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Costs of a Predictable Switch Between Simple Cognitive Tasks Following Severe Closed-Head Injury

Maureen Schmitter-Edgecombe and Michelle Langill

Washington State University

Abstract

The authors used a predictable, externally cued task-switching paradigm to investigate executive control in a severe closed-head injury (CHI) population. Eighteen individuals with severe CHI and 18 controls switched between classifying whether a digit was odd or even and whether a letter was a consonant or vowel on every 4th trial. The target stimuli appeared in a circle divided into 8 equivalent parts. Presentation of the stimuli rotated clockwise. Participants performed the switching task at both a short (200 ms) and a long (1,000 ms) preparatory interval. Although the participants with CHI exhibited slower response times and greater switch costs, similar to controls, additional preparatory time reduced the switch costs, and the switch costs were limited to the 1st trial in the run. These findings indicate that participants with severe CHI were able to take advantage of time to prepare for the task switch, and the executive control processes involved in the switch costs were completed before the 1st trial of the run ended.

Keywords

closed-head injury; traumatic brain injury; executive functions; task switching; set shifting

Multiple-task performance is theorized to involve executive control processes, which supervise the selection, initiation, execution, and termination of each task (e.g., Baddeley, 1986; Logan, 1985; Norman & Shallice, 1986; Rubinstein, Meyer, & Evans, 2001). In the closed-head injury (CHI) literature, much of the research that has addressed multiple-task performance has focused on simultaneous multitask performance rather than successive or rapid alternation multiple-task performance. These studies generally indicate that persons who suffer severe CHI (i.e., brain injury resulting from a rapid acceleration of the head followed by a rapid deceleration without an object penetrating the brain) experience greater difficulty than controls in coordinating and monitoring simultaneous task performances (e.g., Brouwer, Verzendal, van der Naalt, Smit, & van Zomeren, 2001; Leclercq et al., 2000; Park, Moscovitch, & Robertson, 1999; Schmitter-Edgecombe, 1996; Schmitter-Edgecombe & Nissley, 2000; Stablum, Leonardi, Mazzoldi, Ulmita, & Morra, 1994). The few studies that have addressed successive alternation multiple-task performance following CHI have primarily used neuropsychological measures that require set shifting, such as the Wisconsin Card Sorting Test (Heaton, 1981) and the Trail Making Test (Reitan, 1958; e.g., Gansler, Covall, McGrath, & Oscar-Berman, 1996; Greve et al., 2002; Rios, Perianez, & Munoz-Cespedes, 2004). One problem with these neuropsychological measures is that task performance is dependent not

Correspondence concerning this article should be addressed to Maureen Schmitter-Edgecombe, Department of Psychology, Washington State University, P.O. Box 644820, Pullman, WA 99164-4820. E-mail: schmitter-e@wsu.edu.

Maureen Schmitter-Edgecombe and Michelle Langill, Department of Psychology, Washington State University.

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only on set shifting but on many other skills. Therefore, poorer performance by CHI participants could be attributed to deficits in other functions, including matching to sample, visuospatial learning, speeded processing, working memory, and set formation.

A common cognitive paradigm for studying rapid alternation multiple-task performance in the laboratory is the task-switching paradigm. In the original task-switching studies, comparisons were made between performances on blocks of trials in which the same task was repeated and performances on blocks of trials in which the participant switched between two different tasks (e.g., Allport, Styles, & Hsieh, 1994; Jersild, 1927; Spector & Biederman, 1976). In more recent studies, performance in task-switch trials (e.g., Task A to Task B) is compared with performance in task-repeat trials (e.g., Task A in succession) that occur within the same switching blocks (e.g., Meiran, 1996; Rogers & Monsell, 1995). These task-switching studies have documented robust “switch costs,” with response times (RTs) being longer in task-switch than in task-repeat trials (e.g., Gopher, Armony, & Greenspan, 2000; Meiran, 1996; Rogers & Monsell, 1995).

Recent research addressing set-shifting costs has shown that both the magnitude and the duration of switch costs can vary as a factor of several task variables (Gopher et al., 2000). For example, switch costs are reduced when there is an external cue present to signal the switch (e.g., Baddeley, Chincotta, & Adlam, 2001; Koch, 2003; Rubinstein et al., 2001; Saeki & Saito, 2004) and when participants know they must change tasks every r trials (e.g., Goschke, 2000; Meiran, 1996; Rogers & Monsell, 1995; Sohn & Anderson, 2001; van Asselen & Ridderinkhof, 2000). In addition, switch costs are borne entirely by the switch (first) trial in situations where an external cue is present and participants switch predictably between tasks on every r trials (Keele & Rafal, 2000; Rogers & Monsell, 1995). For example, using a cuing paradigm with predictable runs of eight trials, Keele and Rafal (2000) observed no improvement in RT beyond the second trial. In contrast, Monsell, Sumner, and Waters (2003) found a more gradual approach to asymptotic performance when the switch was unpredictable (i.e., the task required on the next trial was unknown until signaled to the participant).

