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Attentional Factors in Global and Selective Response Inhibition in 5- and 6-year-olds

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Abstract

The ability to suppress inappropriate actions at a given time is known as response inhibition. Previous research suggests that there are multiple mechanisms supporting inhibition: a “global stopping” mechanism may be used to suppress all behavior and a “selective stopping” mechanism may be used to suppress specific actions while allowing for the concurrent execution of desired actions. These mechanisms of response inhibition are well understood in adults; however, these mechanisms have not been thoroughly examined in children. In order to assess response inhibition in 5 and 6 year olds, we developed a child adapted version of a measure of response inhibition known as the stop signal task. We hypothesized that some 5 and 6 year old children will reproduce basic effects of selective vs. global stopping mechanisms previously observed in adults while other children may show an under-developed pattern. We found that children do not utilize the same response inhibition mechanism as adults. We also observed that attention deployment, rather than the stopping pathways, may play a larger role in children’s ability to inhibit their actions.

Introduction

As adults, we are often faced with situations where we must stop a behavior. This may be to avoid doing something undesirable or to attend to something more important. Young children, however, have particular difficulty controlling their behavior in this manner. For example, a parent may say to a child, “do not touch the cookie until you have finished the food on your plate,” and the child may fail to do as told – perhaps because it is difficult for children to inhibit the desirable action of eating a cookie in order to attend to the task of eating food on their plate. This ability to suppress inappropriate actions is called response inhibition. Response inhibition is thought to underlie many cognitive abilities, including switching tasks and delay of gratification (Barkley et al., 1997; Diamond et al., 1996; Miyake et al., 2000). The purpose of the current study is to dissociate different types of response inhibition. This may provide insight into how children control their actions.

Response inhibition is thought to be involved in other cognitive areas such as task switching and working memory. Studies on impulse and inhibitory control have shown age-related improvements in children such that children ages three to seven have more difficulty than children ages seven and above in inhibiting inappropriate responses (Kochanska et. al., 1997). Young children also have marked difficulty in task switching; for example, children can easily sort cards by a specific dimension, such as color, but often fail when later asked to sort the cards according to a different dimension, such as shape (Zelazo et al., 1996). Finally, working memory is also thought to improve with age. For example, performance in the digit span task is positively correlated with age (Cowan et al., 1999). Since response inhibition plays a role in various aspects of cognitive abilities, examining this in children may yield further understanding of impulse and self-control. In order to determine how children control their actions, we utilize a newly-developed test of response inhibition.

Numerous tasks are used to assess response inhibition in children, including the Go/NoGo task (Brocki & Bohlin, 2004), the day/night task (Gerstadt et. al, 1994), and the tapping task (Luria, 1966) .One of the most sophisticated measures of response inhibition is the Stop Signal task. However, this task has rarely been used to measure inhibition in children.

In the Stop Signal task, subjects respond as fast as possible to either left- or right-pointing arrows by pressing buttons with their left or right hands, respectively. On a minority of trials, a “stop signal” appears at a variable delay following the onset of the arrows, and the subject attempts to stop his/her response. By adapting the delay according to subjects’ performance, a mathematical model known as the race model (Logan and Cowan, 1984; Band et al., 2003) can be used to calculate the stop signal reaction time (SSRT). SSRT can be understood as the amount of time that is needed to stop a response (see Figure 1). This task is currently thought to yield precise estimates of stopping ability, and might be productively used in developmental research.

However, recent work indicates that the Stop Signal task might confound multiple forms of stopping (Aron & Verbruggen, 2008). In particular, a “global stopping” mechanism may be used to suppress all behavior, and a “selective stopping” mechanism may be used to suppress specific actions while allowing for the concurrent execution of desired actions. These two mechanisms may rely on two discrete pathways within the basal ganglia: an indirect pathway between the prefrontal cortex and the basal ganglia for selective stopping and a “hyperdirect” pathway between the prefrontal cortex and the subthalamic nucleus for global stopping (Aron & Verbruggen, 2008). The indirect pathway contains more synapses and also more focal projections, supporting the selective stopping mechanism (see Figure 2). The hyperdirect pathway has less synapses and more global projections, supporting the global stopping mechanism. One or both of these mechanisms might contribute to performance on the standard stop task.

Recent modifications to the stop task have been argued to dissociate these two distinct forms of stopping. In this modified version of the Stop Signal task, a cue precedes the onset of the go stimuli, informing the subjects they may need to stop their responses on the next trial. If subjects are cued about which hand they may need to stop, they may be more likely to use the selective stopping mechanism than if they had not been cued. Indeed, subjects require significantly more time to stop an initiated response successfully when they are cued versus when they were not cued, yet show less stopping-interference effect in concurrently executing other behaviors, consistent with the use of the slower and more selective stopping mechanism (Aron & Verbruggen, 2008).

Neuronal differentiation of the indirect and hyperdirect pathways may be adult-like as early as 4 years of age, as indicated by a lack of detectable change in globus pallidus volume between ages 4 and 18 (Giedd et al., 1996). However, whether these pathways are functionally mature in young children and whether they can be cognitively dissociated as they can in adults is yet to be determined. This absence of evidence leaves open an interesting possibility: children's marked difficulty with response inhibition might reflect the fact that they have only one pathway available, or that they are inflexible in which pathway they use. We hypothesize that the global and selective stopping pathways may still be developing in middle childhood. Thus, some 5-6 year old children will reproduce basic effects of selective vs. global stopping previously observed in adults while other children may show an immature pattern.

