Surprise! Electromyographical and Behavioural Reactions to Unexpected Events

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Statement of Sources

I declare that this report is my own original work and that contributions of others have been duly acknowledged.

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Callum Hugh Kilpatrick, October 20th, 2021

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Abstract

Inhibitory control, the ability to inhibit movement, is a vital component of everyday executive functioning. The current study creates a novel version of the stop signal task and go/no-go task where participants are required to respond with both hands to changing stimuli which require either a go response (button press) stop/no-go response (inhibit button press) or ignore response (continue current response). Behavioural responses such as RT and accuracy as well as physiological responses using electromyography were taken to assess inhibitory control within the context the pause then cancel model and unexpected events as a factor of inhibition. 24 participants (Mage = 24.5 years) completed four experimental conditions where generalized linear mixed models were used to assess results finding that the addition of an unexpected ignore signal had similar effects as a signal which required stopping, however this effect was minimised in conditions where there was no possibility of stopping required. It was also discovered that participants implemented a proactive method of inhibition in conditions where stopping was required.

Every day, we find ourselves in scenarios where something unexpected occurs rather than what we anticipated. These situations often require us to stop and reconsider the most appropriate course of action for whatever task it is we are attempting to achieve. These are often trivial incidences such as noticing an insect when reaching for your keys or spotting a puddle in front of your step, but also apply to situations with greater consequences such as noticing a pedestrian crossing the road while turning a corner in your car. The context of sport is another example where you have to regularly attempt to predict a course of action yet require the ability to stop, or change, your movement as the information you have is updated. Beginning to swing at a baseball pitch before deciding it's outside the strike zone and stopping to leave it for the catcher or having to change the direction of your run after an unexpected bounce in football are further examples of when an individual has to adjust their actions to unexpected changes in the environment. In each case, a neural mechanism is required to rapidly stop your initial course of action and, if appropriate, allow an alternative action to take its place. This process is broadly described as inhibitory control and is a vital component of adaptive behaviour in our everyday lives (Sebastian et al., 2020).

Appropriate behaviour in an ever-changing environment requires constant correcting of actions. Inhibitory control plays a crucial role in this execution of proper executive functioning. Understanding the neural basis of this process provides significant value in understanding clinical groups with challenges in inhibitory control. Indeed, a number of disorders have been shown to involve deficits in inhibitory control including autism spectrum disorder (Schmitt et al., 2017), attention-deficit/hyperactivity disorder (Mulligan et al., 2011), obsessive compulsive disorder (Chambers et al., 2009), and schizophrenia (Ettinger et al., 2017). Inhibitory control has also been shown to decline as a result of ageing (de Bruin & Sala, 2018). Understanding the mechanisms of effective inhibitory control in healthy individuals allows us to understand the deficits present in people with compromised

inhibitory control by comparing between the two. A greater understanding of the process of inhibitory control could therefore lead to more effective interventions and treatments for these groups of people in assisting their executive functioning, particularly targeting dysfunction in inhibitory control.

Assessment of inhibitory control

Not only does inhibitory control refer to the inhibition of movement, but also includes inhibition of thoughts and verbal responses as well. Extensive literature exists on the mechanisms involved in inhibition of speech and thought which provide insight into that specific area of executive functioning. An inability to inhibit intrusive thoughts and compulsions as seen in obsessive compulsive disorder, for example, is an indication of lack of inhibitory control (Abramovitch & Cooperman, 2015). While inhibitory control in this context is an important component, here specifically, we are focusing on inhibitory control within the context of inhibiting movement.

The assessment of motor inhibition has historically been made in laboratory-based settings using tasks such as the stop signal task (SST) and go/no-go task (GNGT). The GNGT requires participants to either make a response to the imperative go stimulus or refrain from responding to the no-go stimulus. The GNGT and its implications is a well-studied area with a version of the task being studied as early as 1868 by Donders (1868/1969). The SST developed by Logan and Cowan (1984) has a similar basic design, again requiring participants to respond as quickly as they can to an imperative go stimulus, however on occasional trials the go stimulus changes after some time delay to a stop stimulus (e.g., change of colour) which requires the participant to attempt to cancel their initiated response. The timing of the stop signal delay (SSD) (the time between presentation of the go and stop stimuli) can be adjusted depending on whether a participant was able to successfully stop their previous response (a longer SSD makes stopping more difficult) and is tailored to the

individual participant such that they can successfully stop on 50% of trials. Staircasing in this manner allows researchers to compare the efficiency of inhibitory control across individuals, groups of individuals, or across various task conditions or contexts. Critically, for both the SST and GNGT, the stop or no-go stimulus is presented infrequently (relative to the go response) such that there is an expected go response, and the stop stimuli is *unexpected*. The lower the proportion of stop trials presented the more difficult it is to inhibit an action. (Verbruggen et al., 2019).

The obvious difference between the two tasks is that SST requires countermanding of the initiated response (often termed *action cancellation*) while in the GNGT the stimulus requires the participant to immediately discern whether to respond or not respond (*action restraint*) and is thus a balance of preparing to act and respond quickly versus being able to inhibit that response (Schachar et al., 2007). While both tasks require inhibiting an action, there is a lack of consensus over whether a broad construct of inhibition exists that is able to fully explain the neural processes required for both tasks or whether a range of different processes are recruited depending on the context within the execution of inhibitory control is required (Raud et al., 2020).

A criticism of the GNGT is whether it is more closely linked to a choice reaction time task (which shows that as the number of possible responses and stimuli increases, so does reaction time) (Hasbroucq et al., 1999), or whether it is in fact a good measure of motor inhibition. Raud et al. (2020) compared the two tasks, finding that the inhibitory process in the GNGT was much slower (compared to the SST) and more closely related to a choice reaction task, concluding that the two tasks assess different independent inhibitory control networks and employ distinct stopping mechanisms (Raud et al., 2020). A possible issue of using the SST to study inhibitory control is that it requires the use of goal oriented proactive inhibition, whereby an individual attempts to anticipate the need to stop and primes their

sensory-motor system in preparation for the stop signal (Wessel, 2018). However, real world examples of inhibitory control require reactive inhibition which is driven by dynamic reaction following the detection of a changing environment as opposed to proactive inhibition (Jahanshahi et al., 2015). The degree to which lab-based findings relate to real world examples of inhibition could therefore be questioned which has led to a new framework to be developed.

Neuroimaging research which has used functional magnetic resonance imaging (fMRI) to assess the neural networks activated in both the SST and GNGT found that there is a degree of overlap of networks activated in both tasks (Levy & Wagner, 2011, Aron et al., 2014). A uniform fronto-basal-ganglia network has been shown to be associated with stopping and recruits the right inferior frontal cortex (rIFC), pre-supplementary motor area (pre-SMA) and subthalamic nucleus (STN) within the basal ganglia (Tatz et al., 2021). While there appears to be some overlap in networks, other research has found significant distinctions in brain activity between the two tasks. Rubia et al. (2001) found that activation in the GNGT was found predominantly in the left hemisphere, particularly in the medial, mesial, parietal, and inferior frontal cortices while the SST activated predominantly right hemispheric supplementary motor area, anterior cingulate, parietal and inferior frontal cortices. While the two tasks do broadly activate similar brain areas, there is a clear difference between the brain regions activated during the tasks, suggesting a degree of independence in the neural mechanisms utilised in both inhibition tasks.

Proactive versus reactive inhibition

Inhibitory control has previously been thought of as a single stimulus driven reactive mechanism, however recently inhibitory processes have been distinguished into separate reactive and proactive inhibitory processes (Meyer & Bucci, 2016). Reactive inhibition examines an individual's ability to stop their initial response when a stop cue is presented

after the initial response has begun and is generally reflected in the literature as their stop-signal reaction time. Inhibitory control can also be aided by proactive mechanisms, however, whereby prior knowledge of an increased likelihood of needing to inhibit a movement can increase the efficiency of response inhibition through predicting a need to stop (Verbruggen & Logan, 2009). We constantly take in vast amounts of cues which allow us to make appropriate movements, these cues can also inform the possibility of needing to inhibit a movement and thus increase our ability to inhibit a movement. An example where proactive inhibition is employed could include spotting a ball rolling across the street while driving. While the ball itself doesn't require you to inhibit your action it primes you to have a higher alertness to the possibility of needing to inhibit an action in response to the imperative stimulus of a child chasing after it. Thus, your chances of braking and not hitting the child are likely increased having seen the ball, compared to a situation where you didn't see the ball and a child unexpectedly ran out in front of you. Findings have suggested that inhibitory control can occur through both proactive and reactive processes, and that these two processes can interplay depending on the context that inhibitory control is required (van Belle et al., 2014). A hyper-direct and indirect pathway distinction has also been made between reactive and proactive inhibition where a reactive, hyper-direct pathway is employed to stop all ongoing action in response to an unexpected cue. This hyper-direct process potentially inhibits all ongoing motor output as an efficient way of allowing time to interpret the cue (Aron, 2011). The indirect proactive pathway of inhibitory control involves a more complicated, and thus slower (as it involves connections through more subcortical structures), pathway that considers prior knowledge and environmental cues to stop when needed and can potentially allow for selective stopping, where one movement is inhibited while other movements continue to be enacted (Aron, 2011).