Although switch costs have been hypothesized to reflect a number of different underlying processes (Allport et al., 1994; Goschke, 2000; Meiran, 1996; Meiran, Chorev, & Sapir, 2000; Rogers & Monsell, 1995; Wylie & Allport, 2000), the distinction between an active preparation component and a residual component is widely accepted. The preparation component refers to the part of the switch costs that is reduced when participants are given enough time to prepare for the new task (Meiran, 1996; Meiran et al., 2000; Meiran, Gotler, & Perlman, 2001; Rogers & Monsell, 1995). For example, using a predictable task sequence, Rogers and Monsell (1995) found that as the preparation interval increased from 150 ms to 600 ms, there was a substantial reduction in switch costs from over 200 ms to about half that value. This preparation effect is thought to result mainly from an intentional, time-consuming process of advanced task-set reconfiguration that is carried out by the participant prior to the stimulus onset (e.g., Goschke, 2000; Meiran et al., 2000; Rogers & Monsell, 1995; but see Altmann, 2004). Task-set reconfiguration presumably requires the loading of processing algorithms required for the new task into working memory along with inhibition of the processing algorithms for the no-longer-relevant task (Cepeda, Kramer, & Gonzalez de Sather, 2001; Meiran & Gotler, 2001; Monsell, 2003; Ridderinkhof, Span, & van der Molen, 2002; Sohn & Anderson, 2001). Rogers and Monsell (1995) also found that increasing the preparation interval beyond 600 ms did not further reduce switch costs. The residual component refers to the aspects of the switch costs that remain even after long preparatory intervals (e.g., 3,500 ms; Sohn, Ursu, Anderson, Stenger, & Carter, 2000). Several explanations have been offered to explain the residual switch costs, including persistent activation from a previous task (i.e., task-set inertia theory; Allport et al., 1994; Allport & Wylie, 1999, 2000), poststimulus control

processes (Nieuwenhuis & Monsell, 2002; Rubinstein et al., 2001), and a failure to engage in advanced preparation on all trials (i.e., the failure-to-engage hypothesis; De Jong, 2000).

Using a variant of the task-switching paradigm, Stablum et al. (1994) had participants with severe CHI and controls alternate between reading a syllable and indicating whether an arrow was pointing left or right. The preparation interval was about 550 ms, and the switch was predictable but not externally cued. These authors found that in comparison to controls, individuals with severe CHI exhibited inflated switch costs when the tasks alternated every 2 trials but not when the tasks alternated every 10 trials. The authors interpreted these results as indicating that participants with CHI had difficulty with executive control, lacking advance planning for a switch. They based this interpretation on the supposition that controls could prepare ahead for the 2-alternations switch but not the 10-alternations switch because, in the absence of an external cue, it was too difficult to keep track of when the switch would occur.

In the present study, we further address executive control processes involved in set shifting by having individuals with severe CHI and control participants switch between classifying whether a digit was odd or even and whether a letter was a consonant or vowel on every fourth trial. To evaluate whether participants with severe CHI could take advantage of increased preparation time to organize their processing in advance, we manipulated the amount of time participants had available to prepare for the task switch (i.e., 200 ms or 1,000 ms). The task switch was predictable (i.e., on every fourth trial), and unlike in the Stablum et al. (1994) study, we used an external cue in order to maximize participants' opportunity to prepare in advance for the task switch. We also reduced demands on working memory by using univalent (noninterfering) stimuli (i.e., a digit or a letter that contained information relevant to the current task dimension only). We expected that the CHI participants would exhibit greater switch costs than controls. However, if participants with a severe CHI are able to engage in advanced task-set reconfiguration under optimal support conditions, then like controls, they should exhibit smaller switch costs when the preparation interval is 1,000 ms as opposed to 200 ms. Furthermore, if the advanced planning used by participants with CHI is completed before the first trial of the run ends, then similar to controls, the cost of the task switch should be restricted to the switch trial (i.e., borne entirely by the first trial in the run).

Method

Participants

Eighteen individuals (5 female, 13 male) who had sustained a severe CHI and 18 neurologically normal controls (7 female, 11 male) participated in this study. Most of the participants with CHI were identified through patient records obtained from a regional traumatic brain injury rehabilitation program in Spokane, Washington. Others were recruited through presentations made at several head injury support groups. This experiment was completed as part of a test battery that included other experimental (see Schmitter-Edgecombe & Bales, 2005) and neuropsychological tasks, and the participants with CHI received feedback regarding their cognitive functioning in return for their time.

Participants were considered to have suffered a severe CHI if review of medical records indicated that (a) depth of coma, as assessed by the Glasgow Coma Scale (Teasdale & Jennett, 1974), was 8 or less ($n = 12$); or (b) duration of coma was greater than 36 hr ($n = 4$). In the 2 cases for which we were unable to obtain medical records, both the participant and a significant other reported coma duration of 5 days or greater, well beyond the 36-hr coma duration typically used to denote a severe CHI (see Williamson, Scott, & Adams, 1996). All CHI participants self-reported a coma duration of greater than 24 hr ($M = 18.06$ days, $SD = 14.09$; range = 1–48 days), 72% self-reported a coma duration of more than 1 week, and 56% reported a coma duration of greater than 2 weeks. In addition, duration of posttraumatic amnesia (PTA),

assessed retrospectively by careful clinical questioning of the participant, was 7 days or longer for all CHI participants ($M = 95.61$ days, $SD = 119.44$; range = 7–390 days); 83% of participants reported PTAs of more than 2 weeks, and 67% of more than 4 weeks (see Table 1).

