Performance Monitoring in Children Following Traumatic Brain Injury Compared to Typically Developing Children

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Abstract

Children with traumatic brain injury are reported to have deficits in performance monitoring, but the mechanisms underlying these deficits are not well understood. Four performance monitoring hypotheses were explored by comparing how 28 children with traumatic brain injury and 28 typically developing controls (matched by age and sex) performed on the stop-signal task. Control children slowed significantly more following incorrect than correct stop-signal trials, fitting the error monitoring hypothesis. In contrast, the traumatic brain injury group showed no performance monitoring difference with trial types, but significant group differences did not emerge, suggesting that children with traumatic brain injury may not perform the same way as controls.

Keywords

performance monitoring, stop-signal task, traumatic brain injury, pediatrics

Performance monitoring refers to the ability to oversee the accuracy of one's ongoing performance and to make adjustments to future performance in order to meet one's goals.[1-3] The ability to monitor one's performance is critical to cognition, behavioral self-regulation, learning, and social competence and has been found to be deficient in some children who have experienced a traumatic brain injury.[4-6]

In the context of tasks involving dual demands of speed and accuracy, performance monitoring refers to the detection of errors and post error adjustments in speed of responding as well as to the detection of correct responses. The stop-signal task sets up a laboratory analogue of a real-life situation in which one has to balance speed and accuracy while being prepared to inhibit a response when required to do so. In the typical stop-signal task,[7] participants perform a speeded choice reaction time task (go-trials) and on a random subset of trials (stop-trials), a tone (stopsignal) is presented which signals the participants to withhold their response. The stop-signal task affords an opportunity to study the way in which participants monitor

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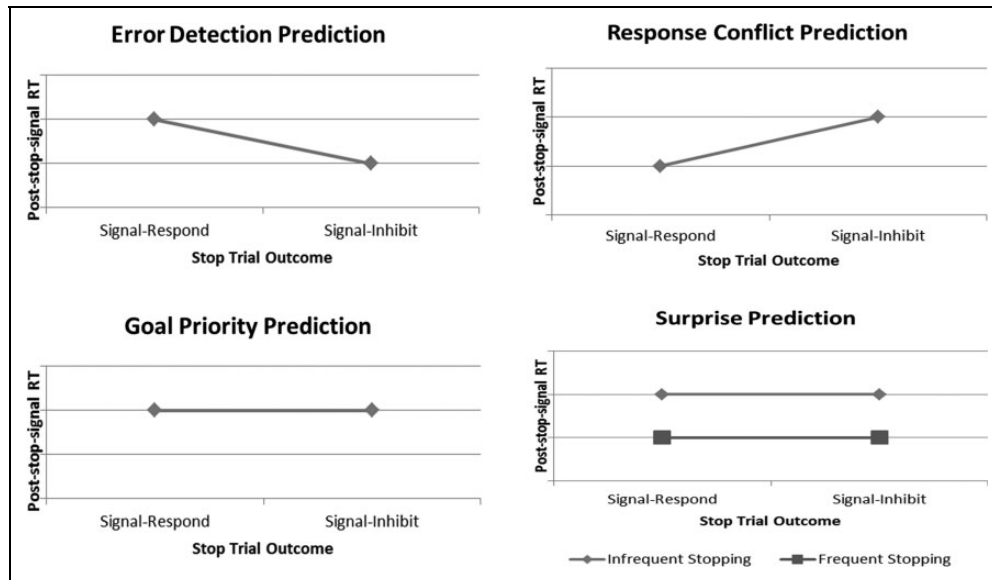Emails: amy.wilkinson@sickkids.ca; russell.schachar@sickkids.ca

Figure 1. Performance monitoring hypotheses. RT indicates reaction time. Modified from Figure 1 in Bissett and Logan.[12]

and adjust the accuracy and speed of their performance. As participants are only able to stop their responses about half of the time (see description of stop-signal task below), successful and unsuccessful attempts to stop can be studied to estimate post response (two words) or post-response adjustment. Individuals have been observed to adjust their response strategies after a stop-signal trial in 1 of 3 ways: they may slow their reaction time after successful stopping (signal-inhibit trial),[8,9] unsuccessful stopping (signal-respond trial),[9,10] or both successful and unsuccessful stopping.[11]