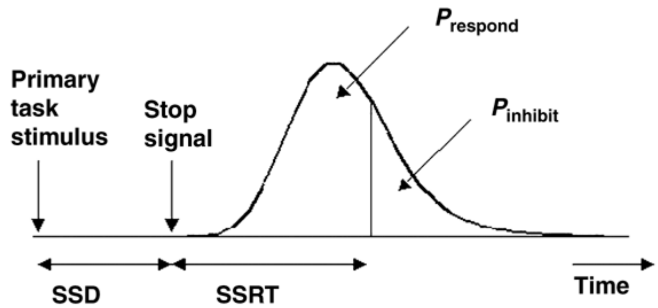

Figure 1. Race-model estimation of SSRT A distribution of no-signal RTs (go trials) is shown beneath the curve. On stop trials, a tone occurs after the primary stimulus at a particular stop-signal delay (SSD). The stop signal divides the no-signal RT distribution into two probabilities: a left part consisting of responses fast enough to escape inhibition ($P_{respond}$) and a right part corresponding to $P_{inhibit}$. Provided SSD is varied to yield 50% $P_{inhibit}$ (the point of median no-signal RT), SSRT is estimable by subtracting average SSD from median no-signal RT. We ensured convergence to 50% $P_{inhibit}$ by using step-up and step-down interleaved staircases. If the subject inhibited successfully on a stop trial, then inhibition was made more difficult on the next stop trial by increasing the SSD by 50 ms; if the subject did not successfully inhibit on a stop trial, then SSD was decreased by 50 ms. Average SSD was computed from the values of four staircases after convergence on 50% $P_{inhibit}$. Taken from Aron et. al, 2003

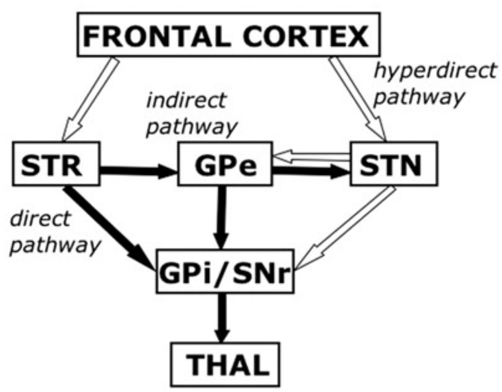

Figure 2. A basal-ganglia model and the Stop-Signal paradigm An influential model proposes three pathways through the basal ganglia (direct, indirect, and hyperdirect). The direct pathway through the basal ganglia is excitatory therefore; it will not be analyzed in this study. SNr, Substantia nigra; THAL, thalamus; STR, striatum. Open arrows are excitatory (glutamatergic); filled arrows are inhibitory (GABAergic). Taken from Aron & Poldrack, 2006

The Current Study

In order to test our hypothesis, we have developed a child-friendly version of the stop signal task, including cued and uncued conditions allowing us to independently measure the efficiency of stopping and its selectivity in developing children (Aron & Verbruggen, 2008). The stop signal paradigm consists of a go task and a stop task. On each trial, a left- or right-pointing arrow stimulus is displayed on a computer screen. On the go task, the subject is to respond as fast as possible with a left or right button press. For the Stop task (25% of trials), the subject attempts to stop his/her response when a stop signal is presented. One challenge in adapting the stop signal task for children is that they often fail to attend to cues that are relevant to future behavior (Chatham et al., 2009). To ensure that children attend to and process the cues in this task, we used an eye-tracking device to measure eye movements and positions. In addition to the stop signal task, we also administered other tasks such as the 1-Dimensional Change Card Sort, as a measure of working memory (Blackwell, Cepeda & Munakata, 2009), the 3-Dimensional Change Card Sort as a measure of task-switching (Blackwell, Cepeda & Munakata, 2009), and Prosaccades and Offset RT as measures of general processing speed (Pratt & Trottier, 2004). Only the results collected from the Stop task will be discussed here.

Methods

Participants

There were 70 five and six-year-old participants ranging from 67-75 months (40 males and 30 females). Each participant's parent received and signed an informed consent form. 6 participants were not analyzed due to the participants quitting in the middle of the task.

Materials, Design, and Procedure

Each participant completed the tasks in a set order within a one 90-minute session: Choice RT, Global Stop task, Double RT, Selective Uncued Stop Task, Selective Cued Stop task, Prosaccades, OffsetRT, 3-Dimensional Change Card Sort (3DCS), and 1-Dimensional Change Card Sort (1DCS). The experimenter was available throughout the session to answer task-related questions.

Choice RT. This task was used as a control measure of reaction time. In this task subjects were introduced to "George the Monkey" and told to press a button with their left hand if a banana appeared to George's left and with their right hand if a banana appeared to George's right. The experimenter then demonstrated how and when to respond on two successive trials. The child completed 24 subsequent trials with a randomly-selected interstimulus interval of 1.2-2s. Upon completion of the task, the child was allowed a short break to pick a small prize (one sticker or toy). The median RT was then calculated by the computer, trials exceeding the median RT by a factor of 2.3 or more were excluded, and the median was recalculated. This median was used throughout subsequent tasks to ensure that subjects did not attempt to slow down.

Global Stop. This task was used to measure the speed with which subjects stopped their responses (Stop Signal Reaction Time). Subjects were told, "Now, we are going to keep giving

George the bananas but George doesn't like brown bananas. If you see a banana over here and it turns brown, you do not want to push this button and if you see a banana over there and it turns brown, you don't want to push that button. George likes the yellow bananas but not the brown ones, those make him sick. You got it? First I get to try and when I'm done, you get to try." The experimenter would then demonstrate the task on 4 trials, 2 of which constituted signal trials, one with a signal delay of 50ms and the other with a delay of 600ms. Subjects were then given 24 practice trials. Signals were presented with 33% frequency, and with an initial signal delay of 600ms. This delay was adjusted according to an adaptive staircase algorithm, such that signal onset delay was lengthened by 50ms following a successful stop, and shortened by 50ms following unsuccessful stops. The child then completed 3 blocks of 48 trials each, with short breaks to select a prize in between each block. If on any trial the reaction time was 2.3 times the median RT calculated above, a "ding" sound was played by the computer and the experimenter encouraged the child to press the buttons more quickly.

