous congruency, response repetition type, and mapping condition. No other significant interaction effects were observed in our preliminary analyses for either task in any of the measures.

To evaluate the effect of mapping condition on initiation times in the Colour-Word Stroop, we performed separate analyses on participants in the different conditions. The mapping A condition revealed a main effect of current congruency alone, demonstrating that the initiation times were faster in congruent trials versus incongruent trials.

In the mapping B condition, we found a classic CSE on response repetition trials and no significant main or interaction effects on response alternation trials. The interesting patterns of initiation times differed from our expectations and contributed to this significant effect. In light of previous hand-tracking research with the Stroop task (Erb et al., 2019; Erb et al., 2016), we anticipated that curvatures in the Colour-Word Stroop task would reveal a significant CSE. However, it was unclear whether the CSE would be specific to response repetition trials (as in the Ericksen flanker task) or be present in both response repetition and response switch trials (as in the Simon task).

A robust interaction between current congruency and previous congruency was observed, demonstrating a clear CSE in curvatures. The lack of a significant interaction among current congruency, previous congruency, and response repetition type further indicated that the CSE was not specific to response repetition or response switch trials. Follow-up analyses confirmed that there was no difference between cC and iC trials, but curvatures were significantly larger on cI than iI trials. Thus, the patterns of effect observed in reach curvatures in the 2AFC Colour-Word Stroop task are similar to those observed in the Ericksen flanker task in that curvatures are uniformly low on congruent trials but elevated on cI relative to iI trials (cC = iC < iI < cI). However, the patterns of effect observed in the Colour-Word Stroop are also similar to those of the Simon task because the CSE is observed in both response repetition and response switch trials.

As is illustrated in Figure 9, results from the Ericksen flanker task (Erb et al., 2016) showed that the CSE was larger in response repeat trials and not present in response switch trials. Additionally, the CSE observed in the Ericksen flanker task is driven by larger curvatures on cI-r relative to iI-r trials and no effect of previous congruency on congruent trials (see Figure 9B). In contrast, results from the Simon task (Erb & Marcovitch, 2019) showed a CSE in both response repeat and response switch trials. Also in contrast to the Ericksen flanker data, a significant effect of previous congruency was observed in congruent trials, with larger curvatures on iC than cC trials(see Figure 9C).