All participants with CHI were assessed at least 1 year following injury ($M = 7.56$ years, $SD = 7.06$; range = 1–22 years) and were experiencing residual cognitive deficits; 72% were more than 2 years postinjury, and 39% were more than 6 years postinjury. As can be seen in Table 1, the majority of participants with CHI suffered their head injuries as a result of a motor vehicle accident ($n = 14$), with the remaining 4 injuries resulting from either a fall of greater than 10 feet ($n = 3$) or a bicycle accident ($n = 1$). To minimize possible developmental effects on performance, we used CHI participants who were at least 16 years old at the time of injury (range = 16–40 years) and less than 50 years old at testing (range = 21–46 years). Participants were excluded from the study if they met any of the following criteria: preexisting neurological, psychiatric, or developmental disorder(s) other than a CHI; a history of treatment for substance abuse; a history of multiple head injuries; a visual field deficit that would impair viewing of a computer screen; or a motor deficit (e.g., tremor) in their dominant limb that would preclude accurate assessment of RT. All participants demonstrated adequate visual acuity as indicated by a Snellen ratio of at least .50 at a distance of 41 cm.

Five of the control participants were neurologically normal undergraduate students participating as a requirement for course credit. The remaining 13 control participants were recruited from the community through the use of advertisement. In return for their participation, they received monetary compensation. To increase the likelihood that the CHI participants' premorbid abilities were roughly equivalent to those of the controls, the age ($M = 30.61$ years, $SD = 9.64$) and educational level ($M = 12.83$ years, $SD = 1.89$) of the CHI participants was closely matched to the age ($M = 30.72$ years, $SD = 10.98$) and educational level ($M = 13.61$ years, $SD = 1.82$) of the control participants. There were also no differences in the educational status of the mothers, $t(33) = -0.56$, or fathers, $t(33) = -0.15$, of the CHI and control participants (see Table 2). In addition, an estimate of premorbid intelligence derived from the Barona Index equation (Barona, Reynolds, & Chastain, 1984), which takes into account six demographic variables (i.e., age, sex, race, education, occupation, and region), revealed that the CHI ($M = 105.08$, $SD = 5.48$) and control ($M = 107.15$, $SD = 7.01$) groups did not differ significantly in premorbid abilities, $t(40) = -0.94$.

To help characterize the CHI population and highlight those areas in which the CHI group was experiencing residual cognitive difficulties, a battery of neuropsychological tests was administered to all participants. As can be seen in Table 3, consistent with the typical cognitive sequelae of a severe CHI, the CHI participants performed more poorly than the controls on tests assessing attention and speeded processing (Symbol Digit Modalities Test [SDMT], Smith, 1991; Trail Making Test, Reitan, 1958), working memory span (Letter Number Sequencing subtest from the WAIS–III; Wechsler, 1997), verbal fluency (Controlled Oral Word Association Test [COWAT]; Benton & Hamsher, 1976), and immediate and delayed verbal memory (California Verbal Learning Test [CVLT], Delis, Kramer, Kaplan, & Ober, 1987; Wechsler Memory Scale—III [WMS–III], Wechsler, 1997). In contrast to the above performances, the groups did not differ significantly on a confrontation naming test (Test of Adolescent/Adult Word Finding [TAWF]; German, 1990) or on several of the measures assessing executive functioning (Wisconsin Card Sorting Test [WCST], Heaton, 1981; Stroop Color and Word Test, Golden, 1978). In addition, the CHI ($M = 98.71$, $SD = 8.74$) and control ($M = 102.67$, $SD = 8.32$) groups did not differ in an estimated Wechsler Adult Intelligence Scale—Revised (WAIS–R) Full Scale Intelligence Quotient (FSIQ), $t(33) = -1.38$, which was derived from participants' scores on the Shipley Institute of Living Scale (Zachary, 1991). Correlations between the Shipley total score, which represents the combination of a 40-item vocabulary test and a 20-item abstract thinking test, and the WAIS–R FSIQ have been found

to be quite high, ranging from .74 to .85 (Zachary, 1991; Zachary, Crumpton, & Spiegel, 1985).

Stimuli and Apparatus

IBM-compatible personal computers with active matrix screens were programmed with SuperLab Pro Beta Version Experimental Lab Software (1999) to present the background display and to collect responses and RTs. The background display consisted of a circle cut into eight equal segments and appeared as black on a white background (see Figure 1). A thickened black line also segregated the circle into two halves along the horizontal diameter (for half of the participants) or vertical diameter (for the remaining participants). Participants sat at a viewing distance of approximately 45 cm. Each letter or number target was displayed in black, uppercase, 40-point type (in Times New Roman font) and appeared 6 cm from the center of the circle. The diameter of the circle was 16 cm. For the letter task, target consonants were chosen from the set *G, K, M, and R*, and target vowels were from the set *A, E, I, and U*. For the number task, even digits included 2, 4, 6, and 8, and odd digits included 1, 3, 5, and 9. All target characters were black against a white background. Responses were made by pressing the 1 and 2 keys on a peripheral numeric keypad.