Double RT. Participants were told "Now two bananas are going to show up at once and you'll get both bananas by pushing these two buttons at the same time. This way, we can get George twice as many bananas. All the bananas will be yellow for now so you don't have to worry about the brown ones." Participants completed 32 trials of this task. If the reaction times of the left and right hands differed by 200ms or more, a recorded voice would say "press the buttons at the same time." The purpose of this task was to give children some practice with responding with both hands, and to ensure that they understood the requirement to press both buttons simultaneously.

Uncued Selective Stop. In this task, subjects had to stop an initiated response while concurrently executing a desired response. They were told “Now, one of the bananas might turn brown. Remember, George doesn’t like brown bananas. Only give him the yellow ones.” The experimenter completed 4 demonstration trials (2 of which were signal trials); next, the subject completed 24 practice trials, followed by 3 blocks of 48 test trials. If at any time subjects did not press the buttons within 200ms of each other, a recorded voice says “Press the buttons at the same time.” Similarly, if any reaction time was larger than 2.3 times the median calculated above, the computer would make a “ding” sound and the experimenter would encourage the subject to press the buttons faster. Signal onset delays began with the asymptotic value reached in the Global stop task and continued to be adjusted in this task, according to the same adaptive algorithm.

Cued Selective Stop. In this task, children were given cues as to which hand they may need to stop. They were told, “Now George thinks he can smell which one of the two bananas might turn brown. If he thinks the banana over here might turn brown, he’ll point at it and if he thinks the banana over there might turn brown, he’ll point at it. Only the banana he points at might turn brown but sometimes George might be right and sometimes he might be wrong so you just have to pay close attention. You got it?” The experimenter then completed 4 demo trials, and the child completed 24 practice trials followed by 3 blocks of 48 test trials. Signal onset delays were modified via the adaptive algorithm, and reaction times were monitored for inter-response intervals greater than 200ms and reaction times larger than 2.3 times the median.

Prosaccades. This task was used to measure the speed at which subjects were able to detect a peripheral stimulus. In the task, they were instructed to look at the center target at the beginning of each trial, but promptly follow the target's movement to the peripheral fixation point when it moved, and hold this gaze until the target returned to the center.

Offset RT. In this task we measured the speed it took subjects to detect visual stimuli. Subjects placed one finger on a star in the corner of the screen and attempted to "pop" blue circles that appeared on the screen by pressing them. Reaction time to remove their finger from the star (finger-offset or finger-lift RT) was recorded across 10 trials.

3-Dimensional Change Card Sort (3DCS). This task was used to measure the frequency with which children were able to switch between tasks. The top half of the screen contained three target images: a large blue cat, a small yellow fish, and a medium red bird (Figure 3). The task was divided into three blocks (shape, color, and size) in which participants were asked to match pictures by the current dimension. Pre-recorded video clips in the lower left-hand corner of the screen relayed instructions. For each block, participants were asked to identify all stimuli by the current dimension (e.g. "Can you press the cat?"), informed of the dimensions for the game (e.g. "In the color game, when you see a red one, press the red one."), asked three non-conflict questions about the game (e.g. "In the size game, what do you press when you see a small one?"), and presented with 12 individual stimuli that matched one target on each one of the dimensions (e.g. a large yellow bird). No feedback or instructions were provided after the introduction of the task. Stimuli were presented in a pseudo-random order so the next stimulus could not be predicted by the participant. Children were categorized by performance on the color and size blocks, as “switcher” (75% to 100% correct) or “perseverator” (0% to 25% correct). Children who accurately categorized 25% and 75% correctly were not analyzed in the data.

1-Dimensional Change Card Sort (1DCS). The 1D card sort was used to measure the speed with which it took subjects to sort the cards. The reaction times were then compared to the reaction times in the 3DCS. The task consisted of 20 trials of simple queries, 10 auditory and 10 visual, about the dimensions for a pattern game. Children were encouraged to respond “as fast as you can,” to encourage goal maintenance. The top half of the screen contained two target images that were present throughout the task: stripes and dots (Figure 4). Pre-recorded auditory clips relayed instructions. First, children were instructed to follow auditory requests in the absence of visual stimuli: “In the pattern game, when I say tap the stripes/dots, tap the stripes/dots.” Trials were presented in random order, with the verbal prompt, “In the pattern game, which do you tap for the stripes/dots?” Next, children were instructed to respond to visual stimuli exactly matching one target presented on the bottom half of the screen: “In the pattern game, when you see stripes/dots, tap the stripes/dots at the top.” Trials were presented in random order, with images appearing at the end of the verbal prompt, “In the pattern game, which do you tap for this one?” All responses were made by pressing one of the targets; reaction time was recorded upon target press.