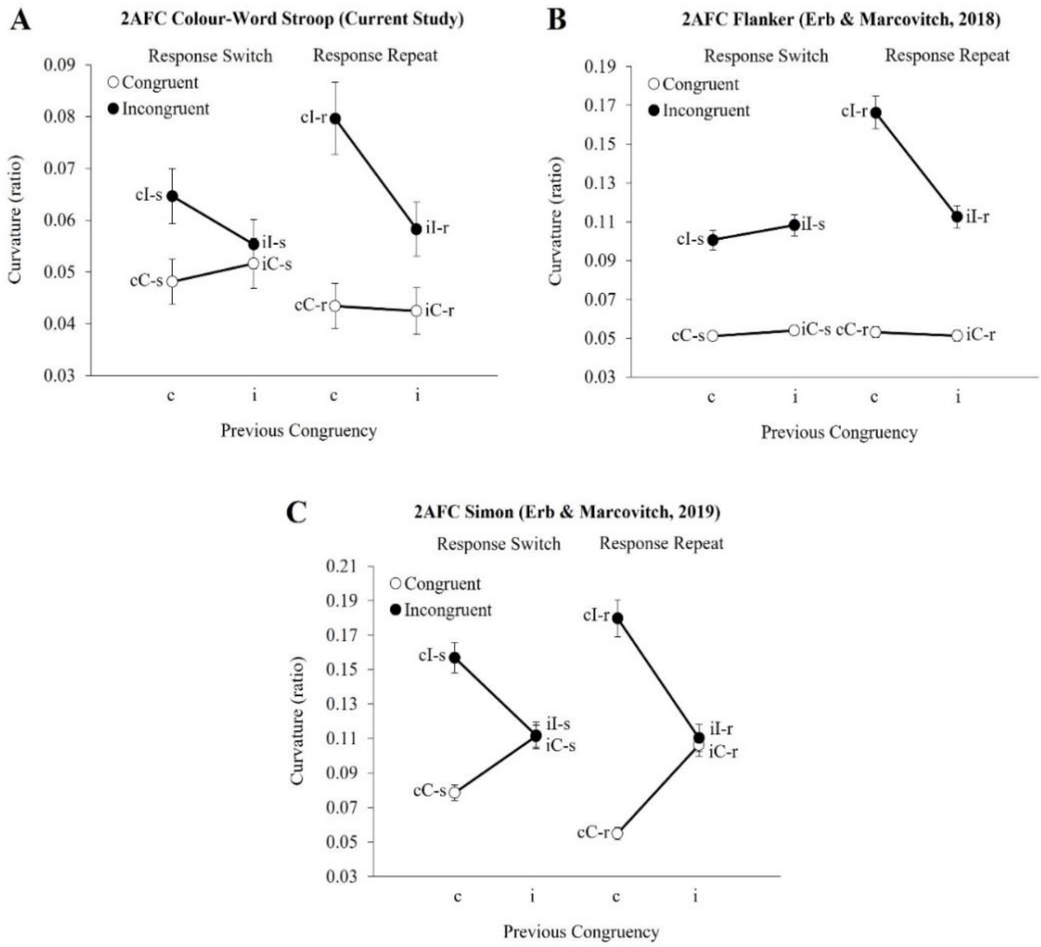

Figure 9. Average reach curvatures as a as function of Previous Congruency, Current Congruency, and Response Type in the ***(A)*** 2AFC Colour-Word Stroop task (current study), ***(B)*** 2AFC Ericksen flanker task (Erb & Marcovitch., 2018), and ***(C)*** 2AFC Simon task (Erb & Marcovitch., 2019).

Since curvatures in the Colour-Word Stroop task do not show larger curvatures on iC trials than cC trials, our findings indicate that the CSE observed in the Stroop task is partially similar to that of the Ericksen flanker task. However, given that the CSE observed in curvatures in the Colour-Word Stroop task was not specific to response repetition trials, our findings also indicate that the Stroop CSE is partially similar to the CSE observed in the Simon task.

Research by Schmidt and Houwer (2014) posit that like the Stroop task, similar congruency effects can also be observed in the Simon task (Simon & Rudell, 1967), where the localized response (for example, a left key press) is interjected with an irrelevant distracting location (for example, right). Hence the congruency effect in the Simon task represents an S-R overlap (Egner, 2007). Like the Stroop and Simon task, the Ericksen flanker task also showcases congruency effects (Ericksen & Ericksen, 1974). The congruency effect can be observed when an irrelevant flanking letter interferes with one's response to the target letter (for example, target "c" along with a distracting "b" on both sides).

The congruency effect in the Ericksen flanker task also represents a S-S overlap but relative to the Stroop task, the overlap occurs at a perceptual level (Egner, 2007; Nieuwenhuis et al., 2006). Therefore, our results build on previous work investigating differences among congruency tasks by providing more detail regarding the within-trial and cross-trial dynamics within the Colour-Word and the Face-Word emotional Stroop tasks. Our findings indicate that the Stroop task data falls somewhere in the middle of the Ericksen flanker and Simon task data.

Additional Considerations

As the previous section makes clear, the patterns of effects observed in the Colour-Word Stroop task and the Face-Word Stroop task show similarities and differences with regard to the patterns of effects observed in other congruency tasks. Our choice to use a 2AFC Colour-Word Stroop task and a 2AFC Face-Word Stroop task raises important questions. One potential question concerns the comparability of a Colour-Word Stroop task and the Face-Word Stroop task. Why did we choose the Face-Word variant and not a Colour-Word emotional Stroop variant like Algom et al., (2004), Chajut et al., (2010), Has et al. (2006), or Song et al. (2017)?

The Face-Word version of the emotional Stroop has been found to be similar in many respects to the Colour-Word Stroop task. However, it has been criticized for not directly being analogous to the Colour-word Stroop by Algom et al. (2004). According to a critique by Algom and colleagues (2004), the congruent and incongruent conditions in both the tasks are not analogous due to the nature of the stimulus presented (for example, colour words and emotional words respectively), and hence the emotional Face-Word Stroop does not qualify as a true Stroop task. Koizumi et al. (2007) examined a ‘Stroop asymmetry’ between the two tasks to assess this claim. They evaluated whether the Face-Word Stroop with superimposed emotional words on facial expressions is analogous to the traditional Stroop. They controlled for task type (naming) and relative saliency between two stimulus elements (word and facial expression) and concluded that the Colour-Word Stroop task and the Face-Word Stroop task do indeed share analogous processing (Koizumi et al., 2007).