Within the context of the stop-signal task, participants may employ a proactive stopping strategy to increase their ability to stop to the 'stop' signals. Behaviourally, this results in a response delay where participants slow down their responses to 'go' signals in anticipation of needing to stop (Jahfari et al., 2010). By comparing participant's reaction times on 'go' trials where there is no possibility of 'stop' trials occurring, to their reaction times on 'go' trials where stop signals are present on some trials, it is possible to discern the degree to which participants have employed a proactive strategy to response inhibition. In the same task, reactive inhibition is measured through the stop signal reaction time (SSRT), which is an index of how efficiently (quickly) stopping occurs once a stop signal is present. SSRT will be explored more in later sections.

global versus selective stopping

Another key dimension in inhibitory control is understanding the different processes involved in global inhibition versus selective inhibition. Global inhibition refers to the cancellation of all initiated movements, regardless of if the movement is goal related or relevant to the stimuli which caused the inhibition. In contrast, selective inhibition refers to cancellation of specific movements while continuing the execution of other movements (Coxon et al., 2007). Everyday scenarios of inhibition generally require a selective inhibitory process as the most appropriate course of action. Spotting a puddle in front of you while walking and texting for example requires you to inhibit your stride but doesn't require inhibition of your texting thus a mechanism is required to selectively inhibit one aspect of action and continue the other (Aron & Verbruggen, 2008). Two main models which describe the mechanisms of selective inhibition have been suggested (Raud et al., 2020). The first proposes that a global inhibition of the motor system occurs via the hyper-direct cortical-subthalamic nucleus pathway before movements which didn't require inhibition are reactivated (Wessel and Aron, 2017). Evidence for this theory can be observed in modified

versions of the stop-signal task which require selective inhibition – specifically, participants make bimanual responses (i.e., simultaneous presses with left and right hands) to the go stimuli, and stop stimuli require only the left or right hand's response to be inhibited, while the other hand continues to respond. Findings indicate that successfully inhibited selective stop trials result in significant slowing in response times of the hand which wasn't required to stop as well as observable inhibition in EMG profiles (MacDonald et al., 2012).

The second theory suggests that distinct mechanisms exist depending on the requirement of selective or global inhibition. Recognition of environmental cues which suggest the increased probability of selective inhibition being required elicits a proactive inhibitory approach which recruits the slow, indirect corticostriatal pathway (Raud et al., 2020). The recruitment of this mechanism slows down stop-signal reaction time (i.e, less efficient reactive stopping) while also reducing the stop-signal interference effect (the reaction time difference between the ongoing, non-cancelled response on 'selective stop' trials and the bimanual response on 'go' trials) (Aron & Verbruggen, 2008). Studies have also found that through practice, selective inhibition can be achieved in choice reaction tasks without a selective cost, furthering the possibility of a distinct selective inhibitory mechanism (Xu et al., 2015). While some studies have found evidence for a distinct selective stopping mechanism, many other articles have not found such effect (Bissett & Logan, 2014). Whether separate mechanisms actually exist for the execution of global versus selective inhibition therefore remains unclear (Munakata et al., 2011).

Surprise framework

More recently, the addition of "unexpected events" has been used to examine inhibitory control within both the SST and GNGT. The unexpected – or surprise - event refer to stimuli which are different to the go stimulus, in that they occur less frequently than the go stimuli (i.e., in a similar proportion to the stop stimuli) but which *don't* require the participant

to inhibit their movement – that is, participants simply ignore the stimulus and respond as they would have done to a go stimulus. Intriguingly, however, findings suggest such stimuli elicit a significant slowing in reaction time in choice reaction tasks. (Waller et al., 2019, Wessel & Aron, 2013). This slowing suggests that stimuli which do not command stopping still result in some type of pause or inhibition of action, before the action is undertaken at a delayed time. These characteristics are similar to those seen in the selective stopping tasks, where delays are observed in the non-stopping hand. It could be hypothesised, therefore that unexpected stimuli, regardless of whether they require inhibition or not, elicit a similar neural response in regard to action inhibition, prior to commanding the re-assessed response (i.e., stop, or continue to respond). Further work is required to determine whether this is indeed the case, or whether cognitive processes differ between required action stopping as opposed to inhibition in reaction to an unexpected stimulus (Tatz et al., 2021). To improve the framework that inhibitory control is examined in, Wessel (2018) suggested that unexpected stimuli which don't necessarily require inhibition should be used to study inhibitory control as it is better at eliciting a realistic, and reactive response than a traditional SST.

A broad explanatory theory of motor inhibition was proposed by Wessel and Aron (2017) using the unexpected event framework. They postulated that the inhibitory control network including the presupplementary motor area, right inferior frontal cortex and subthalamic nucleus, which then effects fronto-basal-ganglia output, is activated following the presentation of an unexpected event irrespective of whether action cancellation is required or not. A global suppressive response was postulated to occur in response to these unexpected events where all cognitive and behavioural processes are interrupted and the entire body inhibits its action, resulting in slowing of motor execution and cognitive disruption, and allowing for attentional reorienting (whether that be cessation of action, or reprogramming of an alternative action).

Sebastian et al. (2020) studied the use of unexpected stimuli in a variant of the GNGT where participants were given a pre-trial cue as to whether it was more likely that an imperative go signal, or no-go signal would occur in that trial. This created conditions of unexpected go and unexpected no-go trials when the imperative stimulus was opposite (incongruent) to what the pre-trial cue had stated was likely, as well as expected go and expected no-go trials, where the imperative cue was congruent to the pre-cue. Of particular interest were the conditions of unexpected action in the unexpected 'go' condition in addition to unexpected inhibition in the unexpected no-go condition. fMRI results found that the purported inhibitory control network, specifically the fronto-basal-ganglia brain network, was activated in both the unexpected go and unexpected no-go trials, suggesting that the unexpectedness of these trials were the key contributor in activating the associated inhibitory network, irrespective of whether action inhibition or action execution was necessitated. Behavioural results also supported this conclusion with reaction times on go trials observed to be significantly slower when the imperative go stimulus was unexpected compared to when it was expected (Sebastian et al. 2020), indicative of a global inhibition (or pause), prior to executing the unexpected action.

Two-stage model of action-stopping

Tatz et al. (2021) also used the unexpected stimuli framework to compare the cognitive and behavioural processes that distinguish between the detection of an imperative stop signal, as opposed to the explicit execution of behavioural inhibitory control. A version of the SST was used where along with the usual go and infrequent stop signals, a third 'ignore' stimulus was infrequently presented which required participants to disregard the change and continue their response as if no change had occurred. Specifically, as in the standard SST, the ignore stimuli occurred in a similar manner to the usual stop signal, i.e., the go stimulus changed to an ignore stimulus at a delay of SSD after the initial presentation.

Responses to the stop and ignore stimuli were assessed in a range of ways including transcranial magnetic stimulation (TMS), electromyography (EMG), and electroencephalography (EEG). Salient stop and ignore signals produced no distinct differences in early-latency inhibitory activity across these measures with any distinguishable difference between the two signals not occurring until around 175ms following presentation (Tatz et al. 2021). It was also found that RT on ignore trials were significantly slower than expected go trials highlighting activation of an inhibitory process in response to the ignore stimulus. Since no behavioural response was provided on successful stop trials (no button press) it wasn't possible to compare the behavioural slowing in stop and ignore trials in the Tatz et al. (2021) design. These findings do provide additional evidence that any unexpected events cause a similar inhibitory effect however has limited capacity to explain inhibition in the context of global versus selective stopping.

An explanatory two-stage theory of inhibitory control was proposed as the behavioural mechanism that describes the process. The first stage involves a global stopping effect in response to the unexpected stimuli while the second stage initiates a new, more appropriate course of action in response to the detection of the unexpected stimuli. This could involve either continuing the initial action, cancelling the initial action, or changing the course of action (Tatz et al., 2021). Referring back to our real-world example of reaching for your keys and perceiving an insect sitting on them. In relation to the two-stage mode, a global inhibitory effect will occur following the unexpected detection of the insect to allow time to discern the appropriate course of action needed. If we perceive a venomous looking spider then we will attempt to cancel our movement, if we perceive a butterfly then we may change our action to shoo the butterfly away, if we realise the insect is in fact a crumb left over from a cookie you just ate then we will continue our initial action of reaching for the keys. In each

case, a global suppression of action occurs, and the time taken to pick up the keys will be slower than if no detection of the unexpected stimulus had occurred.

Electromyography

Electromyography (EMG) is a non-invasive and passive technique that assesses the electrical activity within muscles by placing electrodes over muscle and recording the signal (voltage) for offline analysis. Within the context of inhibitory control tasks, EMG provides further insight into the physiological mechanisms involved in inhibition, adding value and context to a participant's behavioural results. Not only does EMG show the apparent electrical activity involved in enabling an overt response (button press) but more crucially to this research, also shows partial responses that don't result in an overt button press. These "partial responses" are erroneous responses which are inhibited before they advance into an overt behavioural error (incorrect button press) (Burle et al., 2002). In the absence of EMG recordings, trials where participants successfully inhibit their movement, resulting in no button press, would provide limited data since the participant hasn't performed any action behaviourally. EMG allows a closer look at the timing and potential muscle activity that occurred prior to a participant successfully cancelling their response; observing the timing and amplitude of partial response can help with understanding the neural mechanisms associated with inhibitory control to both stop and ignore stimuli, thus potentially uncovering similarities or differences in the motor cortical responses to these unexpected stimuli.

Current study

The current study aimed to build upon the existing literature of inhibitory control by creating novel versions of the SST to examine inhibition within the framework of unexpected stimuli. Overt behavioural measurement of the task such as accuracy, speed, and stop signal reaction time (SSRT) were combined with assessment of physiological responses using EMG to examine the inhibitory effects of various versions of unexpected action and inhibition.

