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Effects of Traumatic Brain Injury on a Virtual Reality Social Problem Solving Task and Relations to Cortical Thickness in Adolescence

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Abstract

Social problem solving was assessed in 28 youth ages 12–19 years (15 with moderate to severe traumatic brain injury (TBI), 13 uninjured) using a naturalistic, computerized virtual reality (VR) version of the Interpersonal Negotiations Strategy interview (Yeates, Schultz, & Selman, 1991). In each scenario, processing load condition was varied in terms of number of characters and amount of information. Adolescents viewed animated scenarios depicting social conflict in a virtual microworld environment from an avatar's viewpoint, and were questioned on four problem solving steps: defining the problem, generating solutions, selecting solutions, and evaluating the likely outcome. Scoring was based on a developmental scale in which responses were judged as impulsive, unilateral, reciprocal, or collaborative, in order of increasing score. Adolescents with TBI were significantly impaired on the summary VR-Social Problem Solving (VR-SPS) score in Condition A (2 speakers, no irrelevant information), $p = 0.005$; in Condition B (2 speakers + irrelevant information), $p = 0.035$; and Condition C (4 speakers + irrelevant information), $p = 0.008$. Effect sizes (Cohen's d) were large ($A = 1.40$, $B = 0.96$, $C = 1.23$). Significant group differences were strongest and most consistent for defining the problems and evaluating outcomes. The relation of task performance to cortical thickness of specific brain regions was also explored, with significant relations found with orbitofrontal regions, the frontal pole, the cuneus, and the temporal pole. Results are discussed in the context of specific cognitive and neural mechanisms underlying social problem solving deficits after childhood TBI.

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Keywords

TBI; Adolescents; Virtual Reality; Social Problem Solving; Brain Structure

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1. Introduction

Individuals who have sustained traumatic brain injury may show dysfunction in several domains of functioning, including both cognitive and social domains. Children and adolescents who have sustained traumatic brain injury (TBI) demonstrate difficulties in social functioning (Hanten et al., 2008; Turkstra, McDonald, & DePompei, 2001; Yeates et al., 2004). After a TBI, children and adolescents are reported to be lonely and dissatisfied with their social situations, have fewer friends, and to rely on family for social needs more than uninjured peers (Yeates et al., 2007). Studies with adolescents have revealed specific aspects of social processing that are impaired in youth with TBI as compared to their typically-developing peers, including identifying emotions and rating conversational skills from video tapes (Turkstra et al., 2001). Another study (Turkstra, Dixon, & Baker, 2004) with adolescents reported differences between youth with TBI and typically-developing peers in judgments of equality of the conversational burden between two people, judgments of appropriateness of language level, and second order Theory of Mind judgments. In this study, there were no differences in the groups on identifying good listeners in a conversation, or on first order Theory of Mind judgments although small sample size may have been an issue. These studies suggest that social outcome in adolescents is affected by TBI, but more empirical data are needed.

Several studies have sought to identify mechanisms underlying negative social outcome and have documented skills that appear to be impaired after TBI. Among the impaired skills is the ability to engage in age-appropriate social problem solving. Yeates et al. (2004) used the Interpersonal Negotiations Strategy Test (INS; Yeates et al., 1991) to study social problem solving in 109 children who had sustained moderate to severe TBI. The INS involves the narrative presentation of conflict scenarios between two people, after which the subject is queried for a solution to the conflict based on problem-solving steps. Scoring reflects a social-developmental model in which responses are rated on the maturational level of the proposed solutions (i.e., how well the solution proposed preserves the relationship between the two people depicted). Yeates et al. (2004) discovered that the children with TBI used less socially mature strategies to resolve conflicts than did a group of 80 age-matched children with orthopedic injuries. Using the INS to assess social problem solving in children after TBI and in children with orthopedic injury, Hanten et al. (2008) replicated and extended the findings of Yeates et al. (2004) that children with TBI were significantly impaired on INS performance relative to children with orthopedic injury, and displayed a notable lack of recovery. In addition, Hanten et al. (2008) found that poorer performance on the INS was related to poorer performance on tasks of memory and language. This is intuitively plausible when taken in the context of well-documented deficits on neuropsychological tests of language and memory after pediatric TBI, and given that the INS is administered in spoken narrative form that must be maintained in memory, with scoring based on spoken language responses.

Although the presence of cognitive and social deficits after TBI has been established, there is recurring criticism regarding the ecological validity of the tests used to assess outcome. For example, in real life a person is seldom required to perform discrete cognitive operations in the activities of daily living. Recent advances in virtual reality gaming (VR) technology have provided an opportunity to marry the specificity of neuropsychological tests with a realism that more closely mimics activities of daily living to achieve a more ecologically

valid assessment of cognitive and social skills. The social-cognitive research community is beginning to take advantage of this opportunity to create more realistic and dynamic measurement tools.

1.1. Virtual Environments and Social Cognition

In social cognitive research, simulating the social environment has become an important objective in the need to balance experimental control with ecological validity. Measures that have components of mundane realism increase the subject's experience of being part of the interaction (Blascovich et al., 2002). Mundane realism is exemplified by tasks in which the experimental demands match the real-world situation to which the task results will be applied, thus the tasks are more likely to elicit responses similar to those in everyday life contexts. Less virtual measures (i.e. paper tests, picture displays) may be experimentally more rigorous, as they allow more controlled experimental responses to independent variable manipulations. However, these types of measures create a sterile environment, in which the measurement reliability of social cognitive processes can take precedence over the validity of those processes in a comparable, real-world situation. With emerging technologies, the trade-off between realism and experimental control can be lessened, as virtual technology can be modified and controlled without compromising measurement (Blascovich et al., 2002; Loomis, Blascovich, & Beall, 1999).