Bissett and Logan[12] discussed 4 competing performance monitoring hypotheses for the response strategies that occur after a stop-signal trial (see Figure 1 for all hypotheses). The error detection hypothesis suggests slowing after errors as the individual attempts to reduce future errors and, therefore, predicts slowing after signal-respond but not signal-inhibit trials.[3,13] The response conflict hypothesis posits that a stop-signal coactivates competing responses between going and stopping; thus, it predicts slowing after signal-inhibit trials when a response is inhibited, but not signal-respond trials (ie, when a response is carried out in the same way as a go-trial).[14] The goal priority hypothesis suggests a stop-signal trial indicates the need for caution, and thus, it reminds participants to increase reaction time in anticipation of future stop-signal trials regardless of whether or not they made a correct response. As such, this hypothesis predicts post stop-signal slowing after both signal-inhibit and signal-respond trials.[15,16] The surprise hypothesis is based on the assumption that participants are more ready to react to a go-signal than a stop-signal because go-signals typically occur more often than stop-signals. Therefore, the surprise hypothesis also predicts slowing after all stop-signal trials but with greater slowing in conditions with a smaller proportion of stop-signal trials than conditions with a larger proportion of stop-signal trials.[17,18] Bissett and Logan found adults slowed equally after both signal-inhibit and signal-respond trials, supporting the goal priority

hypothesis.[12] They showed evidence against the surprise hypothesis, as post stop-signal slowing was greater on a stop-signal task with 40% stop-signal trials than one with 20% stop-signal trials. These hypotheses have not yet been tested in typically developing children or in children with traumatic brain injury.

Traumatic brain injuries commonly affect brain regions that support higher order cognitive functioning, including awareness of performance. Relatively few studies have investigated performance monitoring in children following traumatic brain injury although it has been documented through the assessment of metacognitive awareness.[4,5] In one study, children with traumatic brain injury had poor management skills involving the monitoring and revision of their ongoing performance as a task proceeded in time, which were associated with younger age at injury and injury severity.[4] In another study, children with severe traumatic brain injury were unable to predict their own performance on a future task and demonstrated overconfidence in their own ability, compared to children with mild traumatic brain injury or typically developing controls.[5]

Ornstein et al's[6] work is the only study to have used the stop-signal task to document performance monitoring in children with traumatic brain injury by looking at post error slowing, defined as a difference score between overall mean go reaction time and mean reaction time on go-trials following signal-respond (error) trials (Error + 1 reaction time). Children with traumatic brain injury were found to slow significantly less compared to typically developing children, thus suggesting poor performance monitoring.[6] Deficits in post error slowing were not attributable to age, sex, injury severity, or global slowing, as children with traumatic brain injury did not show deficits in overall mean go reaction time or accuracy. Deficiencies in performance monitoring became increasingly apparent with time since injury. While post error slowing was significantly different between groups, mean go reaction time on trials following signal-respond trials was not different between groups.

While it has been shown that children with traumatic brain injury exhibit less efficient performance monitoring in comparison to their same age peers,[4-6] it is important to know what contributes to these deficits if targeted interventions are to be developed. In the current study, the authors assessed performance monitoring in the context of the 4 performance monitoring hypotheses presented by Bissett and Logan[12] with 2 goals in mind. The first was to understand which of the 4 hypotheses applied to typically developing children. The second was to assess whether children with traumatic brain injury performed in the same manner as matched controls in order to help understand why those with traumatic brain injury commonly have performance monitoring difficulties. The authors examined adjustments after signal-respond and after signal-inhibit trials under 2 conditions (25% and 50% stop-signal trials) to test the predictions of each of the 4 proposed mechanisms for control adjustments in the stop-signal task.