The current study used similar methods used in the Tatz et al. (2021) by including 'ignore' stimuli (along with go and stop stimuli in a SST) which required the participant to disregard the signal and continue the initial required response; however building upon past literature, the current study added the novel addition of requiring participants to use both hands to respond to go stimuli and only cancel one component of this response in stop trials (i.e., selective stopping). In the Tatz et al. (2021) paper, participants responded to the go stimuli with one hand (i.e., unimanual responses to an imperative stimuli), meaning that when participants successfully inhibited a response on stop trials, no behavioural data was recorded as they haven't pressed a button. By requiring selective stopping not only do we receive a behavioural measure in the responding hand, we can also assess the globality of the inhibition by assessing to extent to which the responding hand slows (selective stop cost) (Aron & Verbruggen, 2008). This behavioural slowing can be compared between selective stop stimuli, and ignore stimuli, thus directly comparing the behavioural consequences of unexpected stimuli irrespective of how they are interpreted (requiring stopping or ignoring). The current study will also build upon the examination of unexpected action versus unexpected inhibition explored by Sebastian et al. (2020). In this second part of the experiment unexpected bimanual responses were required on some trials (unexpected action), rather than the expected unimanual responses to the frequent go stimuli. Here we compared any behavioural slowing as a result of unexpected action, to those conditions where unexpected cancellation or ignore stimuli were presented. This novel aspect of the project extends the framework of unexpected events outside the context of stopping. Specifically, we were interested to determine whether unexpected events which didn't require a change of action still resulted in a 'pause', even when the alternative response was additional action with the contralateral hand (bimanual go c.f. expected unimanual go) and stopping was not a possible response.

Electrophysiological responses (assessed using EMG) will be used to aid in detecting responses which are ‘sub-threshed’ where a participant has responded to a stimuli but not to the degree which results in an overt behavioural response (button press) as well as give physiological data in relation to timing and amplitude of electrical activity in the muscles.

Hypotheses

Hypothesis 1 In line with the findings of Tatz et al. (2021), a global and comparable inhibitory effect will be present in both ‘stop’ and ‘ignore’ trials, which will also be consistent for unilateral and bimanual responses.

Hypothesis 2 In line with Sebastian et al. (2020), this will be consistent in unexpected action trials such that an inhibitory effect is present.

Hypothesis 3 Comparable partial responses will be present in both stop and ignore trials. The burst characteristics (latency/amplitude) will be similar in both ignore and stop trials.

Method

Participants.

24 participants (mean age = 24.5 years, SD = 5.5 years), (range 18- 37 years) were recruited using two methods. The first method recruited psychology students requiring course credit using the online University of Tasmania psychology research participation system (SONA). These participants were given two hours of course credit for their time. Other participants were recruited through direct invitations sent to friends, family and colleagues of the researcher who met the age criteria and were reimbursed a $20 Coles Group voucher as compensation for their time. All participants had normal or corrected to normal vision and were not colour blind.

All participants read a study information sheet (Appendix C) and provided informed consent (Appendix B). The study was approved by the Tasmania Human Research Ethics Committee #H001698 (Appendix A)

Procedure/Design

Participants were seated comfortably approximately 80cm from a computer monitor with their forearms pronated and hands resting on a desk (palm down). Their hands were positioned at approximately shoulder width, such that each index finger was positioned on one of two buttons which were mounted vertically. Participants were required to respond to visual stimuli presented on a 240Hz monitor using PsychoPy3 (Peirce et al., 2019) by pressing the buttons by abducting their index fingers (inward movement) to maximise the use of the flexor digitorum interossei (FDI) muscle (see EMG section, below).

Four specific conditions were undertaken, for which participants received specific written instructions on the computer screen. The order in which these were conducted was counterbalanced across the 24 participants (6 participants completing each order of conditions) (Table 1).

Four main experimental conditions were performed by participants which will hereby be referred to as stop signal task (SST), stop signal task with ignore (SSTIgnore), unexpected go task (UGT), and unexpected go task with ignore (UGTIgnore).

At the commencement of each condition, participants were first given 10 practice ‘go-only’ trials to provide a baseline measure of reaction times in the absence of any requirement to have to unexpectedly stop, ignore particular stimuli, or alter the motor response. Trials which were excessively slow (reaction time > 450ms), fast (RT < 100ms indicating guessing or premature response) or asynchronous (bimanual responses with differences in RT > 50ms between the two responses) were excluded, with the participant continuing the initial ‘go-only’ trials until 10 appropriate trials were taken. The average RT in

these 10 trials then served as a baseline measure of RT to which subsequent performance could be compared.

In each trial, two large circles were presented on the left and right side of the participants screen, with the left side circle indicating the response required from the left hand and right side circle indicating the response required from the right hand. Three different coloured circles were used as the stimuli throughout the experiment consisting of yellow, blue, and purple, each requiring a different response. In each trial, the colour of the circle could change on either side, requiring the participant to change their action to whatever the new signal is presenting. A yellow circle acted as the 'go' signal, requiring participants to make a button press as quickly as they could with the hand that the side of the screen the yellow go signal was presented. A blue circle acted as the 'stop' signal, requiring participants to avoid pressing the button on whichever side the signal was presented (UGT, UGTIgnore) or inhibit their initiated response if the circle changed from yellow to blue (SST, SSTIgnore). And finally, a purple circle, which acted as the 'ignore' signal. The ignore signal was always presented after an initial yellow or blue signal and required participants to act as if no colour change had occurred such that if the original signal was a yellow go then they should still press the button or if the original signal was a blue 'no-go' then they should continue not pressing the button. Each trial began with the presentation of a fixation cross, followed by presentation of the stimuli, followed by feedback on RT and response correctness, and finally a black screen before beginning the next trial (Figure 1).

In the SST condition, participants completed 153 trials, which comprised of 100 'bimanual-go' trials, 50 'right-stop' trials, and 3 'left-stop' trials (Figure 1). In every trial within the SST the initial signal comprised of a yellow 'go' signal on both the left and right side requiring participants to initiate a bimanual response (press left button with left hand and right button with right hand). For the 100 bimanual-go trials, this remained unchanged, and

the appropriate response was to press the buttons with both hands. For the 50 right-stop trials, following a stop-signal delay (SSD), a blue stop signal was presented on the right side, requiring participants to attempt to stop their response on the right hand and continue pressing the left hand. SSD refers to the time between presentation of the initial go signal and presentation of the stop signal. SSD was between 50-400ms on each trial and was stair-cased based on success or failure of the previous stop trial meaning if stopping occurred successfully, SSD would decrease by 50ms and increase by 50ms following correct or incorrect response; accordingly, the probability of successfully stopping on a right-stop was ~50% allowing assessment of both successful and failed stops, and calculation of the SSRT (Verbruggen et al. 2019). Three left-stop trials were used as catch trials to attempt to stop participants from focusing entirely on the right side

In the SSTIgnore condition participants completed 303 trials which comprised of 200 bimanual-go trials, 50 right-stop trials, 50 ‘right-ignore’ trials, and 3 catch left-stop trials. Thus, the proportion of trials with unexpected responses (stop trials in the SST task, stop or ignore trials in the SSTIgnore task) remained the same (33%).

The SSTIgnore condition followed a very similar procedure to the SST condition with each trial again beginning with yellow go signals on the left and right side and the change occurring on the right side (plus three left hand catch trials). The SSTIgnore condition had the addition of the purple ‘ignore’ signal on right-ignore trials where participants attempted to ignore the colour change and continue with their original bimanual response (as if no colour change had occurred). The timing of the ignore signal followed the same staircase delay as the most recent SSD which was based on the success or failure of the right-stop trials (Figure 1).

In the UGT condition participants completed 150 trials which comprised of 100 ‘unimanual-go’ trials (50% left go, 50% right go) and 50 ‘bimanual-go’ trials (50% left-then-

bimanual, 50% right-then-bimanual). Each trial would begin with the presentation of a yellow go signal and a blue no-go signal. 50% of trials the yellow go signal would be on the left side with the blue no-go signal on the right side and vice versa. The 100 unimanual-go trials required participants to make a button press with the hand on the side that the appropriate go signal was presented and inhibit a response from the side that blue no-go signal was presented. For the 50 bimanual-go trials the blue no-go signal would change to a yellow go signal, requiring the participant to then also press the button in response to that go signal, resulting in a bimanual press. The delay of the secondary go signal (go signal delay (GSD)) occurred five times at five different delays, specifically at 0ms, 50ms, 100ms, 150ms and 200ms (Figure 1).

In the UGTIgnore condition participants completed 300 trials which comprised of 200 unimanual-go trials (50% left, 50% right), 50 bimanual-go trials (50% left-then-bimanual, 50% right-then-bimanual) and 50 'ignore' signals (50% left, 50% right). Unimanual-go and bimanual-go trials followed the same procedure as in the UGT condition. Each trial again began with a yellow go signal and blue no-go signal on either side. On ignore trials the blue no-go signal would change to a purple ignore signal which required participants to continue as if no colour change had occurred and continue to inhibit a response on that side. The delay of the ignore signal (ignore signal delay (ISD)) was once again presented at 0ms, 50ms, 100ms, 150ms and 200ms (Figure 1). Again, in the UGT and UGTIgnore the proportion of trials (33%) in which an unexpected response (unexpected go/ignore) occurred was constant across these conditions and matched that used in the SST versions of the task.

906 total trials across the four conditions were completed by participants (in addition to the initial practice 10 successful 'go' only trials in each condition). The entire experiment was split into ~ 50 trial blocks with feedback on average reaction time and accuracy presented after each block to encourage participants to perform as well as possible.

Participants were given an opportunity to rest at the completion of each block. Participants also received trial by trial feedback indicating their RT on both hands, as well as whether their response was correct or incorrect. Feedback was also given when a response was >150ms slower than their average RT on the initial go trials to limit proactive slowing (and thus rendering the SSD staircasing procedure inefficient) as well as if the RT between left and right hand was asynchronous (>50ms). The entire experiment took around 90 minutes to complete. Many aspects of the design of the current study used the Verbruggen et al. (2019) consensus paper to guide decisions on how to appropriately investigate inhibitory control using the SST.