Virtual reality (VR) tasks use dynamic graphically displayed interactions between participants, which more aptly capture the mechanisms by which real-life social situations are mediated. As such, it is not surprising to find that virtual environments (VEs) are increasingly being used to study social cognition. For example, neuroimaging research has demonstrated that the medial prefrontal cortex is activated both when observing social communication of virtual others through their facial expressions, as well as when perceiving personal involvement in a virtual situation through direct eye contact with virtual characters (Schilbach et al., 2006). Riva et al. (2007) used college-age participants (19–25 yrs old), to determine the effectiveness of VEs in inducing specific emotional responses by manipulating VR environments that subjects visited (i.e., an “anxious” park, a “relaxed” park, and a “neutral” park). The study confirmed the efficacy of VR environments in eliciting the target emotion. Another study on social paranoia – the first of its kind with regard to its methodology – subjected participants to a VE train ride filled with neutral characters. Although participants were pre-screened for severe mental illness, a significant minority of the participants reported paranoid concerns about the virtual train environment when questioned afterward (Freeman et al., 2008). The validity of VR methodology in social cognition research has also been confirmed for studies with VR characters of social prejudice (Dotsch & Wigboldus, 2008).

Evidence of the realness of virtual reality tasks – whether provoking emotional reactions similar to that experienced in actual circumstances (Moore, Wiederhold, Wiederhold, & Riva, 2002), or promoting the suggestion that an individual is a participant in a particular situation (Biocca, Harms, & Burgoon, 2003; Heeter, 1992) – has provided validation of a novel method for observing social functioning in clinical and normal populations (Cobb & Sharkey, 2007).

1.2. Clinical Application

VR technology has been used in diverse populations, including clinical, to study social processing. Several studies have explored autism and social functioning, and concluded that VEs are an effective medium for both observing and teaching social skills in autistic populations (Mitchell, Parsons, & Leonard, 2007; Parsons, Leonard, & Mitchell, 2006; Parsons & Mitchell, 2002; Parsons, Mitchell, & Leonard, 2004). Beyond the autistic

population, VR characters have also proven more effective than the current paper-pencil techniques in teaching acceptable social skills of a particular culture (e.g., South Indian) to participants from a fundamentally different culture (e.g., non-Asian). Interactions with the virtual characters produced a significantly better understanding of the cultural practices being learned (Babu, Suma, Barnes, & Hodges, 2007).

The ever-increasing complexity and integrity of virtual environment programming (LaViola, Prabhat, Forsberg, Laidlaw, & van Dam, 2009; Livatino & Koffel, 2007; Trenholme & Smith, 2008), as well as its popularity with patients and research participants of all ages (Parsons et al., 2006; Reinkensmeyer & Housman, 2007; Virvou & Katsionis, 2008), makes it an excellent medium for research in domains ranging from skill transference in children with learning disabilities (Cromby, Standen, Newman, & Tasker, 1996), to constructional processes in children with developmental disorders (Jacoby et al., 2006) and social rule violation behavior in patients with prefrontal neurosurgical lesions (Morris, Pullen, Kerr, Bullock, & Selaway, 2006).

1.3. Virtual Reality and Investigations of Traumatic Brain Injury

Limited studies of traumatic brain injury (TBI) have used virtual reality technology to assess or treat TBI. Matheis et al. (2007) found that a VR task was sensitive to memory impairments in adult TBI patients 7 years post injury. In younger TBI patients, research is scarce, but emerging. Lloyd et al. (2006) found route learning performance in a virtual town environment to be highly correlated with real-world performance, and subsequently used this “town” to examine route memory in patients with acquired brain injury. Slobounov et al. (2006) demonstrated the long-lasting effects of visual destabilization after mild TBI in student athletes by developing virtual tasks, which proved sensitive to post concussive symptoms up to 30 days after the injury. Very few, if any, studies utilizing VR technology have examined the social outcome of children and adolescents with TBI.

1.4. Neural correlates of social problem solving after TBI

The advent of advanced methods of brain imaging has provided new tools for understanding the complexities of function after brain injury. Recent studies have demonstrated that specialized regions of the brain are part of highly interconnected distributed networks that may subserve multiple cognitive and social cognitive functions. The networks change with development, both in terms of the physical structures, and the relationships between brain and behavior (Adolphs, Tranel, & Damasio, 2001; Johnson, 2005). Many studies have linked broad regions (i.e., the frontal lobes) to equally broad cognitive processes (executive function), and theories have been proposed that suggest that the pattern of regions involved may be an emergent property of specific tasks (D’Esposito, 2008). Nonetheless, some studies have demonstrated links between defined behaviors and specific brain structures (Bechara, Damasio, Damasio, & Anderson, 1994; Stewart, Meyer, Frith, & Rothwell, 2001). In the quest to accurately assess and predict impairment after TBI, more knowledge regarding relations between specific brain structure (that may have been damaged) and clearly defined behaviors is needed.

TBI often results in both focal and diffuse injury to neural substrate, especially in the frontal, temporal, and parietal cortical structures (Kim et al., 2008; Levine et al., 2008; Oni et al., 2010; Wilde et al., 2005). Damage to these regions, especially ventral medial areas, and the impact of injury on normal development has been associated with deficits in social cognition (Yeates et al., 2007). Further, cortical thinning in these regions has been reported in children with TBI (McCauley et al., 2010; Merkley et al., 2008) as compared to the pattern of cortical thinning associated with maturation in this age range (Giedd et al., 1999). With pathological, posttraumatic cortical atrophy and deafferentation following moderate to severe TBI, we

postulated that the relation of cortical thinning to social problem solving would be altered as compared with typically-developing adolescents in whom cortical thinning is putatively related to enhanced cognitive efficiency (Giedd et al., 1999).

