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Social communication in young children with traumatic brain injury: Relations with corpus callosum morphometry

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Abstract

The purpose of the present investigation was to characterize the relations of specific social communication behaviors, including joint attention, gestures, and verbalization, with surface area of midsagittal corpus callosum (CC) subregions in children who sustained traumatic brain injury (TBI) before 7 years of age. Participants sustained mild ($n = 10$) or moderate–severe ($n = 26$) noninflicted TBI. The mean age at injury was 33.6 months; mean age at MRI was 44.4 months. The CC was divided into seven subregions. Relative to young children with mild TBI, those with moderate–severe TBI had smaller surface area of the isthmus. A semi-structured sequence of social interactions between the child and an examiner was videotaped and coded for specific social initiation and response behaviors. Social responses were similar across severity groups. Even though the complexity of their language was similar, children with moderate–severe TBI used more gestures than those with mild TBI to initiate social overtures; this may indicate a developmental lag or deficit as the use of gestural communication typically diminishes after age 2. After controlling for age at scan and for total brain volume, the correlation of social interaction response and initiation scores with the midsagittal surface area of the CC regions was examined. For the total group, responding to a social overture using joint attention was significantly and positively correlated with surface area of all regions, except the rostrum. Initiating joint attention was specifically and negatively correlated with surface area of the anterior midbody. Use of gestures to initiate a social interaction correlated significantly and positively with surface area of the anterior and posterior midbody. Social response and initiation behaviors were selectively related to regional callosal surface areas in young children with TBI. Specific brainbehavior relations indicate early regional specialization of anterior and posterior CC for social communication.

Keywords

Brain injury; Young children; Joint attention; Gesture; Corpus callosum; Social communication

1.Introduction

Very few studies have investigated direct relations between quantitative measures of brain structure and specific social and cognitive processes during early childhood. Infancy and early childhood are stages of rapid development during which the brain may be particularly vulnerable to disruption by injury or disease (Hebb, 1942). Reorganization of function after early brain injury appears to be less favorable following diffuse or multifocal brain insult, such as traumatic brain injury (TBI), than following focal lesions (Ewing-Cobbs et al., 2008a). Consequently, brain injury sustained early in life may be associated with significant, persistent sequelae. Indeed, long-term follow-up studies of children sustaining TBI early in life document severe, persistent sequelae and limited recovery of function (Koskinicmi et al., 1995). TBI during early childhood frequently results in global and persisting neuropsychological deficits, especially in children with severe injuries (Ewing-Cobbs et al., 2006). Moreover, children sustaining TBI in early childhood tend to have more protracted recovery periods and poorer outcomes in comparison to children injured in later childhood and adolescence. Relative to children sustaining TBI during later years, children sustaining injuries during infancy and preschool years have demonstrated low post-injury scores on measures of intelligence (Anderson et al., 2000; Ewing-Cobbs et al., 2003; Gerrard-Morris et al., 2010), academic achievement (Ewing-Cobbs et al., 2006; Taylor et al., 2008), speeded perceptual motor tasks (Thompson et al., 1994), sustained and selective attention (Catroppa et al., 2007; Dennis et al., 1995), metacognition and executive functions (Anderson et al., 2005; Dennis et al., 1996; Ewing-Cobbs et al., 2004; Levin et al., 1996, 2001; Walz et al., 2010), language and discourse (Chapman et al., 1995), and word decoding (Barnes et al., 1999). Although the reason for this apparent vulnerability to the effects of TBI at younger age is relatively unknown, some investigators have suggested that cerebral regions and/or cognitive functions within a rapid stage of development are particularly vulnerable to disruption by injury, resulting in long-term cognitive deficits (Dennis, 1988; Ewing-Cobbs et al., 1987; Hebb, 1942).

Translational studies suggest the response of the immature brain to injury reflects a complex and poorly understood interplay of numerous variables. In addition to the location and type of brain injury, additional variables such as age at injury, age at assessment, specific outcomes assessed, rate of development of specific skills at the time of injury, maturation of neural substrates, and environmental factors influence outcomes (Giza et al., 2009; Goldman, 1974; Hebb, 1942; Kolb, 2010). Social development appears to be particularly vulnerable to disruption following focal or diffuse injury sustained early in life. Focal injury to medial temporal regions in neonatal monkeys (Malkova et al., 2010), ventromedial frontal lesions in children (Anderson et al., 2006; Eslinger and Biddle, 2000), and congenital or acquired brain insult prior to age 2 in children (Greenham et al., 2010) have been linked to increased risk for long-term social impairment.