Procedure

Each participant was told that the numbers would appear in a specified half of the circle (i.e., above, beneath, left, or right of the thickened black line) and the letters in the other half. The position of the number and letter half of the circle was counterbalanced across participants to avoid the possible influence of location on switching performance. Participants were told to press the 1 key on a keypad when the number was odd or the letter was a consonant, and the 2 key when the number was even or the letter was a vowel. Response keys were pressed with the index and middle fingers of the individual's dominant hand. Sequences of stimuli were constructed so that the same response (i.e., consonant, vowel, odd, or even) could not appear on more than three successive trials. The target (i.e., a number or letter) appeared in successive segments in a clockwise sequence, and the task changed predictably on every fourth trial. The background display (i.e., circle cut into eight segments) provided a reliable external cue to position in the AAAABBBB task cycle. Each target stayed on the screen until the participant responded. Error trials were followed by the word *error*. The response–stimulus interval (RSI) was 200 ms in the 200-RSI task and 1,000 ms in the 1,000-RSI task.

To become familiar with the response key mapping, prior to the switching task, participants began by completing 48 trials of the numbers task followed by 48 trials of the letters task. Half of the participants in each group then completed the 200-RSI switching task followed by the 1,000-RSI switching task; this order was reversed for the other participants. Both the 200-RSI and 1,000-RSI switching tasks consisted of four blocks of 48 trials (192 test trials) preceded by 32 practice trials. To minimize fatigue and eyestrain, participant-paced rest breaks were given between blocks. Rest breaks were followed by 4 warm-up trials. Participants were told to maintain an accuracy rate between 93% and 97% correct. Participants with accuracy rates above 97% at the end of a block were encouraged to respond more quickly to the stimuli. Similarly, participants performing below a 93% accuracy rate were encouraged to respond more carefully on the next 48 trials. With participants operating at the same level of accuracy across tasks, any group or task differences found should not be attributable to differences in speed–accuracy trade-off functions (Strayer & Kramer, 1994).

Design

There were two within-subject independent variables: position in run (1st–switch, 2nd–nonswitch, 3rd–nonswitch, and 4th–nonswitch) and RSI (200 ms and 1,000 ms). Group (CHI or control) was a quasi-experimental variable. The dependent variables were RT and accuracy.

The data from the odd–even trials (RT: $M = 644$ ms; accuracy: $M = 94.09\%$) and the consonant–vowel trials (RT: $M = 663$ ms; accuracy: $M = 93.20\%$) were combined, as there were no significant main effects ($F_s < 2.8$) or interactions ($F_s < 2$) that involved trial type.

Results

Mean RTs for correct responses as a function of group (CHI or controls), position in a run of four trials (1, 2, 3, and 4), and RSI (200 ms and 1,000 ms) are shown in Figure 2. For each participant, RTs larger or smaller than two and one half standard deviations from the mean RT in each treatment condition were removed. This resulted in removal of less than 1% of the data.

Accuracy Data

As can be seen in Table 4, both the CHI and control groups successfully maintained their overall accuracy rate between 93% and 97% correct. A 2 (group) by 4 (position in a run) by 2 (RSI) analysis of variance (ANOVA) on the accuracy data revealed a significant main effect of position in run, $F(3, 102) = 5.71$, $MSE = 0.001$, $p < .001$. Breakdown of this main effect revealed that accuracy rates for Trial 1 ($M = 92.40\%$), Trial 3 ($M = 93.65\%$), and Trial 4 ($M = 93.60\%$) were poorer than the accuracy rate for Trial 2 ($M = 94.90\%$), $F_s(1, 34) > 5.36$, $ps < .05$. In addition, there was a trend for the accuracy rate of Trial 1, the switch trial, to be poorer than that of Trials 3 and 4, $F_s(1, 34) > 2.70$, $ps < .10$.

The ANOVA also revealed that there was no significant difference in overall accuracy rate between the CHI ($M = 93.08\%$) and control ($M = 94.21\%$) groups ($F < 1$) or between the short ($M = 92.91\%$) and long ($M = 94.38\%$) RSIs ($F < 2.6$). In addition, there were no significant two- or three-way interactions ($F_s < 2.7$). These findings indicate that the CHI and control groups exhibited a similar pattern in accuracy rates across position in run and RSIs. Accuracy rates also did not differ across RSIs. Therefore, any differences in RT performance found between groups or across RSIs cannot be attributed to speed–accuracy trade-off differences.

RT Data

The mean RT data were also analyzed by a 2 (group) by 4 (position in a run) by 2 (RSI) mixed-model ANOVA. As expected, the analyses revealed that the overall response rate of the CHI participants ($M = 743$ ms) was slower than that of the controls ($M = 560$ ms), $F(1, 34) = 6.22$, $MSE = 97,101.22$, $p = .01$, Cohen's $d = 1.35$. There was also a significant main effect of position in run, $F(3, 102) = 17.44$, $MSE = 30,184.97$, $p < .001$. Breakdown of this main effect revealed that set shifting produced a significant switch cost; the mean RT on Trial 1 ($M = 779$ ms) of the run (i.e., the switch trial) was significantly greater than that on Trial 2 ($M = 607$ ms), Trial 3 ($M = 607$ ms), and Trial 4 ($M = 611$ ms), $F_s(1, 34) > 16.58$, $ps < .001$. No differences in response rate were found between the nonswitch trials (i.e., Trials 2, 3, and 4; $F_s < 1$), indicating that performance recovered rapidly following the switch. As can be clearly seen in Figure 2, this immediate recovery from the switch cost occurred for both the CHI and control participants at both the short and long RSI intervals. There was no significant main effect for RSI ($F = 0.18$).