Methods

Participants

Fifty-six children (28 with traumatic brain injury and 28 controls) were included in this study. Children with traumatic brain injury were recruited prospectively from 3 regional children's hospitals: Children's Hospital at London Health Sciences Centre (London, Ontario), Hospital for Sick Children (Toronto, Ontario), and McMaster Children's Hospital (Hamilton, Ontario) between 2009 and 2013. The authors included children between the ages of 2.5 and 18 years who had a diagnosis of a mild, moderate, or severe traumatic brain injury. Severity of traumatic brain injury was determined using the highest Glasgow Coma Scale score of 2 scores measured before and after hospital admission. To be included, parents or guardians had to be able to read and speak English. Demographics, injury severity, and acute physiological data were collected in a case report form by trained research coordinators using a procedures manual and entered into a central database at the Hospital for Sick Children. For the present study, a subgroup of children with traumatic brain injury (n = 28) were recruited from this convenience sample (total n = 85) after at least 1 year post injury and asked to return to either London Health Sciences Centre or Hospital for Sick Children for a follow-up research study between 2012 and 2015. Refer to Figure 2 for recruitment details.

Typically developing controls were recruited through flyers posted in Hospital for Sick Children. Control participants were included in the study if they had no history of head injury, neurological, psychiatric, or developmental disorder, including attention-deficit hyperactivity disorder, by parent and/or participant report; were able to read and speak English; and matched a traumatic brain injury participant by age and sex.

In addition, all participants completed the Wechsler Abbreviated Scale of Intelligence-Second Edition, which is a brief standardized test used to estimate intelligence in those aged 6 to 90 years. The 2-subtest form was used, which includes the Vocabulary and Matrix Reasoning subtests and provides a full-scale intelligence quotient (FSIQ-2) score.[19] Participants were included if FSIQ-2 was 2 standard deviations below the mean.

For both control and traumatic brain injury participants, parent or guardian consent and child or adolescent assent were obtained at the time of follow-up testing if the participant was less than 18 years;
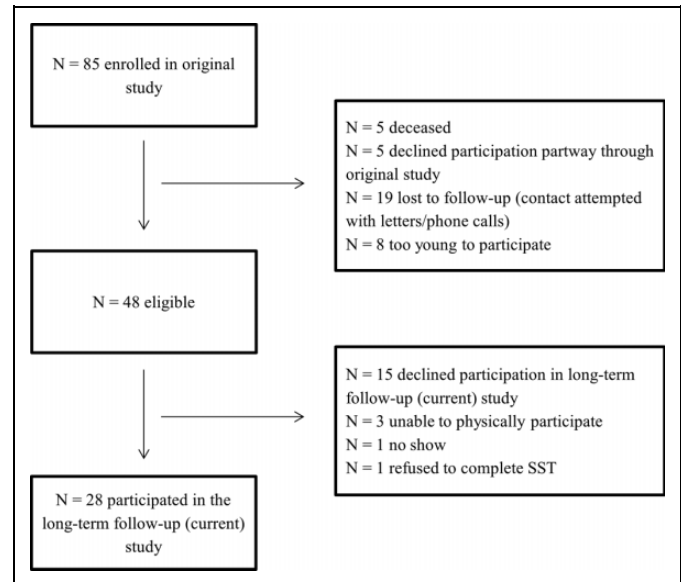

Figure 2. Number of TBI participants enrolled in the current study. SST indicates stop-signal task; TBI, traumatic brain injury.

consent was obtained from the participant if he or she was 18 years or older. An estimate of socioeconomic status was recorded for each participant at the time of testing by asking parents or guardians to indicate total family income by selecting 1 of 7 categories (ie, ranging from less than CAN\$20 000 to greater than CAN\$70 000).

Outcome Measure

Stop-signal task. The stop-signal task involves go- and stop-trials within an ongoing task. The go-trials are a choice reaction time task that individuals are asked to perform as quickly and as accurately as possible by pressing one button if an "X" appears and another button if an "O" appears on the computer screen. The stop-trials involve a tone emitted from the computer, which follows the presentation of the go stimulus and instructs participants to withhold their response on that particular trial. In the stop-signal task, the delay between the presentation of the go-signal and the presentation of the stop-signal is dynamically adjusted so that participants are able to stop their responses on 50% of stop-signal trials. The stop-signal task is primarily used to estimate the latency of the inhibition process, stop-signal reaction time by subtracting mean delay at which a participant is able to stop their responses on 50% of stop-signal trials from mean go reaction time on go-trials without stop-signals.[20] In this study, participants completed 2 different stop-signal task paradigms. One task presented a stop-signal on 25% of the trials, which is the standard stop-signal task, and the other task presented stop-signals on 50% of the trials. The administration order of these 2 conditions was counterbalanced across participants. The use of these 2 tasks (25% and 50% stop-signal task) ensured that the authors could assess the surprise hypothesis.[12] The stop-signal task was administered by a psychology graduate student (first author).