Figure 1. The four experimental conditions that each participant completed in a pseudorandomised counterbalanced order. Left side circle indicating required response with left hand and right side circle indicating required response with right hand. Yellow circles indicated a required go response (button press), blue circles indicating a required no response (avoid button press/cancel button press) and purple circles indicated an ignore response (continue as if no change had occurred).

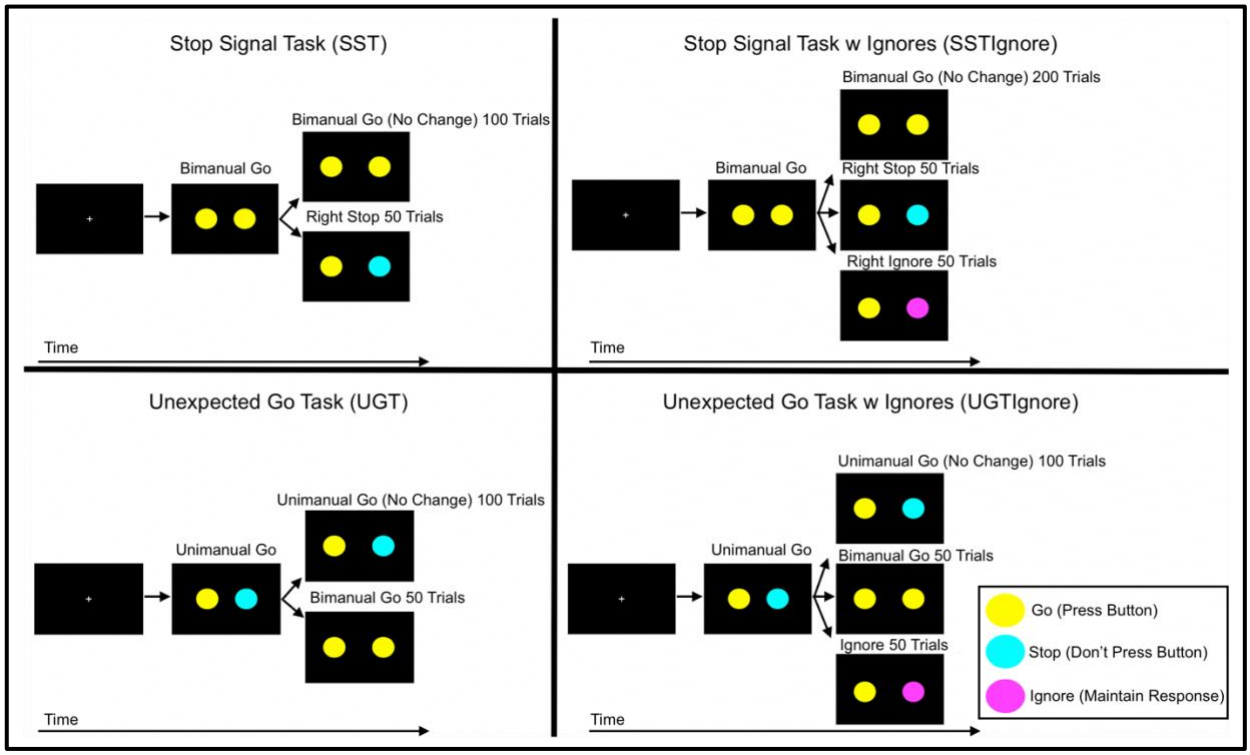


Table 1.

Four possible pseudorandomised orders of experimental conditions which participants were randomly allocated to. 6 participants were allocated to each order.

1st Condition	SST	SSTIgnore	UGTIgnore	UGT
2nd Condition	SSTIgnore	SST	UGT	UGTIgnore
3rd Condition	UGTIgnore	UGT	SST	SSTIgnore
4th Condition	UGT	UGTIgnore	SSTIgnore	SST

Apparatus/Materials

Electromyography

EMG recordings were made using disposable adhesive electrodes positioned on the first dorsal interossei (FDI) of both the participants index fingers. Two electrodes were placed in a belly-tendon montage on the FDI with a third ground electrode placed on the lateral bony aspect of participants' wrists. EMG signals were sampled at 2000Hz and amplified by 1000 before being notch filtered at 50Hz. Before the experiment began, participants were shown their raw EMG signals on a computer screen to aid in explaining how tensing and relaxing the muscles in their hands affects their EMG data. Whenever the signal became noisy (background activity) during the experiment, the researcher would remind the participant to relax their hands between trials.

Data Analysis

Behavioural measures

Psychopy data output provided measures of RT for both the left and right hands (when pressed) as well as whether the required response was correct, or incorrect for the different trial types in each of the four experimental conditions. RT was calculated as an

average of the two responding hands when both buttons were pressed while on Successful stop trials and unimanual go trials (in the UGT and UGTIgnore conditions) only a single RT is measured as only one hand responds. Average response accuracy (proportion of correct responses) was calculated for each trial type (go/ignore/stop/) in each of the conditions. Participants' stop signal reaction time (SSRT) – a measure of the efficiency of the inhibition process - was calculated for the stop trials in the SST and SSTIgnore conditions using the integration method with any go trials omissions (missing RT data) replaced with the maximum go RT (Verbruggen et al., 2019).

Electromyographical measures

EMG data was analysed to provide data on various measures of both overt and covert physiological responses in the different conditions. Following amplification and notch filtering, the signal band-pass was filtered between 20-500Hz to remove high frequency noise and movement artifacts. Rectification and low pass filtering were then applied at 10Hz to create an EMG 'envelope' for plotting and further analysis of burst characteristics. Algorithms by Hodges and Bui (1996) were then used to detect discernible bursts of EMG signal on a trial-by-trial basis. In the context of the task, a burst of EMG represents the presence of (volitional) muscle activity in the FDI above the resting (background) level of activity in the muscle. In trials in which a response (button press) was recorded, we first detected the RT generating burst (primary muscle burst) in both the left and/or right hand/s.

On the basis of the theory of the pause-then-cancel model (see introduction, (Tatz et al., 2021)), we then determined whether, on successful stop trials and ignore trials whether a distinguishable partial burst of EMG occurred before the main RT generating burst. The threshold for partial bursts was determined on a trial by trials basis such the amplitude of the peak was 3 SD above the resting EMG signals within that particular trial, with the temporal separation of at least 20ms between the offset of the partial burst and subsequent onset of the

main RT generating burst. Latency (relative to the imperative go stimulus, stop stimulus or ignore stimulus) and amplitude of partial and peak EMG bursts were also calculated (prior to being normalised to the average RT generating burst in the 'bimanual-go' trials). As well as the latency and amplitude measures, proportion of trials with observable partial responses was also calculated for the stop and ignore trials within the SST and SSTIgnore conditions.

Analysis of EMG parameters will focus on the SST and SSTIgnore conditions, as the analysis and interpretation of the EMG data in the UGT and UGTIgnore is conceptually beyond the scope of the current project.

Statistical Analysis

Analyses assessing factors such as accuracy, SSRT, RT, and EMG parameters were run using the open statistical software Jamovi (The Jamovi Project, 2021). Random intercepts were used to analyse participants to avoid assumption that a similar relationship was followed by each participant, allowing for variation within participant performance. Generalized linear mixed models (GLMMs) were performed on RT data using a gamma distribution and log link function due to the non-normal distribution common in RT data. GLMMs in this fashion accounts for the positive skew found in RT data (Lo & Andrews, 2015). For assessment of response accuracy, GLMMs with a probit link function was used to convert probabilities of response outcomes to a continuous scale for analysis. independent-samples t-test (assuming unequal variances) were also used on RT data. The alpha level of significance for all analyses was set at $p = .05$

Results

RT difference between bimanual go and unsuccessful stop trials

SSRT estimates become unreliable when RT on go trials are faster than RT on unsuccessful stop trials, as this breaks the assumptions of the horse race model (between the stop and go process) upon which SSRT calculations are predicated. RTs in unsuccessful stop

trials (*M* = 0.336s, *SD* = 0.063s, 95% CI [0.331s, 0.341s]) were significantly faster than RT for bimanual go trials (*M* = 0.379s, *SD* = 0.097s, 95% CI [0.375s, 0.383s])) in the SST condition X^2 (1, N = 24) = 64.1, $p < .001$. RTs in unsuccessful stop trials (*M* = 0.319s, *SD* = 0.075s, 95% CI [0.313s, 0.324s]) were also significantly faster than RT for bimanual go trials (*M* = 0.346s, *SD* = 0.080s, 95% CI [0.344s, 0.348s]) in the SSTIgnore condition X^2 (1, N = 24) = 53.7, $p < .001$. These results signify the assumptions of the horse race model of stopping are met and validate use of SSRT measures for indexing stopping ability.

Comparison of SST & SSTIgnore condition

Within the SST the staircase algorithm worked successfully in getting participants to successfully stop half the time on stop trials, with participants successfully stopping on 49.5% of stop trials (*SD* = 6.6%, 95% CI [46.9%, 52.2%]). The addition of ignore trials in the SSTIgnore section affected participants ability to stop where participants only successfully stopped on 42.3% of stop trials (SD = 8.0%, 95% CI [39.1%, 45.5%]). This difference was statistically significant, following a GLMM with a probit link function (with condition as the fixed variable and intercept as the random variable) X^2 (1, N = 24) = 12.6, $p < .001$.