Many experiments have used the Face-Word Stroop task to investigate the automatic processing of emotional images. While scanning our dynamic and complex visual environment, humans encounter a host of different incoming stimuli which need to be filtered down to be processed correctly. This requires a series of processes that establish the importance of certain stimuli over the rest. A primary way of determining the significance of the incoming stimulus is by identifying the emotional significance of the stimulus or event (Compton, 2003 as cited in Palermo & Rhodes, 2007).

Compton (2003) extends this notion by arguing that the emotionally significant stimuli receive enhanced processing via two attentional mechanisms – one which evaluates emotional significance automatically, and the other which gives this stimuli priority in selective attention. Faces are considered the most biologically, evolutionarily, and socially significant stimuli and therefore are expected to receive enhanced processing by these two mechanisms (Compton, 2007; Palermo & Rhodes, 2007; Öhman, 2002; Zhu et al., 2010). Expressive faces, especially happy or angry faces, demand more awareness and are therefore registered faster as compared to other emotions with lower arousal values such as sadness (Fox, 2002; Vuilleumier & Schwartz, 2001).

For instance, Beall and Herbert (2008) presented participants with emotional words overlaid on images of different facial expressions (for example, a happy or angry facial expression). The participants were instructed to either identify the emotional word or the emotion of the facial expression separately to examine the degree of interference for both stimuli. The results indicated more significant and robust interference effects in word processing than face processing. This means that by taking automaticity and interference effects into account, incongruent distractor faces impaired performance more than incongruent distractor words (Beall & Herbert, 2008).

Compton (2003) reviewed different electrophysiological studies and suggested that the emotional value of words is encoded comparatively later in the brain versus facial expressions (Phaf & Kan, 2006). These results corroborate that participants process emotional faces or images more automatically or quickly than affective words. Beall and Herbert (2008) reported a prominent reason for this finding is because faces have more social and biological value mirroring Compton's (2003) findings.

A second question that can be raised about the emotional Stroop task used in the current study concerns why an angry face was used instead of another negatively valenced emotion. The reason anger was selected over an alternative emotion like sadness is because of differences in the automaticity and the arousal value of angry versus sad faces. Beall and Herbert (2010) found that angry facial expressions are processed more automatically than sad facial expressions, suggesting qualitative differences in the two emotions' threatening and non-threatening arousal dimensions. Both anger and happiness are highly arousing emotions with important implications for survival (Russell, 1980, cited in Beall & Herbert, 2008). Happiness signals 'approach' behaviour through affliction or mating potential, and anger warns of danger and elicits a 'withdrawal' behaviour. Consequently, angry and happy were selected as the emotions of interest for the current study, though future hand-tracking work could explore a wider range of emotional expressions.

Limitations and Future Directions

Previous research in the Stroop domain has shown that level of sleep deprivation, fatigue and affect has significant effects on cognitive control and consequently performance (for example, Cain et al., 2011; Gever et al., 2015; Rauch & Schmitt, 2009). Gevers and colleagues (2015) performed a Stroop task to understand the effects of sleep deprivation on top-down cognitive control and concluded that like previous research (for example, Anderson & Platten, 2011; Basner & Dinges, 2011; Lo et al., 2012; Muto et al., 2012; Roca et al., 2012 as cited in Gevers et al., 2015) less sleep impairs ones top-down cognitive control mechanisms in a way that cognitive control no-longer increases upon detection of conflict in the preceding trial. In the current study, we did not account for levels of sleep or fatigue as part of a pre-task assessment which could possibly have an effect on our results.

Due to its holistic approach in understanding cognition and emotion, the emotional Stroop task lends itself as a tool of choice for diagnosing a plethora of pathologies. From generalized and trait anxiety (for example, Coombes et al., 2009; Mogg & Bradley, 2005; Rocher & Pickering, 2017; Phaf & Kan, 2007) to obsessive-compulsive disorder (for example, Vasterling et al., 2004), social phobias (for example, Andersson et al., 2006), depression (for example, Mogg & Bradley, 2005) and posttraumatic stress disorder (for example, Constans et al., 2004).