Social-emotional difficulties are often the most underappreciated, yet the most devastating consequences of TBI (Eslinger et al., 1992; Janusz et al., 2002; Yeates et al., 2007). School-aged children and adolescents with TBI have persisting difficulties in social problem solving, social competence, social perspective taking, and in maintaining friendships (Andrews et al., 1998; Beauchamp et al., 2009; Bohnert and Parker, 1997; Dennis et al., 2001; Ganesalingam et al., 2007; Hanten et al., 2008; Janusz et al., 2002; Yeates et al., 2004). Following moderate to severe TBI in preschool-aged children, social perspective

taking abilities were reduced (Walz et al., 2010) and parent ratings indicated reduced social competence (Ganesalingam et al., 2011).

Young children's social initiation and their response to early social interactions provide critical contexts for learning how to regulate their feelings and behavior (Scaife and Bruner, 1975; Vygotsky, 1978). Joint attention (JA) is an important developmental process that allows children to learn through interactions with others. JA, a cornerstone of communication, is central to the development of social communication, social cognition, and language (Mundy and Jarrold, 2010). JA has been shown to enhance new learning (Hirotani et al., 2009) and is regarded as the foundation for later developing independent problem solving and symbolic thinking (Tomasello et al., 2005; Vygotsky, 1978). In addition, different facets of JA have been defined. Responding to JA involves the ability to follow the gaze and gestures of another person to share a common reference point. Initiating JA involves the child's use of gestures and gaze to direct another person's attention to objects, actions, or themselves (Landry et al., 2004; Mundy, 2003). Initiating and responding to JA have been related to different neural systems. Initiation of JA has been linked to anterior attention networks, whereas responding to JA has been linked to posterior attention networks (Mundy and Jarrold, 2010).

In addition to JA, a broad range of additional social-communicative behaviors, including gestures and verbalization, facilitate learning during social interactions. Words and gestures convey similar communication information during early development but diverge beginning about 2 years of age (Sheehan et al., 2007). Despite their importance for long-term developmental outcomes, social communication difficulties have not been examined systematically in relation to either neuroimaging or to early brain injury.

A large number of social and cognitive processes are thought to rely on transfer of information via the corpus callosum (CC) (Zaidel and Iacoboni, 2003). The CC is the largest commissural white matter bundle and can be divided into several subregions (rostrum, genu, rostral body, anterior midbody, posterior midbody, isthmus, and splenium from anterior to posterior axis). Callosal fibers are roughly topographically organized in relation to the cortical regions that they connect. Thus, parcellation of the CC allows investigation of connectivity of cerebral regions contributing to neural networks involved in social communication skills. Investigations of the topographical organization of the fibers of the CC indicate that the rostrum contains fibers from caudal/orbital prefrontal and inferior premotor cortices; the genu from prefrontal areas; the rostral body from premotor and supplementary motor cortices; the anterior midbody from motor cortex; the posterior midbody from somasensory and posterior parietal cortices; the isthmus from superior temporal and posterior parietal cortices; and the splenium from the occipital and inferior temporal areas (de Lacoste et al., 1985; Schaltenbrand et al., 1972). MRI and diffusion tensor tractography have been used to examine developmental changes in CC regions as well as cortical projections through CC regions. In children ages 4 through 18, volume of the CC increases (Giedd et al., 1996); microstructural metrics indicate increased fiber organization and integrity in conjunction with decreased diffusivity (Hasan et al., 2008, 2009; Lebel et al., 2010). Geometric and parcellation approaches using diffusion tensor imaging to identify cortical projections through CC regions generally converge with the topographical organization. However, tractography studies have subdivided the fibers coursing through the splenium into those originating from posterior parietal, temporal, and occipital lobes (Hasan et al., 2008; Lebel et al., 2010; Park et al., 2008). In relation to the present study, damage to various subregions of the CC after TBI may disrupt functional connectivity between cortical regions subserving specific processes (Beauchamp et al., 2009; Benavidez et al., 1999; Ewing-Cobbs et al., 2008b). As such, morphometric measures

of different CC subregions after injury may highlight specific brain-behavior relations in social and cognitive processes in young children following TBI.