Statistical Analyses

Demographics. Baseline characteristics of participants were analyzed using descriptive statistics of means with respective standard deviations for continuous variables, proportions with respective 95%

Table 1. Stop-Signal Task Variables and Corresponding Definitions.[a]

SST Variable	Definition
Go accuracy	Percentage of total go-trials that were correctly answered
Inhibition accuracy	Percentage of total stop-trials that were correctly inhibited
MGRT	Mean go reaction time; mean of all go-trial RTs
SSRT	Stop-signal reaction time; calculated by subtracting mean delay at which the patient inhibits 50% of the time from MGRT
Signal-respond RT	Tracked signal-respond mean reaction time
Error + 1 RT	Mean RT on correct go-trials following signal-respond (error) trials (ie, trials following a failure to inhibit a response to a stop-signal)
Correct + 1 RT	Mean RT on correct go-trials following signal-inhibit (correct) trials (ie, trials following a correct inhibition response to a stop-signal)
PES	Post error slowing; calculated by subtracting Error + 1 RT from MGRT
PCS	Post correct slowing; calculated by subtracting Correct + 1 RT from MGRT

[a]All accuracy variables are percentages. All reaction time (RT) variables are recorded in milliseconds (ms).

Table 2. Demographic Variables for the TBI and Control Groups.[a]

Demographic Variable	TBI (n = 28)	Control (n = 28)	P
Male; n (%)	16 (57.1)	16 (57.1)	.788
Age at testing in years; mean (SD)	14.7 (4.0); range: 6.0-21.5	14.6 (4.0); range: 6.9-20.6	.887
WASI-II FSIQ-2; mean (SD)	106.8 (14.0); range: 84-135	109.7 (10.3); range: 93-128	.381
SES; median (IQR)	6.5 (3); range: 1-7	7 (0); range: 4-7	.098

Abbreviations: TBI, traumatic brain injury; SES, socioeconomic status; SD, standard deviation; IQR, interquartile range; WASI-II, Wechsler Abbreviated Scale of Intelligence-Second Edition; FSIQ-2, full-scale intelligence quotient.
[a]An estimate of SES was collected by asking parents or guardians to indicate total family income by selecting 1 of 7 categories (ie, 1 = <CAN$20 000, 7 = >CAN$70 000).

confidence intervals, and medians with respective interquartile ranges for ordinal data. Independent Student's *t* test was performed to compare continuous variables and the χ^2 test was used to compare proportions.

Comparing stop-signal task paradigms (25% vs 50%). A 2 group (traumatic brain injury vs control) by 2 condition (25% stop-signal task vs 50% stop-signal task) analysis of variance was performed on 9 stop-signal task variables and post stop-signal calculations (Table 1). This allowed us to compare reaction times on the 25% and 50% stop-signal task and assess the surprise hypothesis.

Performance monitoring. A mixed model with repeated measures was conducted to assess performance monitoring on the 3 reaction times (mean go reaction time vs Error + 1 reaction time [mean reaction time on go-trials following signal-respond trials] vs Correct + 1 reaction time [mean reaction time on go-trials following signal-inhibit trials]) between groups (traumatic brain injury vs Control). This allowed us to assess all 4 hypotheses.

Participant characteristic effects. Multiple linear regression analyses using backward elimination were conducted to determine the effect of any potential covariates including age at injury, age at testing, Glasgow Coma Scale, or sex on the variables related to performance monitoring: mean go reaction time, Error + 1 reaction time, and Correct + 1 reaction time for the 25% stop-signal task and 50% stop-signal task. The authors completed these analyses for both the traumatic brain injury and control groups, but the covariates used for the control group were only age at testing and sex.

Results

Demographics and Injury Characteristics

Age at the time of follow-up assessment in the children and adolescents with traumatic brain injury ranged from 6 to 21

years (1.4 to 5.8 years post traumatic brain injury). The patient demographics are presented in Table 2, and injury severity, injury mechanism, findings on computerized tomography scans, and associated injuries are shown in Table 3.