A selective slow-down associated with threat, emotion, and pathology is a commonly observed pattern in these studies (Chajut et al., 2010). The same pattern has also been observed in other studies in addition to the ones mentioned above, such as Algom et al. (2009) and Bar-Haim et al. (2007). In addition to sleep and fatigue, the current study did not account for other forms of baseline psychometric testing before the task. Future studies can perhaps incorporate the same into the experimental design for more robust findings in a reach-tracking paradigm.

Another important limitation of the current study concerns the participants' English-language understanding and usage. In order keep all variables like age group, cognitive impairments, right-handedness and normal vision consistent with the diverse participant pool, our inclusion criteria was only English speakers. One rationale for the diverse dynamics across tasks, could be that the semantic significance of the emotional or colour word stimuli presented, could be interpreted in another language if the participant did not have English as their first language.

The main idea is that although all of our participants understood English, we had a very diverse sample and many of our participants were likely to have had a different language as their first and primary language. Consequently, the results of our Colour-Word Stroop task may have been impacted by language background. The idea that one can think in their first language and perform a task with a different language was perhaps causing an interference in performance. This paves way for another aspect that future studies can focus on – the effect of bilingualism on performance of the Stroop versus an emotional Stroop task in a reach tracking experimental design. It could possibly be interesting to explore the cross trial dynamics if the above mentioned variables can be controlled better across the tasks.

As an extension to the above-mentioned limitations, one of the main drawbacks of the current study, which can be mitigated for future research, was the presentation of only two choices of emotions and colours. As mentioned before, we used a two alternative forced choice Stroop and emotional Stroop task however previous research which made use of multiple stimuli (both target and distractors) have reported more robust findings for the cross-trial dynamics. More specifically, we used two facial expressions for the emotional version of the task and previous influential research such as Egner et al. (2008) has made use of multiple emotional facial expressions as stimuli. Our rationale for using only two facial expressions and two target colours was to keep the tasks similar and to equate the tasks in terms of potential feature-integration effects.

We only used male faces and we only had one angry face, so the effect of valence may have stemmed from the specific face we used. The limitation of our choice of only two facial expressions of one male face directly integrates itself in the lack of generalizability of our results. One can propose a similar study, understanding the dynamics of the Stroop in a reach tracking paradigm while introducing more robust stimuli such as more facial expressions (i.e., covering more emotions and more genders) and more colour stimuli (i.e., covering more target and or distractors). This would not only increase the generalizability of the results but would also lead to more robust findings which capture more stimulus pairings and hence more congruency effects.

The current study did not account for the developmental differences in performance due to our strict inclusion criteria. Previous research on 'hot' versus 'cool' cognitive tasks take into account different age categories to increase the comparability and generalizability of the task. Within the hot cognitive control paradigm, on the one hand, via an emotional Stroop task, Zelazo and Carlson (2012) suggest that there is a linear pattern of development of affectively charged cognitive control abilities. Essentially pointing to the findings that hot cognitive control abilities get increasingly more specific with age. On the other hand, in sharp contrast to Zelazo and Carlson's (2012) model, Aite et al. (2015) hold that there is a 'U' pattern of development wherein adolescence marks a specific time window for low cognitive control abilities in affectively charged contexts (Somerville et al., 2014). Since we did not investigate the specifics of how age impacts performance in the two tasks, future studies can use our study as a steppingstone and add in different age groups for more robust findings.

Automaticity/Prepotency Effects

Our 2AFC tasks added to the emotion-cognition literature however did have a couple of limitations and future implications which have been mentioned above. Apart from these, an interesting scope that we wished to explore through our study was to uncover which of the two presented stimuli (i.e., colour and word in the Colour-Word Stroop and facial expression and word in the emotional Stroop) had more pre-potency in the responses. The aim here was to find out which of the two stimuli lead to a more automatic response. In previous research of the Colour-Word Stroop task, the automatic response is rather clear, the word presented has more prepotent response than the colour stimuli. However this understanding is not so clear in the emotional variant of the Stroop task. It is unclear if the facial expressions are processed earlier and exert more prepotent effect or if the words are processed earlier and exert more prepotent effect.