The impact of pediatric TBI on the CC has been examined in a number of studies. Due to its particular vulnerability to TBI (Gentry et al., 1988; Mendelsohn et al., 1992), the degree of damage to the CC is frequently viewed as a surrogate marker of the overall severity of diffuse TBI (Bigler, 2001). In pediatric TBI, volumetric studies show post-traumatic atrophy is greatest in the posterior body, splenium, and genu (Beauchamp et al., 2009; Ewing-Cobbs et al., 2008b; Levin et al., 2000; Wu et al., 2010) and correlates with clinical metrics of traumatic axonal injury and cognition (Benavidez et al., 1999; Johnson et al., 1996; Verger et al., 2001). Diffusion tensor imaging studies examining microstructural changes in CC regions following pediatric TBI have identified lower anisotropy and/or increased diffusivity, which suggest alterations in the movement of water molecules and in tissue integrity, in most callosal regions. In a longitudinal study, microstructural metrics associated with tissue integrity continued to show developmental increases despite continued macrostructural volume loss from 3 to 18 months after TBI of varying severity in children and adolescents (Wu et al., 2010).

Despite recent investigations of social competence and social cognition following TBI in young children, few studies have examined neural correlates of social outcomes. Beauchamp et al. (2009) divided the CC into three sections and examined the surface area in relation to parent ratings of social behaviors obtained 10 years after severe TBI sustained at ages 1–7 years. Relative to children with mild–moderate TBI, surface area of the posterior CC was significantly smaller; smaller callosal area, particularly for the mid- and posterior regions, was associated with parent ratings of poorer social development in some domains.

To date, no studies have examined direct measures of social communication behaviors in relation to neuroimaging following TBI in young children. The purpose of the present investigation was to characterize the relations between social communication processes and surface area of midsagittal CC subregions in children who sustained noninflicted TBI prior to age 7. We hypothesized that:

1. surface area of the posterior CC would be smaller in children with moderate–severe TBI than in those with mild TBI,
2. children with moderate–severe TBI would engage in fewer JA interactions, use fewer words, and use more gestures than those with mild TBI, and
3. social response variables would be associated primarily with mid- and posterior CC surface area and that social initiation variables would be associated with anterior CC surface area.

2. Method

2.1. Subjects

Social communication behaviors were evaluated prospectively in 36 children ages 1–72 months at the time of hospitalization for noninflicted TBI at either Children's Memorial Hermann Hospital or Texas Children's Hospital in Houston, TX. The children were enrolled in a prospective, longitudinal study of neurobehavioral outcome following acquired brain injury from 2001 to 2006. Inclusionary criteria were: 1) mild, moderate, or severe TBI, 2) no known premorbid neurologic or metabolic disorder, 3) accidental TBI, 4) no history of prior TBI, and 5) gestational age ≥ 32 weeks. The external cause of injury included fall, motor vehicle collision, sports/play injury, and vehicle/pedestrian collisions. Children with presumed inflicted TBI due to child maltreatment were excluded from the present sample.

This sample was drawn from a total of 144 participants with accidental TBI. Of the 144 children in the study, 66 had research MRIs. Of this group, sedation failure and/or motion artifact resulted in incomplete scans in 24, resulting in 42 scans. Of the 42 children with usable scans, 36 had concurrent social communication measures and were included in the present study. The 36 children included in this paper did not differ in age ($F(1, 142) = 0.70, p = 0.40$; gender $X^2(1, n = 144) = 1.02, p = 0.79$; ethnicity $X^2(4, n = 144) = 2.66, p = 0.62$; or socioeconomic status ($X^2(4, n = 144) = 2.75, p = 0.61$) from the larger sample of 144 children.

The severity of TBI was determined using the Glasgow Coma Scale (GCS) score (Teasdale and Jennett, 1974), and acute computed tomography (CT) or brain magnetic resonance imaging (MRI) findings. Since the GCS score was developed for adults, the motor and verbal scales were modified to accommodate the behavioral capabilities of children from birth through 35 months of age (Ewing-Cobbs et al., 1998). Mild TBI was defined by GCS scores from 13 to 15 with normal acute neuroimaging. Moderate TBI was characterized by lowest post-resuscitation GCS scores from 9 to 12 or from 13 to 15 with neuroimaging evidence of parenchymal injury. Severe TBI consisted of lowest post-resuscitation GCS scores from 3 to 8. We have used this categorization system successfully in prior studies of infants and young children with TBI (Ewing-Cobbs et al., 1997, 1998). Table 1 provides demographic and injury variables for children in the mild ($n = 10$) and moderate-severe ($n = 26$) groups. Socioeconomic status was comparable in the both groups, 75–80% of the children were in the middle socioeconomic stratum.