Traumatic brain injury participants did not differ significantly from control participants in sex, age at testing, Wechsler Abbreviated Scale of Intelligence-Second Edition FSIQ-2, and socioeconomic status (Table 2).

Comparing stop-signal task Paradigms (25% vs 50%)

Significant task effects were found for mean go reaction time, signal-respond reaction time, Error + 1 reaction time, and Correct + 1 reaction time, with slower reaction time on the 50% stop-signal task for all variables. A significant task effect was also found for stop-signal reaction time, with faster reaction time on the 50% stop-signal task. No significant group effects or task by group interactions were found for any of the stop-signal task variables analyzed. Stop-signal task results are presented in Table 4.

Performance Monitoring

The results of the mixed model showed differences in 3 reaction times (mean go reaction time, Error + 1 reaction time, and Correct + 1 reaction time) did not differ by group, $F(2, 108) = 1.50$, $P = .228$. There was a significant effect of reaction time in the control group, $F(2, 108) = 6.34$, $P = .002$. A significant group difference was not found for Error + 1 reaction time, $F(1, 54) = 0.25$, $P = .623$.

Pairwise comparisons were significant for the control group between mean go reaction time and Error + 1 reaction time (difference = 47.05 ms, $P = .001$) and between Error + 1 reaction time and Correct + 1 reaction time (difference = 35.69 ms, $P = .014$), but not for mean go reaction time and Correct + 1 reaction time (difference = 11.36 ms, $P = .428$). Significant differences were not found for the traumatic brain injury group between mean go reaction time and Error + 1 reaction time (difference = 24.85 ms, $P = .085$), mean go reaction time and Correct + 1 reaction time (difference =

Table 3. Injury Characteristics for the TBI Participants.

Characteristic	TBI participants (n = 28)
Age at injury; mean (SD) years	11.3 (3.5); range: 2.8-15.9
Time since injury; mean (SD) years	3.4 (1.3); range: 1.4-5.8
GCS; median (IQR)	13.5 (8.8); 25th percentile: 6.25, 75th percentile: 15
Mild; n (%)	15 (53.6)
Moderate; n (%)	4 (14.3)
Severe; n (%)	9 (32.1)
Intubated; n (%)	16 (57.1)
Mechanism of injury; n (%)	
Motor vehicle collision	12 (42.8)
Bicycle	2 (7.1)
Fall	7 (25.0)
Sport	5 (17.9)
Other	2 (7.1)
CT findings; n (%)	
Subdural hematoma	12 (42.9)
Epidural hematoma	4 (14.3)
Subarachnoid hemorrhage	12 (42.9)
Midline shift	4 (14.3)
Skull fracture	15 (53.6)
Other injuries; n (%)	
Spine fracture	2 (7.1)
Spinal cord injury	2 (7.1)
Cardiovascular injury	2 (7.1)
Thoracic injury	6 (21.4)
Abdominal injury	2 (7.1)
Genital–urinal injury	1 (3.6)
Other fractures (non skull or spine)	11 (39.3)

Abbreviations: TBI, traumatic brain injury; CT, computerized tomography; SD, standard deviation; IQR, interquartile range; GCS, Glasgow Coma Scale.

23.66 ms, $P = .100$), or Error + 1 reaction time and Correct + 1 reaction time (difference = 1.19 ms, $P = .934$).

Pairwise comparisons were not significant when comparing the control and traumatic brain injury group on mean go reaction time (difference = 24.58 ms, $P = .580$), Error + 1 reaction time (difference = 2.38 ms, $P = .957$), or Correct + 1 reaction time (difference = 36.89 ms, $P = .407$; Figure 3).

Participant Characteristic Effects

Regression analyses on the *control participants* for the 25% stop-signal task revealed mean go reaction time and Correct + 1 reaction time did not vary as a result of age at the time of testing or sex. However, for Error + 1 reaction time, younger age at the time of testing resulted in slower Error + 1 reaction time ($\beta = -.501$, $P = .01$), while sex did not have a significant effect. For the 50% stop-signal task, Correct + 1 reaction time did not vary as a result of age at the time of testing or sex, but younger age at the time of testing resulted in slower mean go reaction time ($\beta = -.413$, $P = .03$) and slower Error + 1 reaction time ($\beta = -.487$, $P = .01$).