The ANOVA revealed a significant Group $\times$ Position in Run interaction, $F(3, 102) = 4.60$, $MSE = 30,184.97$, $p < .01$. Breakdown of this interaction revealed that the switch costs, computed as the average of Trials 2, 3, and 4 (i.e., nonswitch trials) subtracted from Trial 1 (i.e., switch trial), were greater for participants with severe CHI ($M = 259$ ms) than for the controls ($M = 83$ ms), $t(34) = 2.17$, $p < .05$, Cohen's $d = 0.72$. Computation of proportional difference scores (i.e., switch costs/average of Trials 2, 3, and 4) showed that the task switch translated into a 38% slowing for the CHI group but only a 15% slowing for the control group. There was also a significant RSI $\times$ Position in Run interaction, $F(3, 102) = 3.42$, $MSE =$

11,493.39, $p < .05$. Breakdown of this interaction revealed greater switch costs at the 200 RSI ($M = 196$ ms) compared with the 1,000 RSI ($M = 146$ ms), indicating that increased preparation time decreased switch costs, $t(34) = 2.10$, $p < .05$. As can be seen in Figure 2, for the CHI group, switch costs amounted to a 44% slowing at the 200 RSI and a 33% slowing for the 1,000 RSI. For the control group, switch costs amounted to an 18% slowing at the 200 RSI and a 13% slowing at the 1,000 RSI. There was no significant Group $\times$ RSI interaction ($F = 0.71$), and the three-way interaction was not significant ($F = 0.82$).

Given that the prior analysis assumes a monotonic scale of measurement, we performed a logarithmic transformation on the RT data and repeated the Group $\times$ Position in Run $\times$ RSI ANOVA to rule out the possibility that interactions were scale-dependent (Loftus, 1978). This analysis allowed us to control for general slowing as the differences between logarithms represent proportions. The analysis replicated the data obtained with the mean RT analysis. Most important, this analysis revealed that the Group $\times$ Position in Run interaction remained significant, $F(3, 102) = 2.84$, $MSE = 0.02$, $p < .05$. In addition, the RSI $\times$ Position in Run interaction remained significant, $F(3, 102) = 3.93$, $MSE = 0.003$, $p = .01$. These results again showed that switch costs were greater for the participants with severe CHI than for controls, indicating that general slowing in speeded processing cannot account for this result. In addition, increased preparation time decreased switch costs for both groups.

Correlational Analyses

To further examine those factors that might contribute to the CHI group's greater set-shifting costs, we conducted correlational analyses. For each group, we examined the relationship between the proportion of switch costs for the 200-RSI and the 1,000-RSI tasks (i.e., [switch – nonswitch]/nonswitch) and the neuropsychological measures of intellectual performance, attention and speeded processing, memory, language, and executive functioning shown in Table 3. Owing to the large number of correlations we used a more conservative alpha level of $p < .01$. Correlational analyses revealed no significant relationships between the neuropsychological measures and the proportion of switch costs for either the CHI group ($rs < .40$) or the control group ($rs < .49$). For the CHI group, correlations were also computed between the proportion of switch costs and self-reported coma duration, retrospectively assessed PTA duration, and time since injury. No significant correlations emerged ($rs < .38$).

Discussion

Task switching involves moving flexibly from one behavior to another in response to changing environmental contingencies. Switch costs are thought to primarily reflect the heightened demand on executive control that results from the requirement to reconfigure the system for one task in the context of interference elicited by a second task. To isolate the executive control processes involved in set shifting, we used a task-switching paradigm adopted from the cognitive psychology literature. We were especially interested in whether participants with severe CHI could make use of increased preparation time to actively prepare for a task switch, and whether CHI participants' switch costs would be restricted to the first trial in the run (i.e., the switch trial). We also reduced requirements on learning and working memory load by having participants switch predictably (i.e., every fourth trial) between easy tasks (i.e., odd-even and consonant-vowel judgments) that were externally cued.

Although the participants with severe CHI exhibited overall larger switch costs than controls, when given predictable advanced knowledge about the upcoming task and an external cue, CHI participants were able to take advantage of the additional time to prepare ahead for the task switch. More specifically, 800 ms of additional preparatory time reduced the switch costs of the CHI and control groups by a similar amount. This preparation effect is thought to result primarily from an active, time-consuming process of advanced task-set reconfiguration (e.g.,

Meiran et al., 2000; Rogers & Monsell, 1995), with a small contribution from passive dissipation (Karayanidis, Coltheart, Michie, & Murphy, 2003; Rushworth, Passingham, & Nobre, 2005). Executive control components hypothesized to be involved in active task-set reconfiguration include selecting the relevant task by updating a task “goal” in working memory (see Mayr & Kliegl, 2000; Rubinstein et al., 2001) and retrieving the new task-specific stimulus–response rule (Koch, 2003).