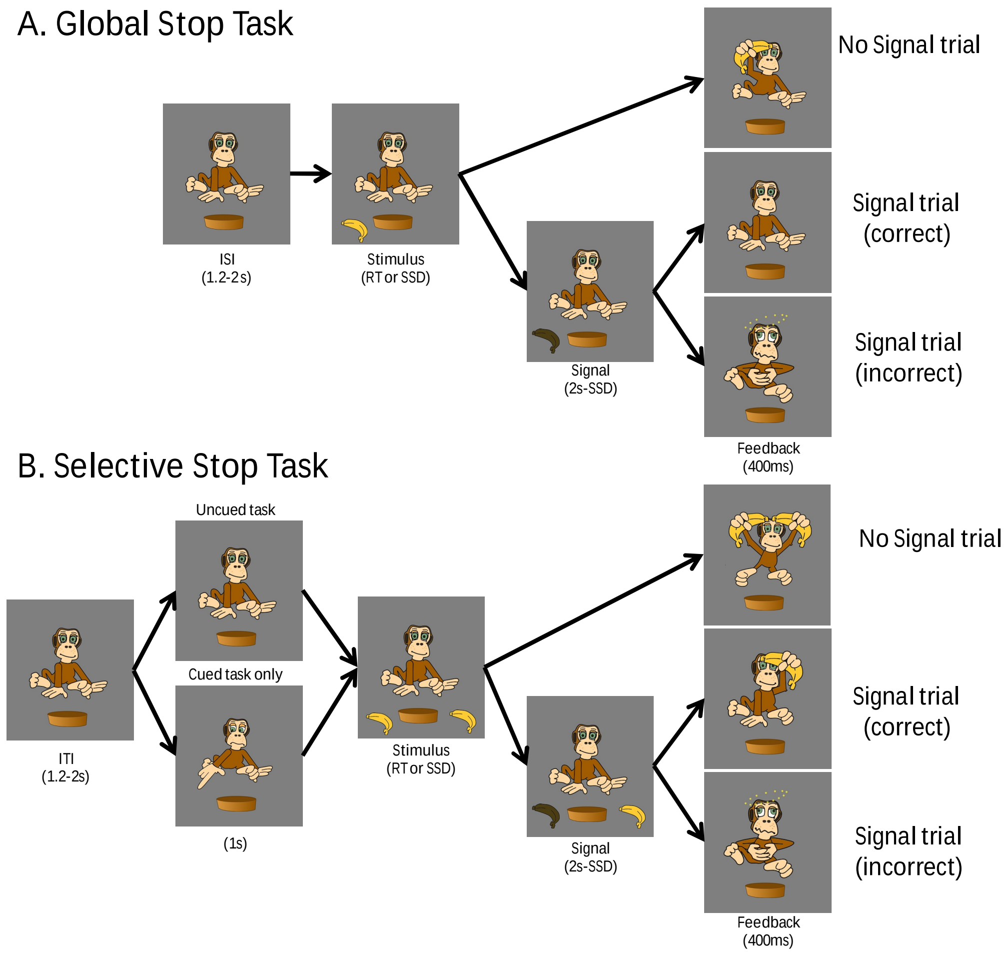

Figure 3. A) In the Global Stop Task, each trial begins with presentation of George without any bananas; following a variable intertrial interval, a yellow banana appears. On No Signal trials (and the preceding ChoiceRT task) this stimulus remains on screen until subjects press the corresponding button on a button box (with the left hand for bananas on the left and with the right hand for bananas on the right). On Signal trials, the banana turns brown with a variable stop signal delay (SSD) which remains on screen until subjects respond (in which case the monkey appears ill) or until the termination of the trial. **B)** As in A, trials begin with the presentation of George without any bananas. In the uncued selective stop task (as well as the Double RT task) the next stimulus is of George with two bananas. On No Signal trials (and the Double RT task), this stimulus remains onscreen until subjects press both buttons, at which point George is shown grasping the two bananas. On Signal trials, one of the two bananas turns brown with a variable SSD. If subjects press the button corresponding to the brown banana, George is shown to be ill; otherwise subjects are then shown an image of George grasping the yellow banana. The selective Stop Task differs only insofar as an additional stimulus is presented, for 1 second, which shows George pointing to the banana that may turn brown.

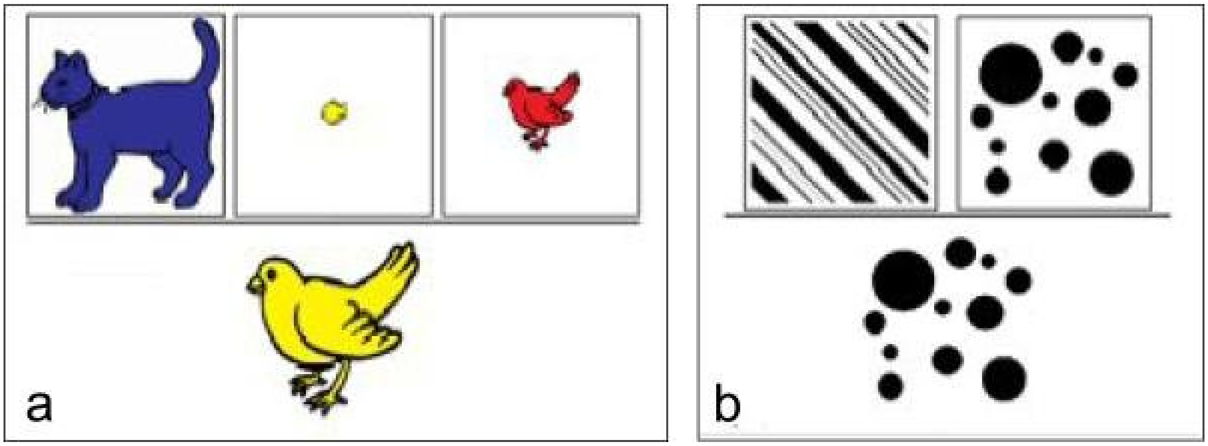

Figure 4. A) 3D Card Sort. Participants selected one of the three target cards along the top row on each trial. Conflict stimuli matched each target on one dimension. No stimuli appeared on the lower half of the screen during simple query trials. **B) 1D Card Sort.** Participants selected one of the two target cards on each trial. Stimuli exactly matched one of the two targets, so no inhibition of an irrelevant dimension was necessary to complete the task. No stimuli appeared on the lower half of the screen during auditory trials. Taken from Blackwell Cepeda & Munakata, 2009

Results

The results from the study are described as follows. First, we describe the data trimming procedures for the stop signal task. Next, we seek to validate the race model assumptions underlying the reliable calculation of SSRT. To examine the selective vs. global stopping hypothesis, we then assess the effects of cueing on SSRT and stopping-interference effect, and its relationship to global SSRT. Next, we describe the results from the gaze data analyses, which show that gaze pattern influences SSRT but not stopping-interference effect. Finally, we perform a novel *correlational* analysis of stopping-interference effect and SSRT which suggests that SSRT and the stopping-interference effect may be intrinsically correlated.