Here we report preliminary findings from a pilot study of adolescent TBI using a social problem-solving task modeled after the INS and adapted for presentation in a VR format (Virtual Reality Social Problem-Solving: VR-SPS). The nature of the conflicts presented is similar to those in the INS. However, as in real life, the conflict is presented through spoken dialog of the characters. The task used a virtual environment as the modality of presentation, with the aim of increasing ecological validity. We also looked at the relation between cortical gray matter thickness in regions typically associated with social cognition and performance on our VR tasks, with the expectation that children with TBI would differ from typically-developing (TD) children in the pattern of relation between task performance and neural structure.

2. Method

2.1. Participants

Twenty-eight youth between the ages of 12 and 19 years were tested, including fifteen youth who had sustained moderate to severe TBI (as determined by the Glasgow Coma Scale) and who were injured at least one year previously. Youth with TBI were recruited from our ongoing study of children with TBI from participants recruited prospectively from consecutive hospital admission with a TBI due to closed head injury in Dallas and Houston medical centers. Moderate TBI was defined by either Glasgow Coma Scale (GCS: Teasdale & Jennett, 1974) scores of 9–12 or by GCS scores of 13–15 with brain lesions (contusions, hematomas) indicated by computed tomographic (CT) scans. Severe TBI was defined by GCS scores of 3–8. All participants were English-speaking, had no pre-existing neuropsychiatric disorder, had at least a 37-week gestational period before birth, and had no previous hospitalization for head injury. All eligible participants from the larger study (based on age and date of injury) who had previously indicated willingness to be contacted for future studies were invited to participate. Of the 25 eligible youth, 2 had acquired orthodontics and 1 had become pregnant, rendering them ineligible because of brain imaging safety concerns. Three families were lost to contact, and four declined because of difficulty with scheduling, leaving the 15 adolescents who were tested. Thus the participation rate of eligible families who were approached was approximately 80%. Families who declined differed from participants on distance required for travel to testing site, but not on indices of brain injury, education, ethnicity or socioeconomic status. As an index of the representativeness of the sample, in the previous overall project of 76 children with TBI, the mean mother's education is 13.0 years, the mean GCS is 6.9, and the gender distribution is approximately 2 males:1 female. We do not include age for comparison because the overall project has a larger age range.

In addition, 13 typically-developing (TD) adolescents were recruited from the community and via advertising on the institutional website and on public bulletin boards specifically to match participants in the TBI group on age, gender, and parental education. Table 1 provides the demographic and injury characteristics of the subjects. There were no significant group differences by Wilcoxon test on age-at-test (median TD=16.64; median TBI=16.83; $p=0.891$) or mother's education (median TD=14.6; median TBI=13.0; $p=0.188$), nor did the groups differ significantly by gender, Chi-square ($n=28$) = 0.144, $p=0.705$. To provide an estimate of the relative intellectual functioning of the groups, scores are included from the Wechsler Abbreviated Scale of Intelligence (WASI - Wechsler, 1999), the Clinical Evaluation of Language Fundamentals – 3rd Edition (CELF - Semel, Wiig, & Secord, 2003), and the Gray Oral Reading Test – 4th Edition (GORT - Weiderholt & Bryant, 2001) are

included in Table 1. All subjects were recruited and assessed with approval from and according to the ethical guidelines of the recruiting institutions.

2.2. Virtual Reality Social Problem-Solving Task (VR-SPS)

Social problem-solving was assessed using a VR task in which participants were presented scenarios portraying a social conflict and then asked questions relating to the scenario just viewed in a semi-structured interview to address four problem-solving steps (Yeates, Schultz, & Selman, 1990). Responses were audiotaped, transcribed, and scored.

The original INS was developed to marry the strengths of two theoretically distinct approaches to social development, the structural approach (Kohlberg, 1969), grounded in Piagetian developmental theory, and the functional approach (Dodge, 1985), grounded in description of information processing steps, and the use of those steps in action selection. Reliability for the INS has been demonstrated in several studies, with a test-retest reliability of $r = .68$ across a four month interval (Yeates et al., 1990). Validity was provided for key elements of the INS model with developmental studies that found significant relationships between children's ages or intellectual development and the INS measurement techniques (Yeates et al., 1990). In one study, for example, the overall adaptive functioning of adolescents with affectively disordered parents was related to their overall level of INS development (Beardslee, Schultz, & Selman, 1987).

In the virtual task, participants were asked to watch six computerized, virtual reality scenarios involving four people, two of whom were in conflict. There were two possible scenario types: the Parent-Youth scenario and the Youth-Peer scenario. In the Parent-Youth scenario, a parent and youth were involved in the disagreement. For example, a girl asks her mother if she can go out for the evening, but her mother asks her to babysit instead. In the Youth-Peer scenario, two friends are involved in a disagreement (i.e. two boys are both interested in the same girl). Male and female participants received gender-matched scenarios in which the characters involved in the argument were the same gender as the participant. In addition we wished to explore the possibility that cognitive processing load might have a disproportionate effect on youth with TBI in the context of social problem solving as compared to typically-developing youth.

The scenarios were developed using the Teen scenarios from the original narrative version of the INS as a model. We originally came up with a list of twelve possible scenarios, and, after discussions with teens, young adults, and parents of teens, narrowed our scenarios down to eight basic scenarios that reflected conflicts young people typically encounter. Of the eight basic scenarios, four illustrated a Parent-Youth conflict (Babysitting, Staying Home Alone, School Fair, Making Dinner) and four illustrated a Youth-Peer conflict (Asking Out, Hole in Jacket, Leaving Work Early, New Kid). Each of these scenarios was then rendered in three different processing load conditions, and in separate versions for males (in which the main characters were male) and females (in which the main characters were female). The scenarios had three possible conditions involving variation in processing load in terms of amount of relevant and irrelevant information presented and the number of speakers. In Condition A, the two characters in conflict present only information relevant to the problem, while the additional two characters are silent. In Condition B, the two characters in conflict present both relevant and irrelevant information during the conversation, while the other two characters remain silent. In Condition C, the two characters in conflict offer both relevant and irrelevant information during the conversation, and the other two characters offer information tangential to the conflict. Each of the basic conflict scenarios were rendered in each of the three conditions and counterbalanced across groups.