We also found that, similar to controls, the costs of the task switch for the CHI group were limited to the switch trial and did not dissipate gradually over a run of trials. That is, in this predictable, externally cued task switch situation, the switch costs of the participants with severe CHI were borne entirely by the first trial in the run, indicating that the executive control processes involved in the switching-time costs were completed before the first trial of the run ended. In unpredictable switch situations, a more gradual approach to asymptotic performance has been found (Milan, Sanabria, Tornay, & Gonzalez, 2005; Monsell et al., 2003). This led Monsell et al. (2003) to suggest that, unlike in the unpredictable switch situation, in predictable switch situations there may be a higher commitment to the new task set after the first trial of a run because the participant knows that the next trial will not require reinstatement of the task set just abandoned. If this is an accurate interpretation, then our data show that like controls, the participants with severe CHI were prepared and highly committed to the new task after the first trial in the run. These results also indicate that the CHI participants did not experience longer proactive task-set inertia from the previously performed task as compared with controls. That is, the dissipating activation of the prior task set did not persist past the first trial for the participants with severe CHI, even at the 200-ms RSI.

The data illustrate that when the task switch is predictable and there is an external cue present to help participants remember which task is next, CHI participants can actively prepare ahead of time for the task switch, with the switch costs localized to the first trial in the run. Despite the CHI group’s ability to actively prepare ahead of time for the task switch, we found that the switch costs of the participants with severe CHI were greater than those of controls at both the 200 and the 1,000 RSI. The log-transformed data analysis, which controlled for general slowing (see Kray & Lindenberger, 2000; Mayr & Liebscher, 2001), indicated that the larger switch costs of the CHI participants did not simply reflect their slower processing speed when compared with controls. What, then, might account for the greater switch costs of the CHI participants?

Our data suggest that the nature of the CHI participants’ greater switch costs may reside in the residual cost component. Currently, there are a number of unanswered questions concerning the complex causation of the switch costs, especially what might account for the residual cost component. According to several authors (Merian, 1996; Rogers & Monsell, 1995; Rubinstein et al., 2001), the residual component of task-set reconfiguration cannot be executed in advance of the stimulus but instead is triggered only by the appearance of a stimulus associated with the task to be performed. One poststimulus process to consider is that of response selection. In this study, the response keys were the same for both tasks; that is, a given keypress indicated both an odd number and a consonant, depending on the task. Thus, interference was high at the level of response sets, and this might explain the greater switch costs for the CHI group in this study. Consistent with this possibility, previous studies in the CHI literature have repeatedly demonstrated inefficiencies in the response selection stage of information processing following severe CHI (e.g., Schmitter-Edgecombe, Marks, Fahy, & Long, 1992; Shum, McFarland, Bain, & Humphreys, 1990; van Zomeran, 1981).

Because the magnitude and duration of switch costs have been found to vary as a factor of several task variables in the neurologically normal population (Gopher et al., 2000), future research will be needed to investigate the boundaries of the current findings. More specifically,

what conditions exaggerate as oppose to reduce or eliminate the magnitude of switch-cost differences between CHI and control groups? For example, given the slowing in processing speed that typically follows severe CHI, will participants with severe CHI be able to prepare in advance for a task switch at shorter RSIs (e.g., 400 ms to 600 ms) that are known to facilitate task-set preparation in neurologically normal controls? Is the ability of individuals with severe CHI to prepare for a subsequent task dependent on external environmental cues, such as used in this study, or can preparation be internally triggered (e.g., by knowing that the task will change every four trials)? Because use of an internal cue can increase memory load, CHI participants may have more difficulty than controls successfully preparing in advance in situations where the cue is not external. This possibility is consistent with Stablum et al.'s (1994) interpretation that, unlike controls, in the absence of an external cue CHI participants were unable to plan ahead for a switch when the task alternated every two trials. In the present study, task switching was also predictable, with a task switch occurring on every fourth trial. In many real-world situations, a task switch may occur rapidly and be unpredictable (e.g., having to swerve the car rapidly to avoid a pedestrian). Because the task-set reconfiguration process is likely to be more difficult in situations when task switches occur unpredictably and infrequently, an even greater switch cost might be seen in the severe CHI population in unpredictable task-switch situations. In addition, in these situations it is possible that the duration of the switch costs will also be greater for CHI participants, with asymptotic performance following the switch being approached at a slower rate as compared with controls. Furthermore, in the present study, the target stimulus on each trial was relevant to only one task. It is possible that the switch costs of the participants with CHI might be even greater in the presence of a stimulus that also activates the currently inappropriate task (e.g., both tasks involve number stimuli).

Future studies will also be needed to examine other issues related to the nature of task-switching difficulties in the CHI population. For example, if the responses for each task were mapped to a separate keypress, thus decreasing interference at the level of the response set, would the greater switch costs of the CHI participants be attenuated? In addition, if given extended practice, would severe CHI participants become more proficient with the task switch and would their switch costs reach a level commensurate with that of controls? Moreover, how well do controlled experimental measures of set shifting relate to aspects of everyday functioning that involve task switching (e.g., cooking proficiency, ability to follow a new recipe)? Given the presence of task switching in many everyday activities, a better understanding of questions such as these could have important implications for the development of rehabilitative techniques.