Data Transformations and Outlier Analysis

Following a preliminary view of our data, trimming procedures were performed on the stop signal RT measure for each participant. The trimming procedure eliminated responses that were too fast to be valid (perhaps an incorrect key stroke) and responses that were too slow (failure to respond). For each task, RTs falling 2.5 standard deviations outside of the mean were eliminated. Also in the double RT task in which participants had to elicit a response using both hands, RTs were excluded if the second hand’s response was more than 200ms apart from the first hand’s response.

Preliminary Analysis: Race Model Assumptions Are Verified

The stop signal paradigm has three assumptions that must be met in order to ensure its reliability in providing an accurate SSRT measure. In this study, all three requirements were met (Figures 5-6). First, RTs on trials where participants failed to stop should be less than the average go RT, validating the claim of Logan's horse race model that stop and go processes race to completion and whichever is finished first will drive behavior (Aron & Poldrack, 2006). This was confirmed in all three phases of the experiment (global: t(60)=13.42, p<..001; uncued: t(57)=10.46, p<.001; cued: t(60)=12.05, p<.001). Next, SSRT and go RT from the go trials on the stop signal task should not be correlated, validating the assumption that there are indeed independent stop and go processes. We confirmed this assumption (R=.01, R=-.12, R=.08; all p>.35)). Finally, stopping accuracy should be the same because an adaptive algorithm was utilized. In the uncued and cued blocks, we found that stop signal accuracy was significantly below 50% (t(61)=5.77, p<.001; t(59)=5.71, p<.001). This was most likely due to fatigue. However, the decrease in stopping accuracy is negligible because the accuracy is between 35 and 85%, which is sufficient for reliable extraction of SSRT (Band et al., 2003).

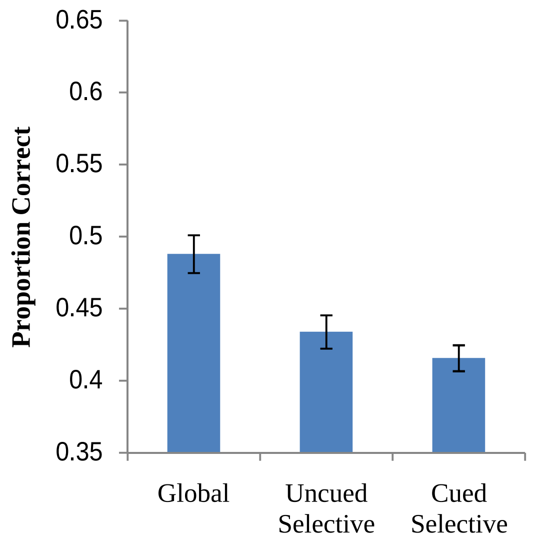

Figure 5. Stop signal accuracy as a function of task type. This graph shows the validation of one of the requirements validated for calculating SSRT. Stop signal accuracy is between 35 and 85% on all task types.

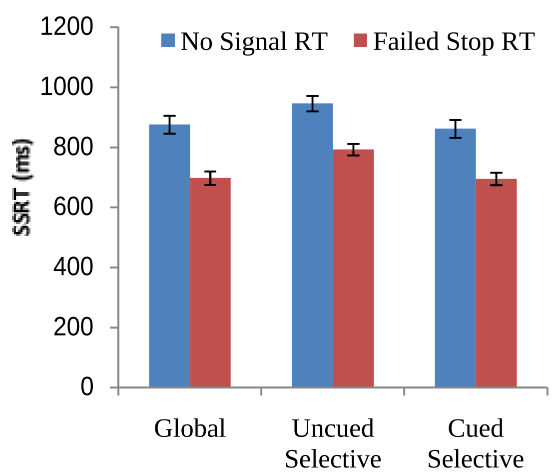

Figure 6. Stop signal reaction times as a function of task type. This graph depicts the validation of another requirement validated for calculating SSRT. In each task type, failed Stop RT is less than GoRT indicating that stopping and going are two independent processes.

Unexpected Effects of Cueing on SSRT and Stopping-interference effect

We hypothesized that cued SSRTs would be slower than uncued SSRTs because cueing should engage the selective stopping pathway which contains more synapses. However, our results demonstrated the opposite effect; cued SSRTs were faster than uncued SSRTs (Figure 7; t(58)=2.64, p=.011). This finding is unexpected because according to the stopping pathways model, cues should engage the slower, more selective stopping pathway, leading to slower SSRTs and a decreased stopping-interference effect. Our results also showed that there is no significant difference in the stopping-interference effect in both the cued and uncued blocks (Figure 8; t(58)=0.51, P=0.61). Although the stopping-interference effect is not significant, the results are going in the opposite direction of what would have been predicted. Once again, if the selective stopping pathway is engaged when cues are presented, we should observe an increase in SSRT and a decrease in the stopping-interference effect. The multiple stopping pathways model is used in adults to explain performance on the stop signal task. However, this model may not be sufficient for explaining unexpected results, suggesting that there may be other phenomena driving these results.

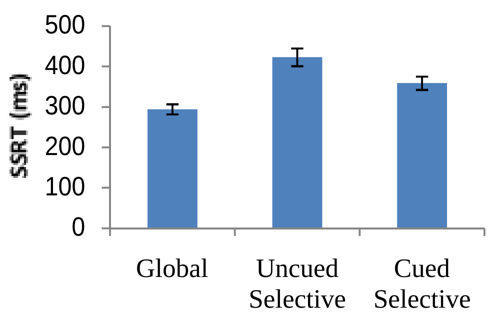

Figure 7. SSRT as a function of task type. This graph shows SSRT across the global, uncued and cued task types. Global SSRT is the smallest. Contrary to the expectations from the stopping pathways model, cued SSRT is smaller than uncued SSRT.