Regression analyses on the *traumatic brain injury participants* revealed mean go reaction time, Error + 1 reaction time and Correct + 1 reaction time did not vary as a result of age at the time of testing, Glasgow Coma Scale, or sex on the 25% stop-signal task. In contrast, younger age at the time of testing resulted in slower mean go reaction time ($\beta = -.540$, $P = .003$), Error + 1 reaction time ($\beta = -.453$, $P = .015$), and Correct + 1 reaction time ($\beta = -.579$, $P = .001$) in the 25% task. On the 50% stop-signal task, mean go reaction time, Error + 1 reaction time, and Correct + 1 reaction time did not vary with any of the independent variables.

Table 4. Performance of TBI and Control Participants on the 25% and 50% SST Presented as Mean (SD).

SST variable[a]	25% SST		50% SST	
	TBI	Control	TBI	Control
Go accuracy %	97.1 (3.6)	97.9 (3.1)	96.4 (5.7)	98.0 (3.2)
Inhibition accuracy %	50.2 (6.8)	53.0 (7.4)	52.2 (5.2)	51.8 (3.4)
MGRT[b]	646.7 (158.0)	622.1 (130.6)	754.6 (185.6)	710.3 (157.7)
SSRT[b]	309.2 (124.8)	302.0 (92.4)	297.1 (124.3)	257.2 (71.8)
Signal-respond RT[b]	556.5 (145.5)	523.0 (103.4)	624.2 (151.1)	603.0 (149.4)
Error + 1 RT[b]	671.5 (193.2)	669.1 (156.5)	788.9 (204.9)	751.2 (169.0)
Correct + 1 RT[b]	670.3 (202.5)	633.4 (141.9)	794.2 (232.4)	740.3 (173.9)
PES	24.9 (75.6)	47.1 (79.4)	34.3 (69.9)	40.9 (58.4)
PCS	23.7 (71.9)	11.4 (46.6)	39.6 (67.4)	30.0 (63.1)
PSS	1.2 (92.7)	35.7 (79.5)	−5.3 (96.5)	11.0 (93.5)

Abbreviations: TBI, traumatic brain injury; SST, stop-signal task; SD, standard deviation; RT, reaction time; MGRT, mean go RT; SSRT, stop-signal RT; Error + 1 RT, mean RT of go-trials following signal-respond (error) trials; Correct + 1 RT, mean RT of go-trials following signal-inhibit (correct) trials; PES, post error slowing (PES = Error + 1 RT − MGRT); PCS, post correct slowing (PCS = Correct + 1 RT − MGRT); ANOVA, analysis of variance.
[a]All variables are presented as mean (SD). All variables, except go accuracy % and inhibition accuracy %, are in milliseconds (ms). 2 × 2 ANOVAs were performed on all of the SST variables.
[b]Variables that had significant task effects (ie, between 25% and 50% SST) at $P < .01$. No significant group effects or interactions were found for any of the SST variables analyzed.
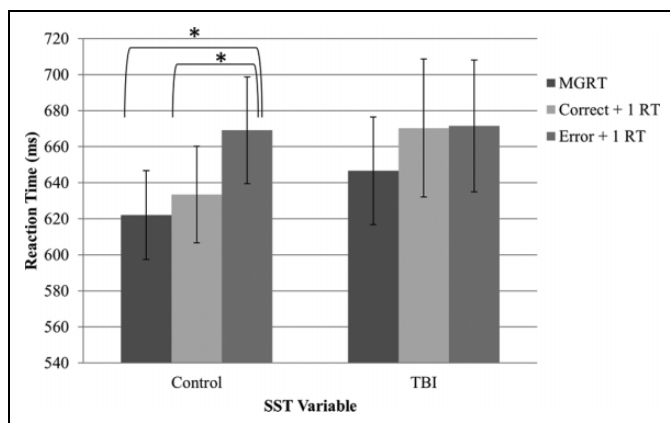
Figure 3. Results of the performance monitoring analysis. ms indicates milliseconds; RT, reaction time; MGRT, mean go RT; Error + 1 RT, mean RT of go-trials following signal-respond (error) trials; Correct + 1 RT, mean RT of go-trials following signal-inhibit (correct) trials; SST, stop-signal task; TBI, traumatic brain injury. Error bars represent standard errors. *Represents a significant difference (*P* < .05) between reaction times.