2.2. Procedure

Written informed consent to participate was obtained from the children's guardians. The protocol was approved by the Institutional Review Board at each medical school and affiliated hospital. The MRI and neuropsychological evaluations were conducted an average of 11.6 months after the injury. Thirty-two of the children received a standard conscious sedation protocol for the MRI as approved by the review board at that time. Each child was evaluated individually by a trained examiner as part of a longitudinal study. Social communication procedures were videotaped and coded by trained staff.

2.3. Outcome measures

2.3.1. Social communication behaviors—The observational analyses of social competence involved a semi-structured sequence of social interactions between the child and an examiner that occurred within the context of toy play. The examiner made a series of *social exchanges* with the child for 5 min. A social exchange consisted of three steps: (1) the examiner says something to the child (*the social request*), and then pauses to give the child an opportunity to (2) *respond* and then, (3) *initiate*. Each social request can be thought of as one test item even though it may consist of multiple phases. For example – “Look at my car. Put the car in the garage.” The examiner pauses for 10 s following a social request. The first 5 s are the response time and the second 5 s are coded as initiating time. Specific behaviors coded both during both responsiveness and initiating periods included: (1) JA, (2) gestures (i.e., pointing, showing, giving), (3) vocalizations/verbalizations. These behaviors have been described in the developmental literature as important indicators of appropriate social development (Butterworth, 1995; Carpenter et al., 2002; Leung and Rheingold, 1981). Points were assigned for each developmental behavior based on the complexity of behaviors within each category as indicated in the social literature (e.g., (Butterworth, 1995). JA codes ranged from 0 (no attention) to 1 (joint attention). Scores for gestures ranged from 1 (reaching) to 3 (symbolic gestures). Vocalization/verbalization points ranged from 1 (simple vocalization) to 5 (complete sentence). Additional information on the validation and reliability of the scoring system may be found in Landry et al. (2002).

2.3.2. General cognitive functioning—To assess general cognitive functioning across the age range, age-appropriate measures were administered and then were combined into composite scores. The Bayley Scales of Infant Development-II (Bayley, 1993) Mental Development Index was administered to children ages 6–42 months. The Stanford–Binet Intelligence Scale-IV (Thorndike et al., 1986) was administered to children greater than 42 months of age.

2.4. MRI acquisition and callosal morphometry

Anatomic MRI scans were performed on a 1.5 T magnet using a quadrature head coil. The research protocol specified: T1-weighted spin-echo 2D images obtained in the sagittal plane using repetition time of 500 ms and echo time of 14 ms, FOV (field of view) = 24 cm., slice thickness of 5 mm skip 2.5 mm, matrix 256×192 , one repetition; proton density; T2-weighted axial 2D spin echo images using a repetition time of 2000 ms, echo time 34 ms/80 ms, FOV 22 cm, slice thickness 5 mm, skip 2.5 mm, matrix 256×192 , 1 repetition; coronal 2D fast spin echo images using a repetition time of 4000 ms, echo time 102 ms, echo train length = 8, FOV = 22 cm, slice thickness 5 mm skip 2.5 mm, 2 repetitions; and axial 2D gradient-echo using repetition time = 800 ms, echo times of 11 and 33 ms, FOV 22, thickness 5 skip 2.5 mm, matrix 256×192 , 2 repetitions.

To obtain the whole brain and CC surface areas, we selected a single midsagittal slice in which the fourth ventricle, pituitary stalk, lower brainstem, and massa intermedia were visible on the T1 series. Following magnification, rotation to the horizontal plane and manual outlining, a semi-automated program divided the midsagittal CC into seven sections (Witelson, 1989). Two raters were trained in measuring surface areas of the CC and of midsagittal hemispheric surface using ImageJ® software (<http://rsb.info.nih.gov/ij/>). Midsagittal hemispheric surface area was used rather than total intracranial area due to the presence of significant atrophy and increased CSF volume in several children. Because the surface area measurements were continuous, inter-rater reliability was calculated using Pearson *r*. Based on measures of 20 scans from two raters, reliability was acceptable for both whole brain, $r = 0.96$, and CC surface area, $r = 0.98$.