We wished to explore this gap in the literature through our valence related question of the emotional Stroop task. In our Face-Word Stroop task, we instructed the participants to focus on the facial expression while completely ignoring the emotion word presented underneath it. This was done to increase the comparability between the two variants of the Stroop task as in the Colour-Word Stroop task the instructions are to ignore the meaning of the word while focusing only on the colour of the word. But there is a possibility that faces are processed more rapidly than the meaning of the word.

In our results we observed significant conflict and congruency effects when both the faces and words are incongruent and against one another. However, it is unclear which of the two stimuli have a faster and more automatic response as compared to the other. Previous research on an emotional Face-Word Stroop has found evidence that individuals process emotional faces or images more automatically or quickly than affective words (Compton., 2003; Beall & Herbert, 2008; Öhman, 2002). Our results do not add to this cohort of research however does report significant congruency effects and open the doors for future reach-tracking research to uncover these dynamics within-stimuli of the Face-Word variant of the Stroop task.

Ongoing follow-up research in the CMND lab of the University of Auckland is extending the current study by building on the limitations mentioned above. This ongoing research seeks to investigate the emotional Stroop cross trial dynamics in a reach tracking paradigm in a more generalisable manner. Unlike the current study, the study includes happy and angry facial expressions from eight males and eight females in order to evaluate the generalisability of the valence effect observed in the current study. The study is also designed to investigate the relative speed with which word and faces are processed by comparing contrasting a condition in which faces act as a distractor with a condition in which emotion words act as a distractor. The aim is to understand which of the two stimuli has more prepotency and consequently larger effects which was not covered in the current study.

Methodological Implication for Future Research

As well as the above mentioned implications, the current study also presents important methodological implications for future research investigating the links between cognition and emotion. Traditionally, in cognitive psychology, the interaction between cognition and emotion has been experimentally explored with relatively constrained, button-press responses. However, such behavioural techniques do not pick up on how interactions between emotion and cognition unfold over time. As noted by Gallivan and Chapman (2014), one of the benefits of reach tracking is that the technique can be used to study responses to real physical objects in the participant’s environment. Additionally, in contrast to mouse tracking, reach tracking does not require participants to perform ‘visuomotor transformations’ such as the ones needed to translate physical movements of computer mouse into the digital cursor (Erb, 2018). I think it's essential to have more continuous behavioural measures which tap into the processes underlying performance in behavioural tasks.

The current study provides a novel and integrative way of looking at emotion and cognition on the same continuum. The two measures of initiation time and curvatures in reach-tracking provide us an exciting direction for congruency tasks such as the Stroop task by tapping into the continuous dynamics which unfold over time in one's performance through the threshold adjustment and controlled selection process. Other behavioural measures such as mouse-tracking (for example, Freeman & Ambady, 2010), button-pressing (Abrams & Balota, 1991), and other face-processing techniques which resemble the dynamics of the reach-tracking technique also provide a new way to look at assessing performance and opens up opportunities to better understand how emotion and cognition interact. Our study, even with its limitations has proven to be a good measure to bridge the gap between 'hot' and 'cool' cognitive control tasks via a sophisticated reach-tracking experimental design opens up opportunities to better understand how emotion and cognition interact.

CONCLUSION

In conclusion, the results of the present study fits in the overarching emotion-cognition debate wherein we saw interesting and robust congruency effects between the Colour-Word and Face-Word Stroop task. We demonstrate that reach tracking can be used to target different patterns of effects in initiation times and curvatures in an emotional Stroop task, indicating that these the task engages the threshold adjustment process and controlled selection process in a manner similar to other "cool" cognitive control tasks. We did not see a correlation between the congruency effects observed in both the versions of the task and we only observed CSEs in the Colour-Word version of the Stroop task. Intriguingly, we do observe that reach movements were more direct when responding to an angry as opposed to a happy face, suggesting that at least some negatively valenced facial expressions are processed more rapidly than positively valenced facial expressions. However, more work is needed to investigate this valence effect, as the current study featured a small number of faces. Finally, the results of the current study contribute to our understanding of how the Stroop task relates to other congruency tasks, indicating that the within- and cross-trial dynamics observed in the Stroop fit somewhere in between those observed in the Eriksen flanker task and the Simon task. Consequently, this study establishes a helpful foundation for future hand-tracking research investigating the links between cognition and emotion to build on.

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