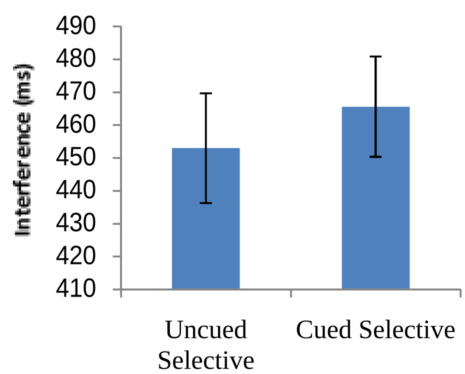

Figure 8. Stopping-stopping-interference effect as a function of condition (uncued or cued selective blocks). This graph depicts a smaller stopping-interference effect in the uncued block than in the cued block. This is also contrary to what is expected based on the stopping pathways model.

Unexpected Results May Reflect Gaze Differences Between Children

One possibility for the smaller SSRTs observed in the cued block is that cueing helps children attend to the correct part of the screen. In the uncued blocks, we noticed that children attending to the part of the screen where the banana will turn brown showed the results similar expected pattern of being slower in the cued blocks than in the uncued blocks. Children attending to the wrong part of the screen showed results similar to the unexpected pattern of being faster in the cued blocks than in the uncued blocks. The result patterns, based on where children are looking, suggested that we should examine the data by dividing children into two categories according to whether they showed a "task-relevant" pattern of gaze or a "distracted" pattern of gaze. Children with a task-relevant gaze pattern are attending to the location where the brown banana may possibly appear and children with a distracted gaze pattern are attending to other parts of the screen instead of where the banana might turn brown.

Our results showed that the effect of cueing on SSRT is different in the two groups. We found that children with a task-relevant gaze pattern showed similar results to the expected pattern of decreased SSRT in the uncued blocks versus in the cued blocks. We also found that children with a distracted gaze pattern had significantly increased SSRTs in the uncued block versus in the cued block (Figure 9). The difference in SSRT as a function of cueing significantly interacted with gaze maturity ($F(1, 39)=7.60$, $P=.009$), indicating that children with distracted patterns of gaze showed a disproportionately large SSRT on the uncued block, relative to the cued block. Although gaze patterns influenced SSRT as a function of cueing, they did not influence the stopping-interference effect as a function of cueing (Figure 10; ($F(1, 39)=0.61$, $P=.44$)). Nonetheless, gaze patterns did influence the stopping-interference effect overall, such that the stopping-interference effect was larger for subjects with task-relevant patterns of gaze across both the cued and uncued blocks (F(1,39)=4.79, p=.035). These findings suggest that the children showing the distracted gaze pattern are primarily contributing to the unexpected results in terms of SSRT.

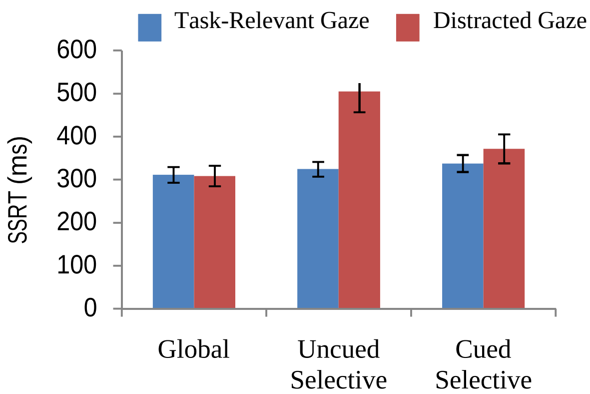

Figure 9. SSRT as a function of gaze pattern in task types. This graph shows no effect of gaze pattern on SSRTs in the global condition**.** Consistent with the stopping pathways model, "task-relevant" gaze children show smaller SSRTs in the unced conditions than in the cued conditions. "Distracted" gaze children show a significant increase in SSRT in the uncued than in the cued block.

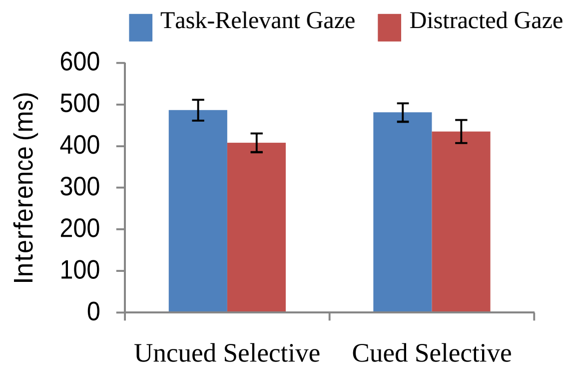

Figure 10. Stopping-stopping-interference effect as a function of gaze pattern in the uncued and cued conditions. This graph demonstrates that there is no significant effect of gaze pattern on stopping-interference effect in both conditions.

Gaze Differences Do Not Affect Noncritical Measures

From the results reported above, gaze pattern influences SSRT but not the stopping-interference effect. In order to determine if gaze pattern influences other measures, we looked at gaze pattern as a function of goRT (go reaction time - measure of the speed with which a response is generated) and stop signal accuracy. There is a marginal effect of gaze maturity on go RT (Figure 11; F(1,38)=3.16, p=.083) but gaze maturity does not interact with task type. In all three blocks, there were no significant differences between RTs of children with task-relevant and distracted gaze patterns. In instances when subjects failed to stop their responses, we also found that there were no significant differences between RTs of children with task-relevant and distracted gaze patterns (Figure 12). Our results also showed that there were no significant effects of gaze maturity on stop signal accuracy showing that the pattern of gaze did not affect participants' stopping percentages (Figure 13).