A GLMM with Gamma distribution and Log link (with trial type as the fixed effect and intercepts and slopes as the random effects) found that participants responded slower on bimanual go trials within the SST condition (*M* = 0.379s, *SD* = 0.097s, 95% CI [0.375s, 0.383s]) compared with the SSTIgnore condition (*M* = 0.346s, *SD* = 0.080s, 95% CI [0.344s, 0.348s]), X^2 (1, N = 24) = 7.51, $p = .006$.

SSRTs in the SST condition (*M* = 0.202s, *SD* = 0.022s, 95% CI [0.194s, 0.211s]) were significantly shorter than SSRTs in the SSTIgnore condition (*M* = 0.234s, *SD* = 0.027s 95% CI [0.223s, 0.245s]), X^2 (1, N = 24) = 38.3, $p < .001$

There was a small but statistically significant difference in RT for right-stop trials (*M* = 0.472s, *SD* = 0.11s, 95% CI [0.461s, 0.482s]) and right-ignore trials (*M* = 0.508s, *SD* =

0.11s, 95% CI [0.497s, 0.520s]) X^2 (1, N = 24) = 4.03, p = .045 when A GLMM with Gamma distribution and Log link (with trial type as the fixed effect and intercepts and slopes as the random effects) was conducted only on trials in which a right hand partial activation was detected in EMG profiles prior to the RT generating burst. In contrast, a similar analysis on trials where a partial burst was present in both hands simultaneously found no significant difference in RT between right-stop trials (M = 0.472s, SD = 0.11s, 95% CI [0.495s, 0.520s]) and right-ignore trials (M = 0.519s, SD = 0.11s, 95% CI [0.504s, 0.533s]) X^2 (1, N = 24) = 0.86, p = .355).

When assessing differences between partial bursts in right-stop and right-ignore trials we have opted to assess partial bursts in the left hand only, as a response was always required in the left hand and thus can be compared more accurately. Within the SSTIgnore condition, 25.4% of all right-stop trials (SD = 4.4%, 95% CI [23.0%, 27.9%]) and 25.8% of right-ignore trials (SD = 4.4%, 95% CI [23.3%, 28.2%]). resulted in a partial burst in the left hand, prior to the main RT generating burst. These proportions did not differ significantly X^2 (1, N = 24) = 0.026, p = .871 following a GLMM with probit link function (with condition as the fixed variable and intercept as the random variable). Comparing successful right-stop and right-ignore trials with left hand partial response within the SSTIgnore condition Using a with Gamma distribution and Log link functions (with trial type as the fixed effect with intercepts and slopes as the random effects) suggests that there was no statistically significant difference in RT for right-stop trials (M = 0.506s, SD = 0.091s, 95% CI [0.494s, 0.518s]) and right-ignore trials (M = 0.502s, SD = 0.12s, 95% CI [0.489s, 0.515s]) X^2 (1, N = 24) = 0.052, p = .820.

All ignore trials versus all stop trials in SST & SSTIgnore.

A GLMM with Gamma distribution and log link (with trial type as the fixed effect and intercepts and slopes as the random effects) was used to compare RT between all (both

successful and unsuccessful) right-stop and right-ignore trials in the SST and SSTIgnore conditions. The GLMM indicated that the fixed effect of trial type was not statistically significant between stop trials (M = 0.397s, SD = 0.12s, 95% CI [0.392s, 0.402s]) and ignore trials (M = 0.414s, SD = 0.14s, 95% CI [0.406s, 0.421s), X^2 (1, N = 24) = 2.96, p = 0.085.

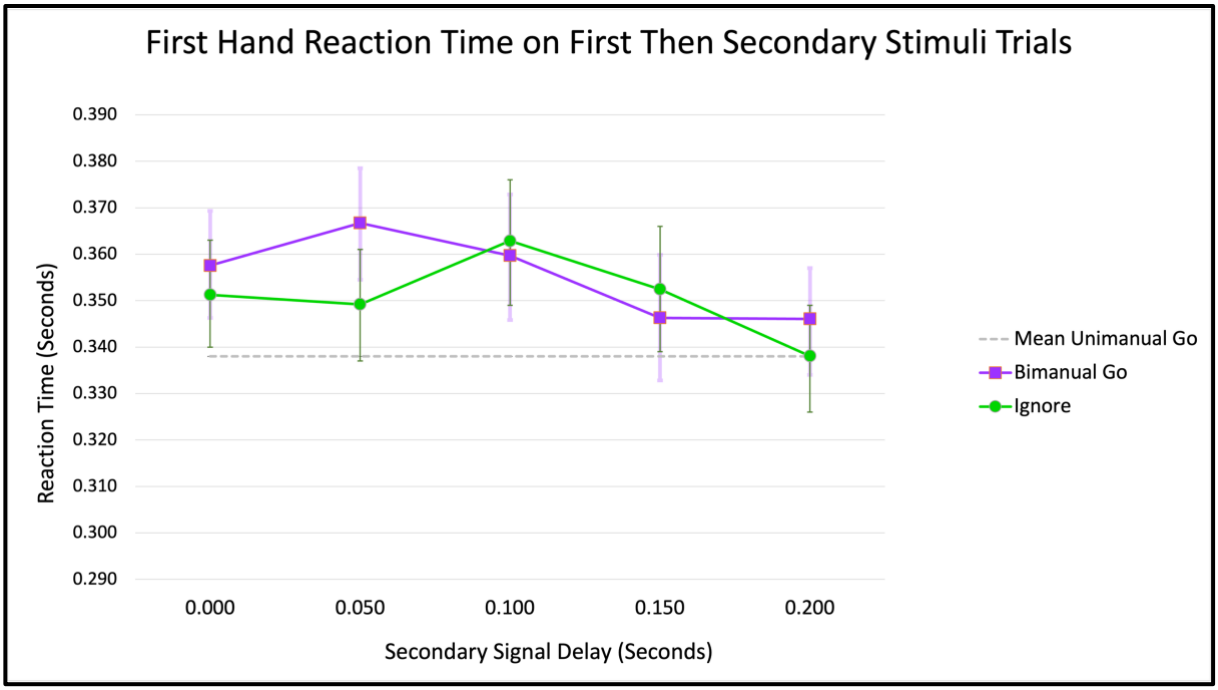
UGT and UGTIgnore analysis

RTs of unimanual-go trials were compared using GLMMS to the less frequent bimanual-go and ignore trials. Separate GLMMs were run with Gamma distribution and Log link (with trial type as the fixed effect and intercepts and slopes as the random effects). Overall, the average RT for unimanual-go responses (M = 0.338s, SD = 0.081s, 95% CI [0.336s, 0.340s]) was significantly slower than ignore trials (which also required a unimanual response) (M = 0.351s, SD = 0.095s, 95% CI [0.345s, 0.356s]) X^2 (1, N = 24) = 5.6, p = .018. Unimanual-go was also significantly slower than both the first responding hand in bimanual-go trials (M = 0.355s, SD = 0.10s, 95% CI [0.351s, 0.359s]) X^2 (1, N = 24) = 2.2, p < .001, as well as the second responding hand in bimanual-go trials (M = 0.371s, SD = 0.088s, 95% CI [0.367s, 0.374s] X^2 (1, N = 24) = 27.9, p < .001.

The addition of a secondary stimulus (colour change after a delay) which occurred in bimanual-go and ignore trials also had an effect on RT for the first responding hand in both trials. Here we compare differences in RT of the first responding hand at each GSD and ISD to assess at which secondary stimulus delay the greatest slowing effect occur in comparison to unimanual-go trials (M = 0.338s, SD = 0.081s, 95% CI [0.336s, 0.340s]). For the ignore trials, the RT difference at the 0ms ISD was not statistically significant X^2 (1, N = 24) = 2.12, p = .145) nor was it significant at 50ms X^2 (1, N = 24) = 1.47, p = .225). A significant slowing was observed at the 100ms ISD $\chi 2(1) = 9.75$, p = .002). But slowing at 150ms X^2 (1, N = 24) = 1.74, p = .187 and 200ms X^2 (1, N = 24) = 0.024, p = .877 was not statistically significant (Figure 2)

For bimanual trials, the effect of a secondary go stimulus had a greater slowing effect on the initial responding hand, as there was a significant slowing at 0ms X^2 (1, N = 24) = 5.06, p = .025), 50ms $\chi 2(1) = 14.7$, $p < .001$) and 100ms X^2 (1, N = 24) = 8.90, p = .003). However, there was insignificant slowing at delays of 150ms X^2 (1, N = 24) = 1.48, p = .223) and 200ms X^2 (1, N = 24) = 2.03, p = .154) (Figure 2)

Figure 2. RTs of first responding hand in trials where a secondary stimulus was presented. Split by timing of secondary signal at 0ms, 50ms, 100ms, 150ms and 200ms (at 0ms both signals are presented simultaneously) trials from UGT and UGTIgnore conditions used. Error bars representing 95% CIs.