2.5. Statistical analysis

Demographic and neurologic variables were compared for children with mild versus moderate–severe TBI using *t*-tests for continuous variables and chi-square for categorical variables. General linear models were used to examine the influence of TBI severity group and age on the social communication measures and the CC surface area measures. Given the directional hypotheses, one-tailed tests were used.

For the total sample, Pearson partial correlation coefficients controlling for age at scan and total brain volume were completed to examine the relation of regional CC surface area with initiate and response variables evaluating JA, gestures, and verbalization.

With small clinical samples, there is a need to balance Type I and Type II error. Controlling alpha may increase the risk of Type II error, which would potentially limit the identification of neurobiological mechanisms that may inform future studies. Therefore, alpha was set at 0.05 for all analyses.

3. Results

3.1. Demographic and neurologic variables by severity of TBI

As seen in Table 1, the mild and moderate–severe TBI groups did not differ significantly in terms of age at injury, age at MRI, gender, socioeconomic status, or external cause of injury.

As expected, the moderate–severe group had lower GCS scores, longer duration of impaired consciousness, and lower IQ scores than the mild TBI group.

3.2. Effect of TBI and age on social communication behaviors

GLMs examined the effect of age at assessment and TBI severity group on communication outcomes. Group $\times$ age interactions were not significant and were trimmed from each model. Tables 2 and 3 provide group means, GLM results, and effect sizes for the social communication scores. For social response variables, the main effect for age at assessment was significant. With increasing age, children responded to social overtures using more symbolic gestures and more complex verbalizations. The main effect for TBI group was not significant, suggesting that social response behaviors did not differ according to TBI severity.

For social initiation variables, increasing age was associated with use of more complex verbalization to initiate a social exchange. Neither JA nor gestures varied with age at assessment. The main effect for group was significant for gestures. The moderate–severe group used more gestures than the mild group to initiate social interaction. Neither JA nor verbalization differed significantly for the mild versus moderate–severe TBI groups.

3.3. Effect of age and TBI severity on subregional callosal surface area

GLMs examined the effect of age at scan and TBI severity on the subregional CC surface areas. Group $\times$ age interactions were not significant for any of the models and were trimmed. Tables 4 and 5 provide group means, GLM results, and effect sizes for each CC region. Age at scan was positively related to surface area of all CC regions except for the rostrum. The main effect for TBI severity was significant only for the isthmus, which was significantly smaller in the moderate–severe than the mild TBI group.

3.4. Partial correlation of regional CC surface area with social communication behaviors

After controlling for age at scan and total brain volume, we examined partial correlation coefficients for the regional CC surface areas in relation to JA, gestural, and verbalization outcomes. Fig. 1 shows significant relations of social response (white arrows) and initiation (red arrows) variables with regional CC areas. For social responses, JA was positively correlated with surface area of the genu, $r = 0.49$, $p < 0.01$, rostral body, $r = 0.39$, $p < 0.05$, anterior midbody, $r = 0.46$, $p < 0.01$, posterior midbody, $r = 0.38$, $p < 0.05$, isthmus, $r = 0.37$, $p < 0.05$, and splenium, $r = 0.40$, $p < 0.05$. When responding to a request, neither gestures nor verbalization correlated significantly with regional CC area.

In relation to the child's initiation of social communication, JA was negatively correlated only with area of the anterior midbody, $r = -0.34$, $p < 0.05$. Initiating interactions using gestures correlated significantly with surface area of the anterior midbody, $r = 0.37$, $p < 0.05$, and posterior midbody, $r = 0.36$, $p < 0.05$. Use of verbalization to initiate a social overture did not correlate with any CC regions.

4. Discussion

4.1. Impact of TBI on brain and behavior outcomes

As hypothesized, the surface area of posterior CC regions was related to injury severity. The isthmus was smaller in young children with moderate–severe than mild TBI. Surface area of anterior and mid CC regions was comparable across injury groups. Injury to the posterior body, isthmus, and splenium is produced in part by axonal shear strain from the falx and tentorium (Tasker, 2006). In pediatric TBI, volumetric studies show post-traumatic atrophy

is greatest in the posterior CC (Beauchamp et al., 2009; Ewing-Cobbs et al., 2008b; Levin et al., 2000).