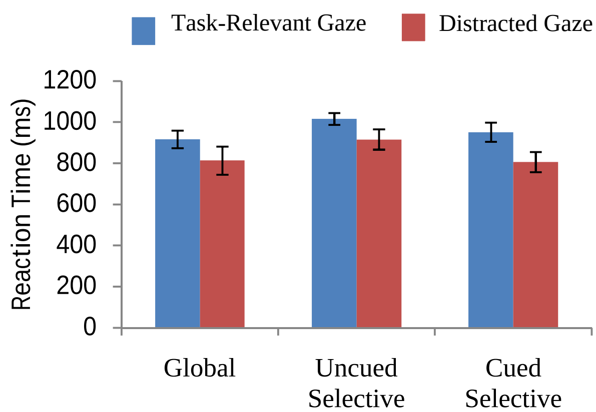

Figure 11. GoRT as a function of gaze pattern in task types. This graph shows the effect of gaze pattern on goRT. There is a marginal effect on goRT; however, gaze pattern does not interact with task type.

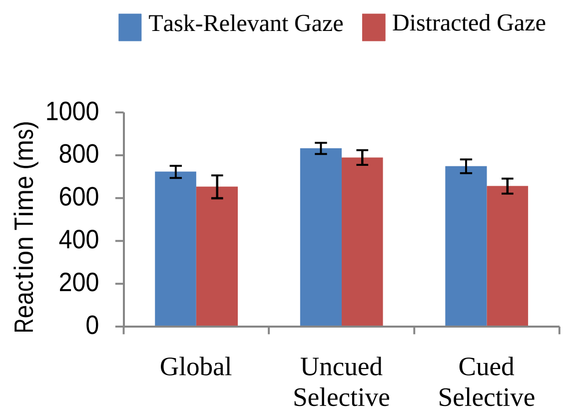

Figure 12. Failed to stop RTs as a function of gaze pattern in task types. This graph demonstrates that there are no significant differences between the RTs of "task-relevant" gaze children and "distracted" gaze children.

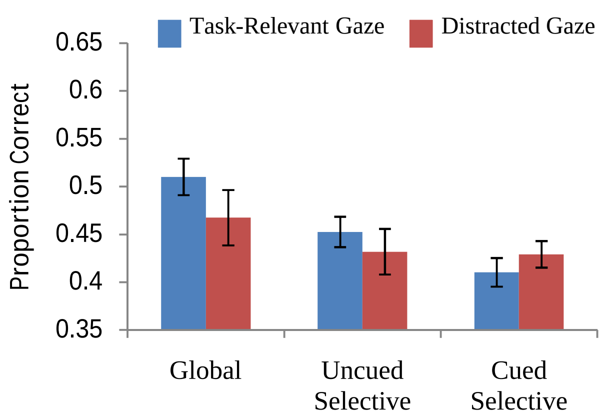

Figure 13. Stop signal accuracy as a function gaze pattern in task type. This graph illustrates that in all three task types, gaze pattern does not influence the percentage of stop signal trials that are successfully inhibited.

SSRT and Stopping-interference effect may be intrinsically correlated

According to the stopping pathways model, the direct pathway used in global stopping contains less synapses and less focal projections than the indirect pathway used in selective stopping. Therefore, if cueing gives rise to increasing use of the selective pathway, SSRT will be larger, and the stopping-interference effect will be smaller on the cued blocks than uncued blocks (Aron & Verbruggen, 2008). This tradeoff between the change in SSRT and the change in stopping interference observed as a function of cueing should result in a negative correlation.

However, there is an alternative interpretation of this tradeoff that is more consistent with the rest of our results, which do not suggest greater use of the selective pathway for stopping in the cued than uncued blocks. In particular, if some manipulation increases SSRT, the same manipulation may by necessity also decrease the stopping-interference effect, for the simple reason that when stopping occurs later (i.e., longer SSRT), it will be more likely to occur after the not-to-be-stopped hand has responded and thus cannot possibly interfere with it. Conversely, if stopping occurs earlier (i.e., shorter SSRT), it will be more likely to occur before the not-to-be-stopped hand has responded, and thus more likely to interfere with it.

In order to ensure that the correlation between SSRT and interference was not due to additional variables, we correlated the individual scores of SSRT and interference (Figure 14). Indeed, we found that the change in stopping-interference as a function of cueing was negatively correlated with the change in SSRT as a function of cueing. Moreover, this correlation does not differ between gaze groups, suggesting that SSRT and stopping-interference may be intrinsically negatively correlated. Since interference is a product not only of how quickly one can stop (i.e., SSRT), but also how quickly one is likely to respond (i.e., goRT) the use of a difference score may control for this latter source of between-subject variance. Consistent with this idea, we observed that goRTs were highly reliable across tasks (R=.74, p<.0005), and that controlling for goRTs when correlating SSRT and interference increased the absolute magnitude of the negative correlation (from R=-.14 [p>.1] to R=-.15 [p>.1] in the cued block, and from R=-.22 [p > .1] to R=-.29 [p<.05]) in the uncued block. This suggests that interference is negatively correlated with SSRT, but that additional confounding factors, such as goRTs, may dilute this correlation unless they are controlled for.

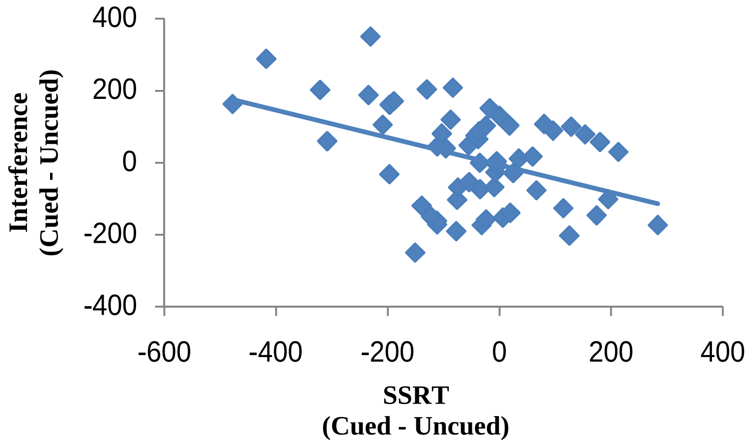

Figure 14. Correlation of interference difference scores as a function of SSRT difference scores. This figure shows that interference and SSRT are negatively correlated when confounding factors such as goRT are controlled for.