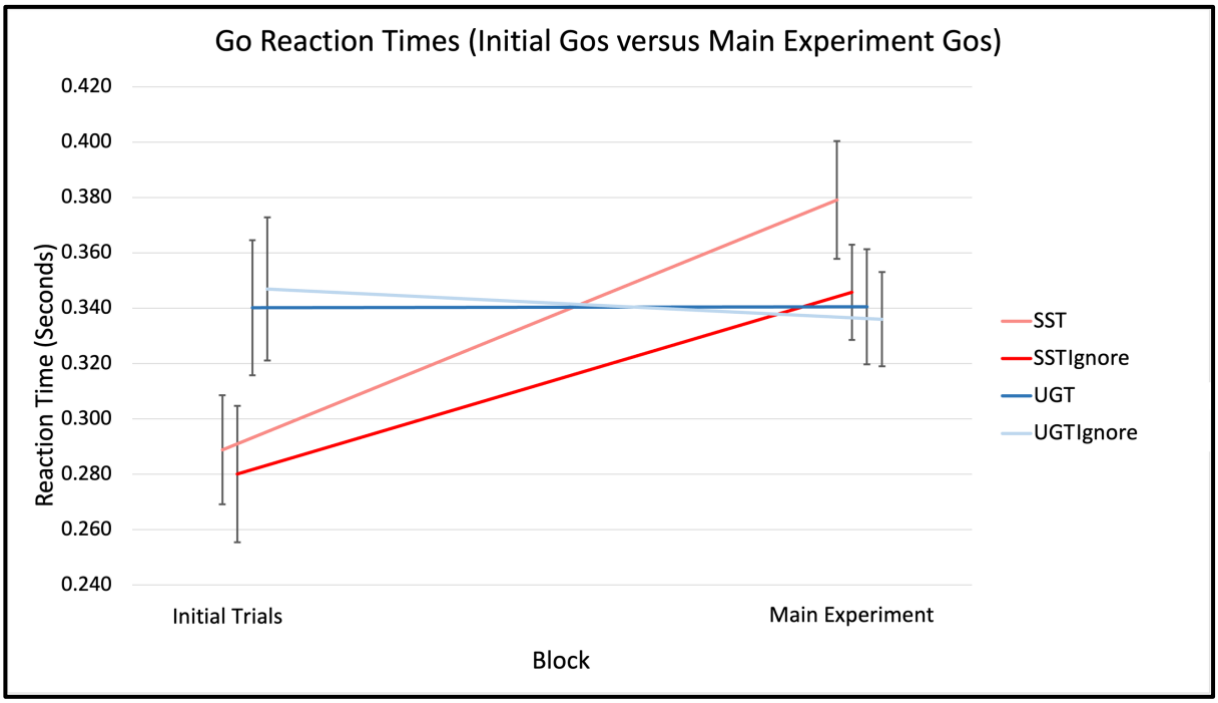


Proactive slowing

Within the SST condition, RTs (seconds) from the initial go only trials (M = 0.289s, SD = 0.050s, 95% CI [0.269s, 0.309s]) were significantly faster than go trials in the main experimental condition (M = 0.379s, SD = 0.054s, 95% CI [0.357s, 0.401s]) $t(23) = -8.1$, $p <$ 0.001. Within the SSTIgnore condition, reaction times from the initial go only trials (M =

0.280s, *SD* = 0.063s, 95% CI [0.255s, 0.305s]) were also significantly faster than go trials in the main experimental condition (*M* = 0.346s, *SD* = 0.044s, 95% CI [0.328s, 0.363s]), *t*(23) = 7.4, *p* < 0.001 Within the UGT condition, reaction times (seconds) from the initial go only trials (*M* = 0.340s, *SD* = 0.062s, 95% CI [0.315s, 0.365s]) were not significantly different from go trials in the main experimental condition (*M* = 0.341s, *SD* = 0.053s, 95% CI [0.319s, 0.362s]), *t*(23) = -0.043, *p* = 0.966. Within the UGTIgnore condition, reaction times from the initial go only trials (*M* = 0.347s, *SD* = 0.066s 95% CI [0.321s, 0.373s]) were also not significantly different from go trials in the main experimental condition (*M* = 0.336s, *SD* = 0.044s 95% CI [0.319s, 0.353s]), *t*(23) = 1.26, *p* = 0.222 (Figure 3).

Figure 3. Mean RT (Seconds) for the initial go-only trials in each condition compared with go trials in the main experiment block for each condition (where stop, ignore and unexpected go stimuli occurred on 1/3 of all trials). Error bars represent 95% CIs around the mean.

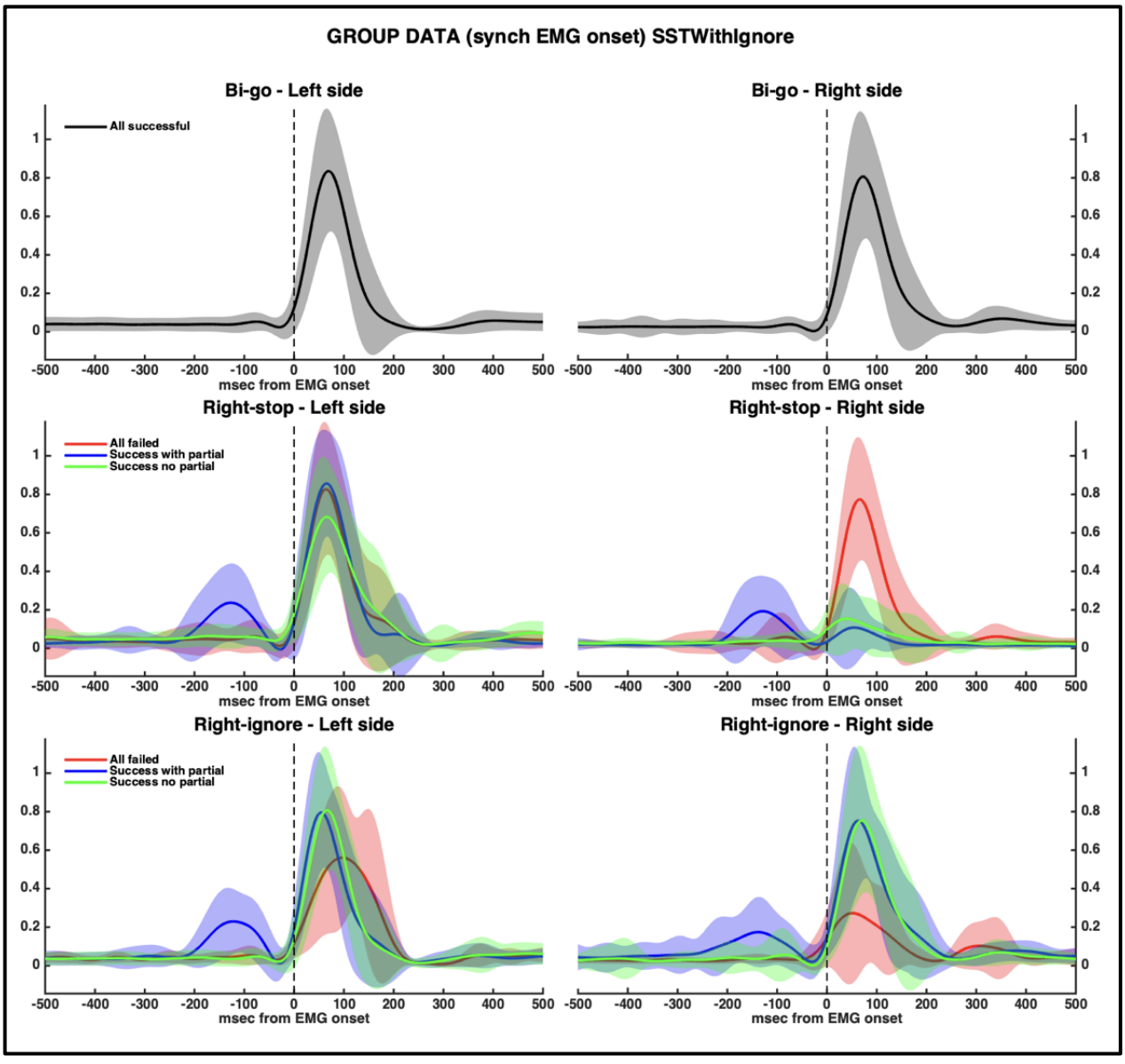


EMG Analysis

Timing of the partial and RT Generating EMG response was also compared between right-stop and right-ignore trials using GLMMs with Gamma distribution and Log link functions (with trial type as the fixed effect with intercepts and slopes as the random effects). Within the SSTIgnore condition there was no significant difference between the timing of left hand partial responses on right-stop trials (M = 0.272s, SD = 0.0073s, 95% CI [0.263s, 0.282s) and right-ignore trials (M = 0.262s, SD = 0.093s, 95% CI [0.252s, 0.273s]) X^2 (1, N = 24) = 1.47, p = .225). Differences in timing between of the RT generating EMG between successful right-stop (M = 0.478s, SD = 0.098s, 95% CI [0.468s, 0.491s]) and right-ignore trials (M = 0.459s, SD = 0.12s, 95% CI [0.446s, 0.473s]) within the SSTIgnore condition was also not statistically significant X^2 (1, N = 24) = 0.564, p = .453. The difference in average latency between partial and RT generating EMG in both right-stop (M = 0.202s, SD = 0.039s, 95% CI [0.187s, 0.218s]) and right-ignore trials (M = 0.201s, SD = 0.042s, 95% CI [0.184s, 0.217s]) was also not statistically significant, X^2 (1, N = 24) = 0.763, p = .782 following a GLMM (Figure 4).

Amplitude of partial burst and RT generating burst EMG responses could also be compared between right-stop and right-ignore trials. Within the SSTIgnore condition there was no significant difference between the EMG amplitude of left hand partial responses on right-stop trials (arbitrary unit) (M = 0.366, SD = 0.25, 95% CI [0.333, 0.399) and right-ignore trials (M = 0.365, SD = 0.26, 95% CI [0.335, 0.395]) X^2 (1, N = 24) = 0.025, p = .874. There was also no significant difference between the amplitudes of left hand RT generating EMG responses on right-stop trials (arbitrary unit) (M = 1.08, SD = 0.26, 95% CI [1.05, 1.11) and right-ignore trials (M = 1.04, SD = 0.25, 95% CI [01.01, 1.06]) X^2 (1, N = 24) = 2.78, p = .095 where GLMMs have been run with Gamma distribution and Log link functions (with trial type as the fixed effect with intercepts and slopes as the random effects) (Figure 4).