Naturalistic dialog was scripted to represent the conflicts, and the resulting scenarios were presented to a panel of four teens and six adults for verification of the naturalness of the dialog. Scenarios were recorded visually in Second Life, and teen actors played the roles of characters in the scenarios. Scenarios were similar in general content, but necessarily differed on some measures of readability. The increase in processing load from Condition A to Condition C is reflected in significant differences in the number of words in the scripts for each condition, the number of characters, paragraphs, and sentences. However, scripts across conditions did not differ significantly on sentences per paragraph, words per paragraph, characters per word, number of passive sentences, Flesch Reading Ease, or Flesch-Kincaid Reading Grade Level. Thus the scripts varied by condition on expected measures, but not on other measures of difficulty (please see Table 3)

Examples of three conditions of a script for a parent:youth scenario are presented below.

Condition A: No irrelevant information is given. Two females are in conflict and talk.

Two males observe.

Mom: Lily, I have to work late tonight.

Lily: You have to work late again? What are we going to have for dinner?

Mom: It would be great if you could make something at home.

Lily: Mom, I'm tired of the food we have here. Can't we just order out?

Mom: We have plenty of food. Besides, ordering out is expensive.

Lily: But I don't know what to make for dinner and we never get to order out.

Mom: Lily, we have all the ingredients to make tuna salad. Just make that and we'll have sandwiches.

Lily: C'mon Mom. It's Friday and we have tuna all the time. Can't we just get a pizza?

Mom: It's the end of the month and we're tight on money.

Condition B: Two females are in conflict and give relevant and irrelevant information.

Two males observe.

Mom: Lily, how was that field trip? Oh by the way, I have to work late tonight.

Lily: You have to work late again? What are we going to have for dinner? The field trip was ok. I've been to that museum before.

Mom: Did they have any new exhibits? It would be great if you could make something at home.

Lily: They had a new exhibit about the Egyptians. Mom, I'm tired of the food we have here. Can't we just order out?

Mom: We have plenty of food. Besides, ordering out is expensive. I'd love to see the pyramids in person.

Lily: (*whining*) But I don't know what to make for dinner and we never get to order out.

Mom: Lily, we have all the ingredients to make tuna salad. Just make that and we'll have sandwiches.

Lily: C'mon Mom. It's Friday and we have tuna all the time. Can't we just get a pizza?

Mom: It's the end of the month and we're tight on money.

Condition C. Two females are in conflict and give relevant and irrelevant information.

Two males give only irrelevant information.

Mom: Lily, how was that field trip? Oh by the way, I have to work late tonight.

Lily: You have to work late again? What are we going to have for dinner? The field trip was ok. I've been to that museum before.

Mom: Did they have any new exhibits? It would be great if you could make something at home.

Jack: Yeah, what did they have at the museum this time?

Lily: They had a new exhibit about the Egyptians. Mom, I'm tired of the food we have here. Can't we just order out?

Mom: We have plenty of food. Besides, ordering out is expensive. I'd love to see the pyramids in person.

Dad: We should do that for our next anniversary.

Lily: (*whining*) But I don't know what to make for dinner and we never get to order out.

Mom: Lily, we have all the ingredients to make tuna salad. Just make that and we'll have sandwiches.

Lily: C'mon Mom. It's Friday and we have tuna all the time. Can't we just get a pizza?

Mom: It's the end of the month and we're tight on money.

All participants received all conditions of the task, thus were administered six different scenarios (two Types (Parent–Youth or Youth–Peer) $\times$ three Load conditions (A, B, or C), but the order in which they were presented was randomized and no participant received a basic scenario in more than one condition (in other words, the “Making Dinner” scenario was presented only in one condition for any subject). The participant was interviewed with nine questions about the nature of the disagreement directly after each scenario was viewed. The questions involved queries relating to the four problem-solving steps (Steps), identical to those presented in the INS: defining the problem (DP) (e.g., “What is the problem here? Why?”), generating strategies (GS) (e.g., “What can you think of that Lily can do to solve the problem? How would that solve the problem? What else could she do?”), selecting specific strategy (SS) (e.g., “What is the best way to solve the problem?”), and evaluating outcome (EO) (e.g., “How would Lily and her mom feel if Lily did that?”).

After viewing each scenario, participants were given a structured interview. The youth's response to the interview questions was scored according to the developmental level he or she demonstrated (impulsive=1 point, unilateral=2 points, reciprocal=3 points, or collaborative=4 points). An illustration scenario from the narrative INS with examples of actual responses for each step, and scoring criteria based on developmental level of response is provided in Appendix A. An average Summary score and a component score for each of the four social problem-solving steps (Define Problem, Generate Solutions, Select Solution, Evaluate Outcome) were calculated, with higher scores representing better social perspective taking and desire to sustain relationships (Yeates et al., 1990, 1991). The INS scoring system has demonstrated internal reliability and predictive validity with pediatric TBI research (Janusz, Kirkwood, Yeates, & Taylor, 2002; Yeates et al., 1991). In the current study, at least 2 raters were used, and inter-rater agreement range for the INS was .89 to .98, reflecting good agreement between raters.

2.3 Data analysis methods

As is common in data from participants with TBI, the data distribution was skewed, which, in conjunction with the small sample size prohibited use of a generalized linear model. Therefore we used the Wilcoxon test, a nonparametric method, to analyze group differences in performance for each load condition separately. For demographic data, Fisher's exact test was used to examine the group differences on gender and race, and the Wilcoxon test for age and years of education. Because of the small sample size in these preliminary data, corrections for multiple comparisons were not feasible. To provide some indication of the strength of the observed effects, effect sizes are provided.