We hypothesized that children with moderate–severe TBI would have lower JA and language scores and increased use of gestures relative to children with mild injury. Contrary to expectation, the severity groups were comparable in terms of using JA and verbalization to respond to and initiate social interaction. Both severity groups used gestures to respond to a social overture. In contrast, children with moderate–severe TBI used more gestures than those with mild TBI specifically to *initiate* interaction. This occurred even though the complexity of language was similar across groups.

In typically developing children, gestural communication diminishes at around 18 months of age when oral language skills expand rapidly; across the second year of life, the correlation between naming and gestures disappears (Bates et al., 1997). Across both TBI groups, children's use of gestures to *respond* socially increased with age; however, no developmental changes were noted for using gestures to *initiate* social interactions. In young children with moderate–severe TBI, the use of gestures to initiate social interaction may indicate a developmental lag or deficit in the continued reliance on gestures to support verbal communication. Young children with moderate–severe TBI often have difficulties on standardized tests of expressive language and in naturalistic discourse (Chapman et al., 1998; Ewing-Cobbs et al., 1997). They may rely on gestures to augment their verbal expression of social and language information. Future studies should characterize not just the frequency and complexity, but also examine the appropriateness of gestures to the social context in young children recovering from TBI.

In addition to conveying meaning, gesturing while engaged in a task allows speakers to conserve cognitive resources (Goldin-Meadow, 2010). Reducing the cognitive load in a social and verbal interaction may be particularly important for young children with moderate–severe TBI. In addition to their weaknesses in expressive and pragmatic language, children with TBI have difficulty storing information in working memory and reduced inhibitory control (Ewing-Cobbs et al., 2004; Gerrard-Morris et al., 2010; Taylor et al., 2008). Gestures may reduce the cognitive and working memory load required in learning contexts, particularly when they explain information or communicate information that is not part of the child's spoken repertoire (Goldin-Meadow, 2010). After TBI, children's use of gestures may conserve cognitive resources by reducing the quantity of information held online in working memory. Additional research is needed to better characterize the interplay between development of verbalization, gestural communication, and social-executive processes.

4.2. Relations of CC regions with social communication outcomes

In the present study, we found different patterns of correlations for specific CC regions with social responses and initiations. Overall, we found limited support for our hypothesis that social responses would be associated with mid- and posterior CC regions and that social initiation behaviors would correlate with anterior regions. Of the social response variables, JA correlated significantly with anterior, mid, and posterior regions. Of the social initiation variables, JA and gestures correlated with area of mid but not with anterior CC regions.

Despite the centrality of JA to subsequent development, very little is known about the neural networks supporting its development. For social responses, JA was significantly and positively correlated with all CC regions, except for the rostrum. This pattern of correlation with anterior, mid, and posterior callosal regions is consistent with the extensive networks involving temporal, parietal, and frontal regions that have been implicated in different facets of JA. Responding to a JA overture appears to be related to parietal and temporal cortices

and to the posterior attention network (Posner and Rothbart, 2009). The posterior network is involved in perceiving the gaze and head orientations of other people and in perceiving spatial relationships between objects and people (Frieschen et al., 2007). Functional MRI studies in adults have documented activation of the superior temporal and intraparietal sulci in passively observing gaze shifts (Pelphrey et al., 2003). Recent studies examining establishment of JA dissociated activation in these regions. Encoding information about another person's gaze and using that information to redirect one's own gaze to establish JA was related specifically to activation of the posterior superior temporal sulcus and cuneus; the intraparietal sulcus was related more generally to encoding spatial direction and shifting attention (Laube et al., 2011; Materna et al., 2008). Sharing intention during eye contact, which provides the social context for JA, has been related to activation in the right inferior frontal gyrus (Saito et al., 2010) and anterior portion of the medial prefrontal cortex (Schilbach et al., 2010). Clearly, extensive neural networks support responding to JA. Our finding that the surface area of multiple CC regions correlated with responding to JA is consistent with this widespread network.

There is very limited research on neural networks specifically related to initiation of JA. Initiating JA appears to be associated with frontal cortical activity during early development (Grossmann and Johnson, 2010) and is supported by the anterior attention network that regulates self-initiated deployment of attention (Mundy and Jarrold, 2010). The anatomical correlates of the anterior network include regions of the anterior cingulate, medial superior frontal cortex including the frontal eye fields, as well as inferior and orbital prefrontal cortex (Rueda et al., 2004). Interestingly, in a recent functional MRI study, Schilbach and colleagues found dissociations in activation sites for responding to and initiating JA. Responding to JA engaged anterior medial prefrontal cortex. In contrast, initiating JA interactions activated part of reward-related circuitry involving the ventral striatum that is associated with emotional and motivational aspects of behavior (Schilbach et al., 2010).