Figure 4. EMG profile of failed trials, successful trials with a partial burst and successful trials without a partial burst of left and right hand for each trial type within the SSTIgnore condition. Top panel shows average EMG profile of successful bimanual go trials in both hands (left side for left hand, right side for right hand). Middle panel shows average EMG profile of right-stop trials, showing failed stops, successful stops where a partial burst was observed and successful stops where no partial burst is observed for both the left and right hand. Bottom panel shows average EMG profile of right-ignore trials, showing failed trials, successful trials where a partial burst was observed and successful trials where no partial burst is observed for both the left and right hand. Timing is synced to the onset of the peak RT generating burst, showing the EMG activity of a partial burst (in blue) prior to the peak RT generating burst is similar for successful stop and ignore trials (see text for descriptives).



Discussion

The current study used behavioural and physiological measures to assess performance in a novel version of a selective inhibitory control task. Participants responded (using both hands) to a combination of one of three stimuli, requiring either an action, inhibition of action, or to ignore the stimuli.

Similarities between stop and ignore trials

In relation to hypothesis 1, a comparable inhibitory effect was observed in a range of measures between stop and ignore trials within the SSTIgnore condition. In accordance with the Tatz et al. (2021) paper, the current study attempted to provide evidence for the proposed pause then cancel model of inhibitory control. Filtering trials by presence/absence of partial EMG response was a valuable tool in distinguishing between trials where an inhibitory process had taken place. Significant value to the comparison of stop and ignore trials was the physiological similarity in proportion, timing, and amplitude of observed partial and RT generating EMG responses following detection of the changing signal (consistent with hypothesis 3). The significant value added to the Tatz et al. (2021) paper was the addition of a second responding hand, and requiring selective inhibition, meaning that a behavioural RT response is given on all trials as opposed to no RT generated on successful stop trials. A Bayesian paired samples t-test was run to follow up the relationship between RTs of stop and ignore trials where a partial burst is present finding $t(23) = 0.358$, $p = .724$ with a BF10 = 0.00036 meaning that H0 is 2778 times more likely than H1. Further adding value to the proposed pause then cancel model. A challenge in assessing differences between stop and ignore trials in the SSTIgnore was that in ignore trials it is difficult to detect when a participant has begun a bimanual press too quickly and failed to detect the ignore signal versus when they have inhibited their response in reaction to the ignore signal before reinitiating a bimanual press (as both result in a successful trial). The use of EMG measures

to detect and filter by partial EMG responses is therefore crucial in making comparisons between stop and ignore trials in this manner. Here we also assessed the possible option of using all stop and ignore trials (regardless of success) in absence of EMG measurements where it was found there was no significant difference in RT between the two trial types. The similarities in behavioural and physiological responses between stop and ignore trials lends support to unexpected events being the explanatory factor of inhibitory control as opposed to stop signals specifically.

Differences between SST and SSTIgnore condition

There were a number of key differences observed between the SST and SSTIgnore condition including slower bimanual go times in SST compared to SSTIgnore, slower SSRT in SSTIgnore, as well as less accuracy in stop trials within SSTIgnore. The likely explanation as to this observation is that while the proportion of trials where an unexpected stimulus change remained the same (1/3) the proportion of trials that specifically required stopping was different (1/3 for SST, 1/6 for SSTIgnore). The more infrequent the stop signal, the more difficult it is to inhibit an action (Verbruggen et al., 2019). The infrequency of stop signals within the SSTIgnore condition relative to the SST meant participants failed stop trials at a higher proportion. A minimum SSD of 50ms was used so when a participant failed a stop trial at a SSD of 50ms the SSD would not change, remaining at 50ms until a stop trial was successful and increased back to 100ms. This meant that some participants got stuck regularly failing stop trials at 50ms at a higher occurrence in the SSTIgnore, leading to a lower proportion of sucessful stop trials (42.3%) than the desired ~50% achieved in the SST condition. While any unexpected events may cause an inhibitory effect these results promote that the likelihood of needing to inhibit an action also effects the way a task is completed when inhibition isn't required (Aron, 2011).

Proactive slowing

A slowing in RT between the pre-experimental go-only trials in comparison to go trials within the experiment suggests evidence for a proactive slowing (Jahfari et al., 2010). It was evident that a proactive slowing strategy was used by participants when completing the current experiment as RTs were significantly faster in the pre-experimental stage of the SST and SSTIgnore condition suggesting that participants began to slow down their responses following the addition of the possible need to inhibit their response on stop trials (Verbruggen & Logan, 2009). The proportion of trials where a stop was required also played an impact on the degree to which proactive slowing was implemented as the slowing was less significant in the SSTIgnore condition where stop trials were less frequent (Verbruggen et al., 2019). There was no significant slowing between initial pre-trial unimanual-go trials and unimanual-go trials within the experimental stage of the UGT and UGTIgnore condition suggesting that without the possibility of needing to inhibit a movement participants continued to go as fast as possible on go trials. This distinction where a proactive slowing strategy was used in the SST and SSTIgnore conditions but not in UGT and UGTIgnore conditions proposes that in line with van Belle et al. (2014) an interplay of both proactive and reactive processes can be utilised dependant on the context in which they are required.

Inhibitory effect in UGT and UGTIgnore conditions

The observation of an inhibitory effect of unexpected stimuli within the UGT and UGTIgnore conditions in relation to hypothesis 2 was present to some degree, however, was much less clear in comparison to the SST and SSTIgnore conditions. There was some slowing present in the first hands response on trials where a secondary stimulus was presented, however this was dependant on the delay at which the second signal occurred (most significant differences at around 0ms, 50ms and 100ms) and wasn't a large difference. The current study differs from Sebastian et al. (2020) in that there is never a trial that is

entirely a no-go, a response is always required on either hand before attention is shifted to the other side. This lack of inhibition needed to perform the UGT and UGTIgnore conditions may have been more consistent with a choice reaction time task (Waller et al., 2019, Wessel & Aron, 2013) as opposed to inhibitory control. The current study adds to Sebastian et al. (2020) by showing that unexpected stimuli appear to elicit a significant pause when the possibility for the need for stopping is required but when stopping isn't an option, then the pause doesn't occur to the same extent. Proactive slowing is of no benefit when accurate performance is not contingent on being able to stop. Another finding was that there was no significant difference in whether the secondary signal was a go or ignore signal meaning that the slight delay in first hand RT was explained by the unexpected nature of the secondary stimuli (Wessel & Aron, 2017), as opposed to its requirement for either going or ignoring.

Implications

Inhibitory control is a well-studied and important area of motor control however still has area where a greater understanding is need. In a clinical setting, a wide range of populations have difficulties in inhibitory control and thus abilities in adaptive behaviour as a whole are reduced. Some research has found that aspects of inhibitory control can be improved upon through intervention (Preuss et al., 2017) meaning improving our understanding of the cognitive processes associated with inhibitory control and the contexts which distinguish which mechanisms are utilised should help better inform targeting interventions. Here we add value to the pause then cancel model of inhibitory control within the context of surprising, unexpected events as a predictor and pose possible improvements upon the research method of inhibitory control.

Limitations and suggestions

While there wasn't a large slowing effect observed in the UGT and UGTIgnore conditions, this could be explained as a function of the task due to the novel design of these

sections. A potential redesign of the experiment to include both unexpected stop and unexpected go trials within the same condition could elicit a slowing effect in unexpected go trials by adding the possibility of needing to stop, another option could also include requiring both hands to respond simultaneously on all bimanual go trials, requiring the participant to inhibit their initial unimanual go response to respond simultaneously. Future research may also be directed by further analysing the proportion of stop signals to assess the degree of proactive stopping implemented. Real-world instances of action and inhibition should also be examined in the context of real-world unexpected stop signals and real-world unexpected ignore signals to better understand inhibitory control in the context that it is most often used.

Conclusion

The current research adds value to the pause then cancel model of inhibitory control as well as further the understanding of a proactive slowing mechanisms whereby internal knowledge of the possibility or impossibility of the need to stop an action affects the degree to which individuals proactively slow their responses to allow more time for accurate movements.

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Appendix A

Ethics Approval Letter

Ethics Approval Letter

27/05/2021

To: Dr Hinder

Project ID: 16981

Project Title: Understanding the influence of cognitive processing and brain connectivity on rapid motor responses across the lifespan: A model-based neuroscience approach (H0016981)

The amendment received in support of the above named project has been approved by the Tasmania Social Sciences Human Research Ethics Committee on the 27 May 2021.

Approval has been granted to add Research Assistant Dr Sauro Salomoni and Hons Student Callum Kilpatrick, and for the following documentation:

Submission Document Name	Submission Document File Name	Submission Document Type	Submission Document Date	Submission Document Version
H0016981_Info_Sheet_May2021_tracked_changes	H0016981_Info_Sheet_May2021_tracked_changes.docx	PARTICIPANT INFORMATION AND CONSENT FORM	24/05/2021	3.4 tc
H0016981_Info_Sheet_May2021_Clean	H0016981_Info_Sheet_May2021_Clean.docx	PARTICIPANT INFORMATION AND CONSENT FORM	24/05/2021	3.4 clean

Please ensure that all investigators involved with this project have cited the approved versions of the documents listed within this letter and use only these versions in conducting this research project.

This approval constitutes ethical clearance by the Tasmania Social Sciences Human Research Ethics Committee. The decision and authority to commence the associated research may be dependent on factors beyond the remit of the ethics review process. For example, your research may need ethics clearance from other organisations or review by your research governance coordinator or Head of Department. It is your responsibility to find out if the approvals of other bodies or authorities are required. It is recommended that the proposed research should not commence until you have satisfied these requirements.