3. VR-SPS Results

Results are first presented for the Summary score for each of the conditions (A, B, and C). Then results for the problem-solving Steps (Defining Problem, Generating Solutions, Selecting Solution, Evaluating Outcome) within each condition are presented. In previous studies of social problem-solving in children with TBI, group differences varied by problem-solving step (Hanten et al., 2008). Please see Table 2 for mean, median, and standard deviation (SD) by group and task condition and p-values and effect sizes for comparisons.

3.1. Summary score

The mean, median, SD, p-value, and effect size by Condition and Steps are displayed in Table 2. There were no significant findings for scenario type (Parent-to-Youth or Youth-to-Peer,) so the types were combined for analyses. Adolescents with TBI were significantly poorer on Summary VR-SPS score in all three processing load conditions by Wilcoxon test than TD adolescents.

3.2. Score by problem-solving steps

The initial step in problem solving, Defining Problem, showed significant group differences in all three conditions, with TD adolescents performing better than adolescents with TBI on Conditions A, B, and C.

The second step, Generating Solutions, showed a different pattern, with TD adolescents making significantly higher scores than TBI adolescents only on Condition C.

In the third step, Selecting a Solution, there were also differences in the groups on performance, with TD adolescents again making higher scores than TBI adolescents, but only in Condition C.

On the final step, Evaluating Outcome, TD adolescents made significantly higher scores than TBI adolescents on Condition A, and on Condition C, but differences were marginal on Condition B.

Figure 1 displays the comparison of the median score for adolescents with TBI and TD adolescents for each of the processing load conditions and each processing load step.

3.3. Summary of results for VR-SPS

In general, the results on this task parallel our findings for the narrative version of the INS, in that adolescents with TBI showed impairment in social problem solving across several problem-solving steps relative to typically-developing adolescents. We also manipulated the complexity of the social interaction, varying the dialog between two people exchanging information about a single conflict to four people exchanging information both relevant and tangential to the conflict. This manipulation revealed that in Condition C, the most complex condition, group differences were significant for analysis of the Summary Score and for each of the four problem solving steps. For Conditions A and B, groups differed on the Summary Score, but significant differences were inconsistent among problem solving steps. Only the Defining Problem step was sensitive to group differences in all three Conditions. In previously reported studies of social problem solving using the original, narrative form of the INS, injury group differences were more apparent at the more complex stages of social problem solving (GS, SS, EO) than at the initial stage of defining the problem (Hanten et al., 2008; Yeates et al., 2004). In the current study using the VR version, group differences were apparent even at the DP stage, suggesting the VR-SPS may prove to be slightly more sensitive to deficits in identifying the social problem. Processing load did not appear to have an effect on TD adolescents, but adolescents with TBI showed poorer scores in the most complex scenarios.

4. Relationship of Social Problem Solving Behavior to Brain Structure: Correlations with Cortical Thickness

4.1. Magnetic Resonance Imaging

T1-weighted 3D sagittal images were acquired on Philips Intera 1.5T whole body scanners (Philips, Cleveland, OH). Parameters included 1.0 mm-thick slices, 0 mm slice gap, echo time (TE) = 4.6 ms/repetition time (TR) = 15 ms, field of view (FOV) = 256 mm, and a reconstructed voxel size M/P/S (mm) = 1.0/1.0/1.0.

4.2. FreeSurfer Volumetric Analyses

FreeSurfer is a free software package developed at the Athinoula A. Martinos Center for Biomedical Imaging that may be used for a number of procedures, including morphometric measurements of the brain. In our study, FreeSurfer was used for cortical reconstruction and segmentation as in procedures described by Dale, Fischl and colleagues (eg., Dale, Fischl, & Sereno, 1999; Fischl, Liu, & Dale, 2001; Fischl et al., 2004) and others (Han et al., 2006; Jovicich et al., 2006; Segonne et al., 2004). This method utilizes both intensity and continuity information from the entire three-dimensional MR volume in segmentation and deformation procedures to produce representations of cortical thickness. The validity of measurement of cortical thickness has been established with histological analysis (Rosas et al., 2002) and manual measurements (Kuperberg et al., 2003; Salat et al., 2004). QDEC (Query, Design, Estimate, Contrast) is a FreeSurfer application intended to aid researchers in performing inter-subject/group averaging and inference on the morphometry data (cortical surface and volume), was used to explore cortical thickness differences between groups and the relation of cortical thickness to behavioral indices for each of the above tasks. In order to limit the number of analyses performed, in the VR-SPS task, the Summary score was used

for Condition C, the most sensitive condition. In addition, for Condition C, we analyzed relations of the specific problem-solving steps (DP, GS, SS, EO) to cortical thickness. Analyses were performed using general linear models with age controlled at each surface vertex. Statistical parametric maps of the cortical mantle were generated to illustrate the relation of cortical thickness to behavioral variables and overlaid on a pediatric template based on the typically-developing adolescents (Figure 2). A statistical threshold of $p < .01$ was used, and values displayed are either positive relations (in blue) or negative relations (in red). The displayed p-value is a $-\log(10)$ p-value, rather than a conventional p-value.

5. Volumetric Results

5.1. VR-SPS Task, Condition C

Groups differed in their relation of the Summary score to cortical thickness most prominently in the right medial orbitofrontal region and the cuneus. The relation was positive, that is, better performance was associated with greater cortical thickness, but in the TD group only. The groups showed a similar pattern of positive association between orbitofrontal and cuneus thickness and task performance for each of the problem-solving steps. In the DP step, groups differed in their relation of cortical thickness and task performance in temporal areas with decreased cortical thickness associated with better task performance. In addition, for the EO step, there were robust group differences bilaterally in relation to the medial prefrontal region, which again showed decreased cortical thickness associated with task performance.

Within-group correlations of cortical thickness with performance on the VR-SPS revealed that task performance in the TBI group was significantly related to the temporal pole and the cuneus, and most strikingly in the GS condition, with increases in cortical thickness related to better performance.