Discussion

In this study, we examined the possible mechanisms underlying response inhibition. Previous research suggests that the direct and indirect pathways may be responsible for suppressing inhibition. In the adult literature, providing cues about which response to stop through cues engages the selective stopping mechanism (Aron & Verbruggen, 2008). We hypothesized that some children would show patterns similar to adults while other children would show opposite or different patterns. Our results demonstrated that children are not showing the expected adult-like patterns. We observed that it takes children *longer* to stop in the blocks where they have no cue about which hand to stop than in the blocks where cues are given. Based on the stopping pathways and previous work done in adults, the cues should engage the selective stopping pathway which allows the suppression of specific tendencies without suppressing all current tendencies. Because the selective stopping pathway contains more synapses, the presence of the cues should result in an increase in the amount of time needed to stop a response. Also, the selective stopping pathway has more focal projections resulting in a smaller stopping-interference effect - the response on the hand that needs to be executed should not interfere with the hand that needs to be stopped. In contrast to these predictions, our results show that with the help of cues, children are showing an increased stopping-interference effect and smaller SSRTs. This inconsistency with the stopping pathways model implies that our results are not driven by children's underdeveloped pathways or their inability to use the pathways.

One possible explanation for these unexpected results is the role attention may play in response inhibition, particularly in children in the age range used in the study. Children paying attention to the correct side of the screen (without the help of cues) showed a more adult-like pattern. Children looking at uninformative locations on the computer screen showed different patterns of what is observed in adults. We categorized children as having “task-relevant” or “distracted” gaze patterns and found that the children with a task-relevant gaze pattern were the ones that had larger SSRT in the cued blocks than in the uncued blocks. These children also showed similar stopping-interference effect levels in both blocks. However, children with distracted gaze patterns had a smaller SSRT in the cued block than in the uncued block. They also had an increased stopping-interference effect in the cued blocks than in the uncued blocks.

One explanation of these results is that children with the distracted gaze pattern may be using a reactive pattern (Chatham, Frank & Munakata, 2009) where they are reacting to situations only as they happen and not planning ahead. In this case, children may be attending to the monkey until the cues prompt them to look at the relevant portion of this display - the locations where the bananas appear and may turn brown. One thing to note is that middle childhood is a period where critical changes are occurring in the brain more specifically, the prefrontal cortex (Kanemura et al., 2003)**.** These unexpected effects of cueing on SSRT and the stopping-interference effect could reflect immature pathways. However, based on the gaze data, it is clear that deployment of attention plays an important role in the development of response inhibition.

There is an observed stopping-interference effect in stop signal tasks such that response from the hand that needs to be executed is slowed if the other hand's response must be inhibited (Coxon, Stinear, & Byblow, 2007). Previous studies have shown that when cues are presented, SSRT and the stopping-interference effect tend to go opposite directions such that a longer SSRT correlates with a smaller stopping-interference effect. Our results suggest that there may be an intrinsic tradeoff between the stopping-interference effect and SSRT. In instances where stopping occurs later (i.e., longer SSRT), interference is more likely to occur after the hand that needs to be executed has responded and thus, the hand that needs to be stopped cannot interfere with the speed with which the hand that needs to be executed responds. On the other hand, if stopping occurs earlier (i.e., shorter SSRT), interference will be more likely to occur before the hand that needs to be executed has responded and thus, the hand that needs to be stopped is more likely to interfere with it.

One caveat to interpreting these results is that children's performance can be very task-dependent (Munakata, 2001). The stop signal task is a particularly long and laborious technique for measuring response inhibition. For this reason our results may in part reflect accumulating fatigue as the task progressed, in addition to the differences between types of response inhibition we attempted to measure.

One of our key motivations was to expand our understanding of response inhibition so that we can utilize such knowledge to possibly build upon current models of neurological disorders such as ADHD, OCD, and various others. In several of these cases, inhibitory deficits are thought to play a role in the abnormal behaviors that characterize such pathologies. These inhibitory deficits may have an origin in response inhibition, or may relate more directly to the kinds of immature attentional deployment we observed here in children. Thus, our work adds to the broad literature on immature attentional deployment in children by suggesting that attention is an important component of the inhibitory processes, and may play a role in disorders currently characterized by inhibitory deficits. This study also shows importance of utilizing gaze data in interpreting results. Had we not collected gaze data, we might have focused on the selective stopping pathways model as an explanation of our results. Instead, the analysis of gaze data revealed that attentional deployment is a more viable interpretation of our results.

Future work will focus on running the stop signal and three-dimensional card sort tasks in older children (72 month olds). This will help determine if there is a correlation between card-sorting task performance and response inhibition in the stop signal task. Future work will also observe the role of attentional deployment in these tasks. The stop signal task is also currently being piloted in adults to see if we can reproduce the effects from the previous adult study.

Conclusion

We used the child-adapted stop signal task to measure response inhibition in 5 and 6-year-olds. Our results demonstrate that children do not show similar patterns of response inhibition as adults in terms of the stopping pathways model. This suggests that there may be other phenomena that play into response inhibition. We also found that there may be an intrinsic tradeoff between the stopping-interference effect and stop signal reaction time. This account is speculative and other factors may explain the unexpected results. These lingering questions create interesting avenues for future research concerning response inhibition.

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