Discussion

The first goal of the present study was to understand which of the 4 performance monitoring hypotheses presented by Bissett and Logan[12] applied to typically developing children. The authors showed that typically developing children slowed significantly more following signal-respond trials than signal-inhibit trials on the 25% stop-signal task, which is in keeping with the error monitoring hypothesis. The second goal was to identify whether the traumatic brain injury group responded to stop-signals in the same way as the control group. The authors found that the traumatic brain injury group did not respond at a significantly different rate on trials following signal-respond and signal-inhibit trials. While the typically developing control group had a greater difference in reaction time between Error + 1 reaction time and Correct + 1 reaction time in comparison to children with traumatic brain injury, significant group differences were not seen. When performance on the stop-signal task was compared between the 2 paradigms (25% vs 50%), control and traumatic brain injury groups both showed more slowing on trials following signal-respond and signal-inhibit trials on the 50% stop-signal task than the 25% stop-signal task, inconsistent with the surprise hypothesis and providing further evidence for the error monitoring hypothesis.

While our findings supported the error monitoring hypothesis for typically developing children, Bissett and Logan[12] found typically developed adults to increase reaction time after both signal-respond and signal-inhibit trials, consistent with the goal priority hypothesis (discussed below). Our findings are supported by previous studies that have found typically developing children[6,10] and adults[3,13] slow following an inhibition error. However, when comparing the control and traumatic brain injury participants, the authors did not see the same between group findings as Ornstein et al,[6] who found children with traumatic brain injury to slow significantly less than a control group following an inhibition error. The fact that only control children slowed following an error, however, suggests that a group difference may have emerged with a larger sample, as there was significant variability.

Consistent with Ornstein et al,[6] the authors did not find an effect of age at time of testing, sex, or injury severity for the traumatic brain injury participants on the individual variables related to performance monitoring on the 25% stop-signal task. The authors did find, however, younger age at the time of injury had an effect on performance monitoring, resulting in slower reaction time for all go-trials, including those after both signal-respond and signal-inhibit trials for the traumatic brain injury participants. Dennis et al[4] saw a relation between younger age at injury and worse performance monitoring, but this study used a task other than the stop-signal task. When looking at just the control participants, the authors found a relation between slower reaction time after signal-respond trials and being younger on both the 25% stop-signal task and the 50% stop-signal task. The authors also found younger age at testing was related to slower mean go reaction time on the 50% stop-signal task, but not the 25% stop-signal task. A large study looking at inhibitory control across the life span found speed of reaction time to increase with age,[21] which corroborates these findings. Age could potentially explain the difference between our results and those of Bissett and Logan,[12] which looked at a typical adult population. Perhaps task-specific priorities change with increasing age and thus adults slow after all stop-signals, regardless of whether they manage to inhibit or respond to the stop-signal, whereas children slow only after making an error.

While the difference between the 2 stop-signal task paradigms helped to disprove the surprise hypothesis, it also gave us confidence that our manipulation of the task worked. The authors saw all participants had significantly slower reaction times for all variables on the 50% stop-signal task in comparison to the 25% stop-signal task, except for stop-signal reaction time. The faster stop-signal reaction time on the 50% stop-signal task could be due to a practice effect as a result of having so many stop-signals (half of all trials) during this task. Faster stop-signal reaction time on the 50% stop-signal task may also be a result of the slower mean go reaction time on the go-tasks, which allowed the participants to be more prepared to respond to the stop-signals and therefore improved stop-signal reaction time. While there was not a significant group by task difference, the control participants appeared to benefit from this preparation during the 50% stop-signal task more than the traumatic brain injury participants.

The authors also investigated the core stop-signal task outcome variables between groups. As was expected based on the literature,[6,22] the authors did not see a significant difference between traumatic brain injury and control participants on go percent accuracy, inhibition accuracy, or mean go reaction time (see Table 3). However, the authors expected to see significantly slower stop-signal reaction time in traumatic brain injury,[6,22-25] which was not found. The standard deviations for the reaction times for both the control and traumatic brain

injury groups were large and may have obscured possible significant differences. An opportunity to increase the sample size in the future would determine the reliability of these results.