In contrast to the TBI group in which there were minimal apparent relations, significant within-group relations for the TD group were apparent in the frontal regions, particularly for the EO condition and the frontal pole, with decreases in cortical thickness associated with better performance (see Figure 2).

6. Summary and Discussion

6.1. Virtual Social Cognition Tasks

Our VR-SPS task yielded results similar to our previous findings with narrative format (i.e., the original INS format) to test social problem solving in adolescents with TBI in that adolescents with TBI were significantly more likely to provide impulsive, self-centered solutions to social conflicts than were adolescents who had not sustained a head injury. Thus results from our virtual version were correspondent to the narrative version results.

Within our virtual task, we also wished to test how differences in the cognitive processing burden inherent to real-life human interaction might affect social problem solving. We found that in scenarios with increasing degree and sources of relevant and irrelevant information (in Condition C), group differences in social problem solving became more pronounced. Condition C was more difficult for both groups, but this could not be attributed to bias caused by a specific scenario, as each basic scenario was represented in Conditions A, B, and C, and counterbalanced across groups. The finding of increased processing load giving rise to greater group differences in social problem solving is supported by our previous findings of a relationship between social problem solving and memory (Hanten et al., 2008).

The current study also investigated group differences in the steps of social problem solving: defining the problem (DP), generating solutions (GS), selecting an appropriate solution (SS), and evaluating probable outcome (EO). As suggested above, we found adolescents with TBI performed more poorly at each of these stages under the most demanding condition, that is, the scenarios involving four people in conversation, in which both relevant and irrelevant information was presented. Different from our previous findings with the similar narrative version of the social problem-solving task (Hanten et al., 2008), in the virtual task we found that the most consistent group differences, and with the strongest effect sizes were in the DP conditions. At first glance, this seems counter-intuitive: why would the easiest step in problem solving show the greatest impact of TBI, and why vary from previous findings? An examination of methodological differences in the two distinct formats reveals plausible answers to these questions, as well as insights for putative mechanisms underlying social problem-solving deficits.

In the original form of the INS, the social problem is presented in spoken, narrative form. An example:

Steve and Carl are friends. One day at school, they are trying to decide what to do on the weekend. Steve wants to invite the new kid in their class to see a movie with them, but Carl says he doesn't feel like having the new kid along.

Thus the important elements of the social dilemma are delineated and presented in a well-organized fashion, culminating with a succinct account of the conflict.

In contrast, in the VR version of the task, the social conflict is presented as spoken, naturalistic dialog between two visually represented characters. The following is an example of the simplest condition, which matches the narrative condition in terms of number of actors and nature of the conflict depicted:

Luis: Hey, Devin. What are you up to this weekend?

Devin: Not much. What about you?

Luis: Well, I was thinking we could go see that movie that just came out. Maybe we could invite that new kid, Brandon from Biology.

Devin: A movie sounds cool, but I don't know about Brandon.

Luis: That movie looks awesome. Why don't you want Brandon to go?

Devin: Brandon gets on my nerves.

Luis: I hung out with him last week and he was pretty cool.

Devin: I don't know.

Luis: Dude, give him a chance.

Thus, even in the simplest scenario, in the VR version subjects must identify and extract elements of the dilemma from conventional dialog elements like speech acts (e.g., the greeting, "Hey, Devin"). Because dialog sometimes relies on indirect communication, this may be nontrivial. In the example above, in order to understand that Devin is rejecting the suggestion to include Brandon in the weekend plans, Luis must first decipher that "...I don't know about Brandon" in actuality means "I don't want Brandon to come with us." Although an in-depth psycholinguistic analysis of the conversational interaction is beyond the scope of this study, it should be noted that even in this simple example, several steps are required for comprehension. At minimum, content information must be interpreted, selected, and integrated to extract the gist in order to identify the conflict.

Studies in our lab have identified selective learning, that is, the ability to select high value items for remembering from a mixed-value group of items, as an area of impairment after TBI (Hanten et al., 2004). Hanten, et al. (2004; 2002) demonstrated that children with TBI are impaired in extracting relevant information from both visual and auditory presentations as compared to typically-developing children in spite of relatively preserved memory span. A similar pattern has been reported by Sandra Chapman and her colleagues in studies of discourse processing, in which children with TBI show impaired ability to extract and summarize salient information from discourse (Chapman et al., 2006; Gamino, Chapman, & Cook, 2009) while demonstrating relatively preserved memory for concrete detail. These two lines of study suggest that among the mechanisms that should be considered for social processing deficits is the ability to extract and integrate relevant information.

Different from the narrative version, the VR-SPS task presents not only the cognitive basis of the conflict, but also emotional content relayed through prosodic cues provided by the voices of the avatar characters. Deficits in emotional processing have been reported in children with TBI (Tonks, Williams, Frampton, Yates, & Slater, 2007). Especially relevant to the current study are deficits in emotional prosody recognition after TBI (Schmidt, Hanten, Li, Orsten, & Levin, in press). Given the reported deficits of auditory emotional processing, it might be postulated that poor auditory emotional processing may also contribute to the observed group differences in performance.