The participants with CHI in this study had all suffered severe head injuries in young to middle adulthood and were left with residual deficits at a time point more than 1 year postinjury. Even so, one limitation to this study was that there was considerable heterogeneity in the age of participants at the time of injury, as well as in the time between injury and the current testing. It is possible that injury to the brain during the teen years, when the frontal lobes are still developing, could have a greater or a qualitatively different effect on executive control processes involved in task switching. Given our limited sample size, we were unable to clearly evaluate the effects of age at injury, time since injury, or the possible interaction of these two variables on task switching. The small sample size may have also limited our ability to identify meaningful relationships between switch costs and the neuropsychological variables. In addition, although the control group and the CHI group were well matched in terms of demographic variables and estimated premorbid intellectual abilities, the control group had not experienced a trauma and may have differed in terms of risk-taking behaviors.

Future studies that examine the association between brain imaging data and switch costs in the CHI population are also needed. Functional brain imaging studies have described a reasonably

consistent network of areas that are involved when participants switch repeatedly between tasks. This network of areas most commonly involves the dorsolateral and ventrolateral prefrontal cortex, the medial prefrontal cortex including the supplementary motor area (SMA), the pre-SMA and the anterior cingulate cortex, and the parietal cortex (e.g., Dove, Pollman, Schubert, Wiggins, & von Cramon, 2000; Swainson et al., 2003; Sylvester et al., 2003). Patients with lesions to the frontal lobe have demonstrated deficits in set shifting (e.g., Rogers et al., 1998; Troyer, Moscovitch, Winocur, Alexander, & Stuss, 1998; Vilkkki & Holst, 1994), and it may be that shift costs will be greatest in those participants with CHI who exhibit the greatest frontal lobe damage. Such analyses were precluded in this study because of sample size and the limited information that we had available regarding current brain injury location. Future studies could examine these issues in a better characterized CHI population.

In conclusion, we used a predictable, externally cued task-switching paradigm to investigate executive control processes in a severe CHI population. Similar to controls, we found that participants with severe CHI were able to make use of a longer preparatory interval to prepare in advance for an upcoming task, and that the executive control processes involved in the switch costs were completed before the first trial of the run ended. These results suggest that when provided with a predictable switch and external cues, participants with severe CHI can successfully exert executive control and begin to reconfigure the system in advance for a new task. Despite these findings, the CHI participants exhibited greater switch costs than controls. Given that the ability to switch rapidly and fluidly between tasks is an important component of many everyday activities, future research is needed to better understand the nature of severe CHI participants' greater switch costs. In terms of rehabilitation, it may also be useful to examine the impact of intervening directly with task switching in persons with severe CHI, perhaps through training this specific function repeatedly and to a degree of automaticity.

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Figure 1.
Background display with example stimulus.

Figure 2. Mean reaction times for the severe closed-head injury (CHI) and control groups plotted as a function of response–stimulus interval (RSI) and trial in run, with the first trial in the run representing the task switch. Error bars indicate standard error.

Table 1
Injury Characteristics of Severe Closed-Head Injury Participants

Participant	Injury type	Time since injury (years)	Coma (days)	PTA (days)	Brain injuries and Glasgow Coma Scale (GCS) score from medical records
1	Bike accident	12	11	28	Large right temporal lobe hematoma; midline shift; left retromastoid skull fracture. GCS = 7.
2	MVA	7	2	10	Small right occipital horn hemorrhage. GCS = 7.
3	MVA	4	28	42	Diffuse axonal injury; bilateral frontotemporal contusions; diffuse swelling; small ventricles; midline shift. GCS = 4.
4	MVA	3	30	42	Large left temporal lobe contusion; small right frontal and parietal contusions; parenchymal hemorrhages; right occipital and frontal fractures. GCS = 3.
5	MVA	21	18	90	Diffuse swelling; right subfrontal hemorrhage; skull fracture. GCS = 4.
6	Fall	4	5	24	Diffuse swelling; hemorrhagic contusions of left temporal, parietal, and frontal regions; subarachnoid hemorrhages; right temporal bone fracture. GCS = 8.
7	MVA	2	42	90	Diffuse axonal injury; hemorrhagic foci in cortical gray matter junction in left parietal and right frontal regions; hemorrhagic foci in mid pons; blood in right lateral ventricle. GCS = 4.
8	MVA	5	21	42	Diffuse axonal injury; brain hemorrhage.
9	MVA	1	1	30	CT unremarkable.
10	MVA	12	11	21	Diffuse axonal injury; left frontal hemorrhage; midline shift.
11	Fall	8	16	20	Diffuse cerebral swelling; subarachnoid hemorrhage in frontal area; right frontal and temporal contusions. GCS = 4.
12	MVA	1	21	390	Hemorrhage at gray-white interface of right anterior frontal lobe; blood in interperpendicular fossa and tips of occipital horn of left lateral ventricle; extensive scalp lacerations. GCS = 4.
13	Fall	1	2	7	Skull fracture in region of frontal sinus; soft tissue contusion overlying right frontal bone.
14	MVA	2	21	365	Diffuse axonal injury; right occipital subarachnoid hemorrhage; left parietal subdural hemorrhage; midline shift. GCS = 6.
15	MVA	3	8	10	Diffuse axonal injury; diffuse frontal contusion. GCS = 8.
16	MVA	20	35	120	No medical records available.
17	MVA	22	5	30	No medical records available.
18	MVA	5	48	260	Diffuse axonal injury; diffuse swelling; hemorrhagic foci and cortical contusions in frontal and temporal regions bilaterally. GCS = 3.