One explanation for the difference in our findings could be due to the wide age range. Conflicting results about the relation between age at the time of injury and response inhibition have been reported. Leblanc et al[24] found younger age at injury to be related to greater impairment in response inhibition. While Schachar et al (2004) and Sinopoli et al[22] showed younger children with traumatic brain injury to have poorer response inhibition overall, they did not find a relation with age at the time of injury and response inhibition.

Another explanation for our findings could be due to the variable amount of time between injury and follow-up testing. Our follow-up was conducted between 1 year to almost 2 years post injury. Leblanc et al[24] found stop-signal reaction time to be slower in children shortly after traumatic brain injury compared to age-matched controls, but stop-signal reaction time increased over the first 2 years post injury eventually closing the gap between those with and without traumatic brain injury. This improvement in performance 2 years after injury may also explain why the authors did not see a group difference on performance monitoring in this study. However, Sinopoli et al[22] found that stop-signal reaction time was still poor in children with traumatic brain injury from 1 to 6 years post injury, a similar range to this study.

Conflicting results have also been reported for the relation between injury severity, as measured by Glasgow Coma Scale, and the stop-signal task. Comparable to our findings, Leblanc et al[24] and Sinopoli et al[22] did not find a relation between the two, but Schachar et al (2004) saw a relation with long-lasting deficits in the stop-signal task and severe traumatic brain injury.

Due to the heterogeneity of the participants, further investigation is needed to understand the relation between age at injury, time since injury, mechanism of injury, injury severity, and the stop-signal task. Although the authors have a wide age range and a large time since injury, these factors were controlled for in our analyses by looking at age at time of injury and age at testing. However, with a larger number of participants, analyses could be conducted on participants divided into age groups, such as children and adolescents, to gain further understanding of the effect of age on performance monitoring. Additionally, serial testing may have shown differences in recovery over time, especially early on in recovery, as performance monitoring may prove more useful in differentiating injured participants during the subacute setting. While severity did not appear to impact performance on the stop-signal task, it would be important to assess the impact of severity in a future study with a larger number of participants more equally spread across severity and representative of injury severity in the general population.

Conclusions

Typically developing children were found to slow reaction time significantly more after making an error than a correct response following a stop-signal. This pattern of responding falls in line with the error monitoring hypothesis and previous knowledge about the responses made by typically developing children following an error on the stop-signal task.[6,10] Although typically developing children slowed more following a stop-signal, compared to children who had sustained a traumatic brain injury, a significant difference between groups was not found. As the inability to monitor performance over time can distract from a child's overall ability to function, as well as confound cognitive deficits in areas such as learning and memory,[4-6] it is important for future studies to isolate the variables that are related to poor performance monitoring post traumatic brain injury.

Author Contribution

Amy Wilkinson contributed to conception and design, acquisition, analysis, and interpretation; drafted the manuscript; gave final approval; and agrees to be accountable for all aspects of work ensuring integrity and accuracy. Maureen Dennis contributed to conception, design, and acquisition; critically revised the manuscript; gave final approval; and agrees to be accountable for all aspects of work ensuring integrity and accuracy. Dr. Dennis passed away prior to the completion of the manuscript. She was very involved at the beginning of this project and read and revised early drafts of the manuscript. She agreed to be a part of this project and manuscript before she passed away, but it was not completed at the time of her passing. Margot Taylor contributed to conception, design, and interpretation; critically revised the manuscript; gave final approval; and agrees to be accountable for all aspects of work ensuring integrity and accuracy. Anne-Marie Guergeurian, Kathy Boutis, Karen Choong, Craig Campbell, Douglas Fraser, Jamie Hutchison, and Russell Schachar contributed to conception, design, acquisition, and interpretation; critically revised the manuscript; gave final approval; and agrees to be accountable for all aspects of work ensuring integrity and accuracy.

Ethics Approval

The data included in this article were obtained in compliance with national research ethics standards and following review by ethics committees at each collection site (Hospital for Sick Children: The Hospital for Sick Children Research Ethics Board approval number 1000012562 and 1000022462; London Health Sciences Centre: UWO HSREB using form 2F001 (Full Board Submission) June 2008; McMaster Children's Hospital: Hamilton Research Ethics Board project number 09-210).

Declaration of Conflicting Interests

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