6.2. Brain-Behavior Relationships

In the Virtual Social Problem-Solving tasks, the two groups, TBI and TD, differed significantly in relation of the VR-SPS Summary score to cortical thickness, most prominently in the medial orbitofrontal region and the cuneus, for each of the problem-solving steps except for the DP, in which both groups showed brain-behavior relations that were similar in location, but a tendency for the TD group to show a negative relation with performance and cortical thickness, and positive (or no relation) in the TBI group. In addition, for the EO step, in which the future consequences of a decision are evaluated, there were robust group differences in relations with the medial prefrontal region, again with the TD group showing a negative relation in the frontal regions, and the TBI showing little or positive relations. Both groups showed positive relations with the orbitofrontal cortex. An abundance of literature links the orbitofrontal cortex to emotion- and reward-based decision-making (Bechara, 2005; Bechara et al., 1994; Kringelbach, 2005; Rolls, Hornak, Wade, & McGrath, 1994). It appears to be involved in signaling the affective value of stimuli, encoding expectations of future reward, and updating expectations (O'Doherty, 2007). Further, and relevant to our study, the medial orbitofrontal cortex is active during assessment of both actual and imagined future rewards (Bray, Shimojo, & O'Doherty, 2010). Theories relating to social decision making, especially as it involves an element of risk, suggest the interplay of at least two neurological systems, an amygdala-mediated system that provides positive or negative signals for immediate consequences and a reflective prefrontal system that provides positive or negative signals for future consequences. When the prefrontal system is immature or impaired, decisions favoring immediate rewards are more likely (Bechara, 2005). The cuneus, most commonly associated with visual processing, has also been implicated in cognitive control in clinical populations, with gray matter volume in the cuneus associated with better inhibitory control (Haldane, Cunningham, Androustos, & Frangou, 2008). Interestingly, pathologic gamblers have demonstrated increased activity in the dorsal visual stream including the cuneus relative to controls (Crockford, Goodyear, Edwards, Quickfall, & el-Guebaly, 2005). Given the high probability of prefrontal and orbitofrontal region compromise in children with moderate to severe TBI, our data support the hypothesis that group differences in evaluating the outcome of a problem-solving strategy, with the patients with TBI favoring an impulsive,

immediately rewarding strategy, may be the result of differences in these key regions of the brain.

Within-group correlations showed that task performance in the TBI group was significantly and positively related to the temporal pole and the cuneus in the EO and GS conditions and negatively related to the DP condition. Although the temporal pole has long been associated with declarative memory, especially in semantic memory (Schacter & Wagner, 1999) recent neuroimaging research has brought to light its role in aspects of affective and emotional processing, including memory retrieval for emotions (Dolan, Lane, Chua, & Fletcher, 2000), empathy (Rankin et al., 2006) and the process of evaluating of others people's emotions (Lee & Siegle, 2009). Further, the temporal pole appears to be central to processing emotional saliency of multiple sensory inputs (Royet et al., 2000). In the GS condition, the subject is asked to generate solutions to the social dilemma at hand, and in the EO condition to evaluate the solution, which may rely on similar mechanisms. We propose that an explanation for the finding of better performance associated with greater temporal pole cortical thickness is that better memory for and evaluation of the emotions, both visual and auditory, displayed by the characters in the virtual scenarios are likely to facilitate the generation of appropriate and acceptable solutions to the social problems displayed. With cortical atrophy related to severity of TBI (Wilde et al., 2005), we interpret the positive relations of cortical thickness with performance to reflect injury-related processes superimposed on maturational changes in adolescents (Giedd et al., 1999).

In contrast to the TBI group, the most robust relations for the TD group were shown between the EO condition and the frontal pole, with decreases in cortical thickness associated with better performance (see Figure 2). Studies of relational reasoning in patients with frontotemporal lobar degeneration suggest that the frontopolar region is important to complex reasoning (Morrison et al., 2004), is specifically involved in multiple-dimensional reasoning (Cho et al., 2010;Waltz et al., 1999) and has been found to be involved in monitoring or evaluating decisions in higher primates (Tsujimoto, Genovesio, & Wise, 2010). Although extrapolation of these findings to our own must be approached cautiously, they do provide support for the notion that normal frontal pole development, which, in this age group, is associated with cortical thinning in specific regions reflecting elimination of redundant synapses (Giedd et al., 1999), may be important to the evaluation of decision choices in social problem solving.

We acknowledge that there are several shortcomings in this study, chief among them that the sample size of these preliminary data do not allow firm conclusions. However, the effect sizes are reasonably large, which suggests that more data may allow the detection of significant differences in some conditions that just missed, such as that for Condition B for both Generating Solutions and Evaluating Outcome. Nonetheless, results must be interpreted cautiously because of the lack of correction for Type I errors, and it may be that even with a larger sample, correction for alpha slippage will reduce the significance. Further, the small sample size in conjunction with the skewed distribution of the sample, typical for studies of TBI, precluded valid analysis of interesting potential interactions, such as the effects of Condition by Group, and the effects of age-at-injury, which would be best addressed within a larger study. In addition, with a larger sample, the contribution of language processing to social- problem solving could be explored, as well as effects of memory on social problem solving. Nonetheless, we are encouraged by the specificity and the strength of the findings. Taken together, we suggest an integrated approach using advanced methodologies in both behavioral analysis and neuroimaging to delineating specific mechanisms relating to social problem solving and decision making, and the neural mechanisms underlying impairment after TBI.

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Figure 1. Median scores on Virtual Social Problem-Solving Task by Condition of processing load (A, B, or C) and by problem-solving step (DP, GS, SS, EO).

Figure 2. QDEC analysis showing relations of performance on the VRSPS task (Evaluating Outcomes, Condition C) to cortical thinning by group. The displayed p-value is a log (10) p-value, rather than a conventional p-value. The panel on the left displays the relation to performance in the TD group, and the panel on the right displays the relation of task performance on the TBI group. The differences between groups were significant ($p < 0.01$).

Demographic and injury characteristics of TBI and OI participants and group means for standardized tests of IQ, reading competence, and expressive language.