Note. Coma duration and posttraumatic amnesia (PTA) duration are based on self-report. Recent brain scan information was not available; descriptions of brain injuries were based on computed tomography (CT) scan or magnetic resonance imaging scan results at the time of hospital admission. Therefore, these descriptions may not be an accurate reflection of the areas of the brain that suffered sustained damage. MVA = motor vehicle accident.

Table 2
Demographic Data for the Severe CHI and Control Groups

Demographic variable	<i>M</i>		<i>SD</i>		<i>n</i>		Cohen's <i>d</i>
	CHI	Con	CHI	Con	CHI	Con	
Age (years)	30.61	30.72	9.64	10.98	18	18	0.01
Education (years)	12.83	13.61	1.89	1.82	18	18	0.42
Mother's education (years)	13.35	13.83	2.29	2.37	17	18	0.19
Father's education (years)	13.59	13.72	2.79	3.12	17	18	0.05
Barona Index FSIQ estimate ^a	105.08	107.05	5.48	7.01	18	18	0.31

Note. CHI = closed-head injury; Con = control; FSIQ = Full Scale Intelligence Quotient.

^aEstimated Wechsler Adult Intelligence Scale—Revised FSIQ was based on the Barona Index equation (Barona, Reynolds, & Chastain, 1984), which takes into account the following six demographic variables: age, sex, race, education, occupation, and region.

Table 3
Demographic Data and Mean Summary Data for the Severe CHI and Control Groups

Test variable	<i>M</i>		<i>SD</i>		<i>N</i>		Cohen's <i>d</i>
	CHI	Con	CHI	Con	CHI	Con	
WAIS-R estimated FSIQ ^a	98.71	102.67	8.74	8.32	17	18	0.46
SDMT total oral correct	54.72	69.65*	18.45	14.23	18	17	0.90
SDMT total written correct	47.00	61.29**	14.56	11.46	18	17	1.09
Trails A (time)	33.94	22.41*	21.73	6.17	18	17	0.71
CVLT total recalled Trials 1–5	38.50	54.76**	18.96	9.57	18	17	1.07
CVLT Long-Delay Free Recall	7.29	12.06**	4.86	2.46	17	17	1.24
WMS-III Logical Memory I total	35.00	43.67*	11.77	8.78	18	18	0.83
WMS-III Logical Memory II total	18.72	29.06**	9.86	5.09	18	18	1.31
TAWF total correct	31.94	34.94	7.47	1.63	17	17	0.56
Trails B (time)	90.11	50.59*	70.32	15.60	18	17	0.76
WAIS-III Letter/	8.94	11.65*	3.95	3.24	18	17	0.85
Number Sequencing							
COWAT total correct	33.11	43.76**	9.55	10.41	18	18	0.97
WCST-64 Failure to Maintain Set	.88	.61	.89	.61	16	18	0.35
WCST-	7.06	8.22	3.91	5.19	16	18	0.25
64 Perseverative Responses							
WCST-64 Conceptual Responses	47.06	45.28	8.53	9.91	16	18	0.19
Stroop Interference (T score)	54.43	53.12	6.97	9.68	14	17	0.15

Note. Unless otherwise indicated, mean scores are raw scores. CHI = closed-head injury; Con = control; WAIS-R = Wechsler Adult Intelligence Scale—Revised; FSIQ = Full Scale Intelligence Quotient; SDMT = Symbol Digit Modalities Test; CVLT = California Verbal Learning Test; WMS-III = Wechsler Memory Scale—Third Edition; TAWF = Test of Adult Word Finding; WAIS-III = Wechsler Adult Intelligence Scale—Third Edition; COWAT = Controlled Oral Word Association Test (PRW form); WCST = Wisconsin Card Sorting Test.

^aWAIS-R estimated FSIQ was derived from participants' total score on the Shipley Institute of Living Scale (Zachary, 1991).

*
 $p = .05$.

**
 $p = .01$.

Table 4

Proportion of Responses Correct (and Standard Deviations) as a Function of Group, Position in Run, and Response–Stimulus Interval (RSI)

Group and condition	Position in run			
	Trial 1	Trial 2	Trial 3	Trial 4
Closed-head injury				
200 RSI	.90 (.09)	.94 (.10)	.94 (.09)	.93 (.10)
1,000 RSI	.92 (.13)	.96 (.10)	.93 (.13)	.93 (.13)
Controls				
200 RSI	.93 (.07)	.94 (.07)	.93 (.08)	.93 (.07)
1,000 RSI	.94 (.05)	.96 (.04)	.96 (.05)	.96 (.05)