In accordance with the National Statement on Ethical Conduct in Human Research 2007 (updated 2018), it is the responsibility of institutions and researchers to be aware of both general and specific legal requirements, wherever relevant. If researchers are uncertain they should seek legal advice to confirm that their proposed research is in compliant with the relevant laws. University of Tasmania researchers may seek legal advice from Legal Services at the University.

All committees operating under the Human Research Ethics Committee (Tasmania) Network are registered and required to comply with the National Statement on the Ethical Conduct in Human Research 2007 (updated 2018).

Therefore, the Chief Investigator's responsibility is to ensure that:

(1) All investigators are aware of the terms of approval, and that the research is conducted in compliance with the HREC approved protocol or project description.

(2) Modifications to the protocol do not proceed until **approval** is obtained in writing from the HREC. This includes, but is not limited to, amendments that:

(i) are proposed or undertaken in order to eliminate immediate risks to participants;
(ii) may increase the risks to participants;
(iii) significantly affect the conduct of the research; or
(iv) involve changes to investigator involvement with the project.

Please note that all requests for changes to approved documents must include a version number and date when submitted for review by the HREC.

(3) Reports are provided to the HREC on the progress of the research and any safety reports or monitoring requirements as indicated in NHMRC guidance.

Guidance for the appropriate forms for reporting such events in relation to clinical and non-clinical trials and innovations can be located under the ERM "Help Tab" in "Templates". All adverse events must be reported regardless of whether or not the event, in your opinion, is a direct effect of the therapeutic goods being tested.

(4) The HREC is informed as soon as possible of any new safety information, from other published or unpublished research, that may have an impact on the continued ethical acceptability of the research or that may indicate the need for modification of the project.

(5) All research participants must be provided with the current Participant Information Sheet and Consent Form, unless otherwise approved by the Committee.

(6) This study has approval for four years contingent upon annual review. A Progress Report is to be provided on the anniversary date of your approval. Your first report is due on the anniversary of your approval, and you will be sent a courtesy reminder closer to this due date. Ethical approval for this project will lapse if a Progress Report is not submitted in the time frame provided.

(7) A Final Report and a copy of the published material, either in full or abstract, must be provided at the end of the project.

(8) The HREC is advised of any complaints received or ethical issues that arise during the course of the project.
(9) The HREC is advised promptly of the emergence of circumstances where a court, law enforcement agency or regulator seeks to compel the release of findings or results. Researchers must develop a strategy for addressing this and seek advice from the HREC.

Kind regards,

Ethics Executive Officer

UNIVERSITY of TASMANIA

Appendix B

Participant Consent Form

Participant Consent Form v1.0: 11/2017

PARTICIPANT CONSENT FORM

Understanding the influence of cognitive processing and brain connectivity on rapid motor responses across the lifespan: A model-based neuroscience approach

1. I agree to take part in the research study named above.
2. I have read and understood the Information Sheet for this study.
3. The nature and possible effects of the study have been explained to me.
4. I understand that the study involves making voluntary responses (e.g. button presses) in response to visual stimuli presented on a screen. The activity of my hand and forearm muscles may be recorded using passive self-adhesive electrodes.
5. I understand that participation involves the risk that I may get some minor fatigue from concentrating on the visual stimuli and making repeated movements. Frequent rest breaks will mitigate this risk as much as possible. Minor irritation/redness may occur from the electrodes used to record muscle activity.
6. I understand that all research data will be securely stored on the University of Tasmania premises for five years from the publication of the study results, and will then be destroyed unless I give permission for my data to be stored in an archive.

   I agree to have my study data archived.

   Yes ☐ No ☐
7. Any questions that I have asked have been answered to my satisfaction.
8. I understand that the researcher(s) will maintain confidentiality and that any information I supply to the researcher(s) will be used only for the purposes of the research.
9. I understand that the results of the study will be published so that I cannot be identified as a participant.
10. I understand that my participation is voluntary and that I may withdraw from the experiment at any time without any effect. If I withdraw, my data will be removed from the project

    Following completion of the project I may request that any data I have supplied be withdrawn from the research; any requests to withdraw data must be received within two weeks of completion of the experiment.

Participant's name: _____

Participant's signature: _____

Date: _____

Participant Consent Form v1.0: 11/2017

Statement by Investigator

☐ I have explained the project and the implications of participation in it to this volunteer and I believe that the consent is informed and that he/she understands the implications of participation.

If the Investigator has not had an opportunity to talk to participants prior to them participating, the following must be ticked.

☐ The participant has received the Information Sheet where my details have been provided so participants have had the opportunity to contact me prior to consenting to participate in this project.

Investigator's name: _____

Investigator's signature: _____

Date: _____

Appendix C

Participant Information Sheet

Participant Information Sheet v3.0: 06/2020

PARTICIPANT INFORMATION SHEET

Understanding the influence of cognitive processing and brain connectivity on rapid motor responses across the lifespan: A model-based neuroscience approach

1. Invitation

You are being invited to take part in a research study funded by the Australian Research Council (FT150100406). The research team are:

Lead Investigator:	Dr Mark Hinder
Co-Investigators:	Prof Andrew Heathcote,
Student investigators:	Mr Rohan Puri, Mr Angus Reynolds, Ms Tess Nikitenko, Mr Roderick Garton, Ms Anna Read, Mr Simon Weber, Mr Callum Kilpatrick

2. What is the purpose of this study?

The study will further our understanding of rapid decision-making processes, and inhibitory control in healthy young and older participants.

3. Why have I been invited to participate?

You have been asked to participate as you fulfil the age requirements of our intended cohorts, and have expressed an interest in participating (either via SONA or via other advertisement/email response)

4. What will I be asked to do?

After reading this information sheet you will be asked to provide your (written) consent to participate in the study.

You will then be asked to respond to visual (presented on a black box or computer screen) or auditory stimuli with rapid finger movements or pushing buttons with one or both index fingers. Often, a choice will have to be made as to whether the visual stimulus requires a left or right hand response (decision-making task). This decision may depend on the location or colour of the stimulus, or a perceptual judgement.

In some experiments, EMG will be collected from muscles of your hands and forearms. To ensure the best possible recording, the skin will be prepared by scrubbing it with a mildly abrasive paste and then cleaning it with an alcohol wipe. Self-adhesive recording electrodes will then be placed on the muscle/s of interest and activity recorded to a personal computer for offline analysis.

Sessions may last up to 1.5 hours including all set-up including information and consent, experimentation, breaks and final de-brief. Experiments will conducted online via your internet browser or in the Sensorimotor and Ageing Research Laboratories (Psychology Research Centre, Ground Floor) or the TasCL Laboratory (Social Sciences Bldg, Room 228), both located at the Sandy Bay Campus of UTAS, part of School of Medicine, Division of Psychology. If multiple sessions are required, participants will be informed of this prior during the recruitment process; if multiple sessions are required, at least 24-48 hours will be provided between sessions.

The investigator will inform you of exactly what task you will be doing today, how long it will take, whether muscle recordings are required, and whether multiple sessions are required. You will also receive specific instructions on the computer screen while undertaking the task.

5. Are there any possible benefits from participation in this study?

By participating in the study you are assisting our ongoing research projects which aim to improve the understanding of decision-making and inhibitory control across the lifespan.

You will either receive research credit for participating (via the SONA system – 1 credit per 1 hour completed), $20 Coles-Myer gift card per session, and/or have the chance to win a Coles-Myer gift card ($50/$100/$150, depending on the study size based on how well you perform in the experiment. Please ask the investigator if you are unsure which category you fall into.

6. Are there any possible risks from participation in this study?

While the decision-making tasks are not physically demanding you will be asked to perform multiple blocks of up to ~100 responses (up to ~8 mins per block). To minimise physical and mental fatigue (due to concentrating on the screen, holding hands on buttons), frequent rest periods will be provided throughout the session. We encourage you to stand and stretch, have a drink of water, or have a short walk during these breaks.

While the adhesives used on the electrodes used to record muscle activity are hypoallergenic some participants may feel minor irritation, especially on removal of the electrodes upon completion of the experiment.

7. What if I change my mind during or after the study?

You are free to withdraw at any time and can do so without providing an explanation. If you do withdraw, then your data will not be included in the final analysis.

8. What will happen to the information when this study is over?

The data will be kept for at least 5 years following completion (publication) of the research. This data will not be identifiable to you. De-identified data will be archived, if you consent.

9. How will the results of the study be published?

Data will be published in academic peer-reviewed journals. Following publication, links to articles will be available via the UTAS research portal: https://rmdb.research.utas.edu.au/public/rmdb/q/warp_home

10. What if I have questions about this study?

If you have any questions please contact the lead investigator, Dr Mark Hinder, Mark.Hinder@utas.edu.au, 6226 2945, or ask the investigator who is running the experiment. Other investigators can also be contacted by email (Andrew Heathcote: Andrew.Heathcote@utas.edu.au; Rohan Puri: Rohan.Puri@utas.edu.au; Angus Reynolds: Angus.Reynolds@utas.edu.au; Roderick Garton: Simon Weber: Simon.Weber@utas.edu.au) Callum Kilpatrick: callumk0@utas.edu.au

This study has been approved by the Tasmanian Social Sciences Human Research Ethics Committee. If you have concerns or complaints about the conduct of this study, please contact the Executive Officer of the HREC (Tasmania) Network on +61 3 6226 6254 or email human.ethics@utas.edu.au. The Executive Officer is the person nominated to receive complaints from research participants. Please quote ethics reference number H0016981."

Should you wish to participate, you may keep this information sheet for your records; you will also be asked to sign a consent form. Thank you.