Table 1

	TBI (N = 15)				TD (N = 13)			
	Mean	SD	Range		Mean	SD	Range	
WASI	100.4	13.4	79–120		108.8	12.2	84–129	
GORT	16.7	6.5	8–30		24.1	4.1	17–30	
CELF	37.7	4.5	27–43		41.4	2.8	36.44	
Age of Injury (yrs)	13.43	2.35	9.16 – 16.66		na	na	na	
Age at Test (yrs)	16.66	2.22	12.38 – 19.70		16.87	2.1	13.19 – 19.94	
Post-Injury Scan Interval (months)	38.81	10.47	11.32 – 52.96		na	na	na	
Mother's Education (yrs)	13.0	3.02	6 – 16		14.62	2.02	11 – 18	
Initial GCS	6.87	3.81	3 – 15		na	na	na	
Gender Distribution		8 male; 7 female				6 male; 7 female		
Ethnicity Distribution		1 African American; 7 Caucasian 5 Hispanic; 1 Asian; 1 Biracial				2 African American; 6 Caucasian 5 Hispanic		
Mechanism of Injury		4 motor vehicle accidents; 1 bicycle 2 RV/off road; 6 fall; 1 sports/play 1 hit by motor vehicle				na		

Table 2

Mean, Median, SD, p-value, and effect sized (Cohen's D) for comparisons of adolescents with TBI to typically-developing uninjured adolescents by Condition (A, B, or C) of the Virtual Problem Solving task.

Condition	TBI(N=15)			TD(N=11)			P-value from Wilcoxon test	Effect size Cohen's D
	Mean	Median	SD	Mean	Median	SD		
Summary Score	A	9.40	9.04	0.10	10.70	10.77	0.82	1.40
	B	9.61	10.00	1.05	10.66	11.25	1.14	0.96
	C	9.01	9.16	1.39	10.58	11.00	1.09	1.23
Defining Problem	A	2.34	2.33	.30	2.62	2.58	.28	0.93
	B	2.33	2.33	.43	2.75	2.75	.26	1.14
	C	2.49	2.49	.26	2.76	2.76	.29	0.96
Generating Solution	A	2.26	2.37	.41	2.56	2.50	.33	0.81
	B	2.23	2.25	.30	2.45	2.50	.28	0.76
	C	2.02	2.12	.44	2.48	2.63	.35	1.14
Selecting Solution	A	2.40	2.50	.43	2.60	2.75	.46	0.19
	B	2.60	2.50	.34	2.68	3.00	.51	0.45
	C	2.30	2.50	.59	2.68	3.00	.46	0.70
Evaluating Outcome	A	2.40	2.25	.49	2.93	2.88	.33	1.21
	B	2.44	2.50	.46	2.77	2.75	.34	0.79
	C	2.20	2.25	.50	2.66	2.75	.30	1.07

Table 3

Readability and language statistics for the three task conditions. Asterisks denote significant differences among the conditions.

Measure	Mean Condition A	StDev A	Mean Condition B	StDev B	Mean Condition C	StDev C
Words*	117.00	19.60	161.50	21.65	181.94	22.83
Characters*	465.81	72.48	644.63	88.32	726.63	94.29
Paragraphs*	9.00	0.00	9.00	0.00	11.00	0.00
Sentences*	12.88	1.41	18.31	1.72	20.75	1.48
Sentence per paragraph	1.39	0.14	1.99	0.21	1.86	0.13
Words per Paragraph	9.17	2.02	8.81	1.24	8.75	1.09
Characters per word	3.78	0.19	3.78	0.17	3.77	0.14
Passive sentences	0.03	0.05	0.03	0.05	0.02	0.04
Flesch Reading Ease	93.83	3.84	93.88	3.91	94.23	3.44
Flesch-Kincaid Grade Level	2.40	0.85	2.29	0.67	2.24	0.62

APPENDIX A

Example social conflict scenarios and responses at each developmental (scoring) level by problem-solving step. Taken from the INS (Yeates, et al., 1990)

Scenario: Randy and Tom are friends. They have been assigned to work together on a science project in school and only have two days to finish the project. They meet after school and Randy says he wants to start working on the project right away, but Tom wants to play softball first.				
Steps/ Interview Query	Impulsive: 0 pts	Unilateral: 1 pt	Reciprocal: 2 pts	Collaborative: 3 pts.
Step 1: Defining the problem (DP) "What is the problem here?" "Why is that a problem?"	Physical terms only: <i>They have a project to finish in two days.</i>	Self or other's needs <i>They're not going to finish on time if Tom doesn't work with Randy. Because it is a grade.</i>	Contrasting both self and other's needs <i>One of them wants to play softball and the other one wants to get going on the project. So, they need to figure out what they're going to do first and then go do the other thing.</i>	Mutual goals & long-term relationships <i>Two friends have a project to work on and don't agree when to start working on it. They might agree to work on the project first and decide to play after finishing the project because both are important but they don't want to argue and stop being friends.</i>
Step 2: Generating alternative strategies (GAS) "What are the things you can think of that Randy can do to solve the problem?"	Physical, with little difference between impulse and action <i>Poison him; break his leg or something...be like, 'no you can't play softball'</i>	Emphasize assertion of power or appeasement, conformity <i>Just tell the reasons why they should go ahead and do the project now</i>	Satisfying both participants in a "just" fashion <i>He can flip a coin...So they can choose whether they start on the project or play softball</i>	Collaboration with shared goals <i>Ask Tom to help him with the project first and then promise to play softball with him the rest of the week so that both get what they want</i>
Step 3: Selecting specific strategy (SSS) "What would be the best way to solve the problem?"	For immediate gratification or self-protection <i>Go ahead and do the project as fast and as early as you can</i>	To please self or other in the short-term <i>Both work on it because a project is a test grade, and a zero on that is really going to hurt you</i>	To satisfy self, other, and relationship <i>Do half the project each day and play softball the other half</i>	To optimize collaboration, sustain relationship <i>To sit down with his partner and say, 'Hey, you know we need to work on this. What's a good time for you to work on this and have no distractions?'</i>
Step 4: Evaluating Outcomes (EO) "How would Randy know if he had really solved the problem?"	Based on immediate needs of self <i>By asking a grown-up that he knows</i>	Based on personal satisfaction of either self or other <i>They get an 'A' on the project</i>	Based on balance with emphasis on a fair exchange <i>They'd finish the project, and Tom and Randy played softball, too.</i>	Based on long-term effects of relationship <i>He'll know because they'll both be playing together, and they would be friends and want to play again and again.</i>