In our sample, initiation of JA was specifically and negatively correlated with surface area of the anterior midbody. According to the Witelson (1989) partitioning schema, the anterior midbody is composed of motor fibers. However, recent diffusion tensor imaging studies examining statistical topographic projection from cortical lobes through the CC question this pathoanatomical demarcation. Fibers arising from the superior frontal cortex and cingulate extend into both the anterior and posterior midbody; fibers arising from sensorimotor cortex also pass more posteriorly through the posterior midbody and isthmus (Park et al., 2008). Therefore, it is possible that smaller surface area of the anterior midbody is associated with changes in interhemispheric connectivity of fibers from the superior prefrontal regions and cingulate. Activation in these regions has been related to control processes, such as working memory, conflict monitoring, task switching, and inhibitory control (Casey et al., 2005; Cutini et al., 2008; du Boisgueheneuc et al., 2006). One possible explanation for our findings is that smaller anterior midbody area may reflect reduced cognitive control and inhibition, resulting in increased JA overtures. Clearly, additional research on typically developing children and in those with acquired and neurodevelopmental disorders is needed to identify relations of structural cerebral connectivity underlying initiation and inhibition of specific behaviors.

Spoken language and gestures appear to be processed by similar networks involving inferior frontal and posterior temporal regions (Xu et al., 2009). Functional MRI studies of gesture production and reception in adults have identified common and distinct areas of activation. To illustrate, Lindenberg et al. found that inferior frontal, medial frontal, and posterior temporal cortices were activated when perceiving and imagining producing specific gestures. Gesture expression was related to activation in widespread regions, including occipital, posterior medial and inferior temporal gyri, superior and inferior parietal lobules,

supplementary motor, inferior frontal, and dorsolateral prefrontal cortices (Lindenberg et al., 2011).

In the present study, neither gestures nor verbalizations produced in response to a social request, nor verbalizations during social initiation, was related to regional CC areas. In contrast, the use of gestures to initiate a social exchange was positively correlated with area of the anterior and posterior midbody. Larger anterior and posterior midbody area, which may facilitate integration of symbolic motor planning and execution, may enhance the use of gestures to initiate and regulate social interaction. Larger anterior midbody area was also associated with initiation of fewer JA overtures; young children with larger anterior midbody area may rely more on gestures than on JA to commence social communication.

Gestural communication is a core component underlying learning language and provides additional semantic information to aid comprehension. In young children, gestural communication skill is predictive of subsequent expressive and receptive language development (Sauer et al., 2010). Gestural communication is disrupted by laterality and location of early focal brain injury. Bates and colleagues found that left hemisphere injuries involving temporal regions showed sparing of word comprehension and gesturing; in contrast, right hemisphere injury, especially when involving parietal regions, was associated with severe delay in gestural development (Bates, 2005). Additional research is needed to identify how focal and diffuse brain injury sustained at different developmental stages influences the interrelated developmental trajectories of JA, gestures, and verbalization.

The present study is unique as it examines neuroimaging and social communication findings in young children with TBI of varying severity in a prospective sample. However, there are a number of methodological limitations. The lack of a typically developing comparison group reduces our ability to detect injury-related changes in both communication behaviors and callosal area following both mild and moderate–severe TBI. The sample size is small, which limits both power to identify group differences and generalizability of the findings. Additional research is needed to investigate mechanisms through which family environment and rehabilitation interventions influence specific social and communication outcomes after early TBI. Future longitudinal studies using enhanced structural imaging procedures and larger samples of children will contribute to our understanding of the ways in which early brain injury affects the development of both brain and behavior.

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Significant Relation of Social Communication Behaviors with Regional Corpus Callosum Surface Area

Fig. 1. Social response (white arrows) and initiation (red arrows) behaviors that correlated significantly with regional callosal surface areas in children with mild and moderate–severe TBI.

Table 1

Neurologic and demographic information by severity of brain injury.

	Severity of TBI	
	Mild (<i>n</i> = 10)	Moderate–severe (<i>n</i> = 26)
Age at injury (<i>M</i> , <i>SD</i>)	36.0 (23.8)	32.7 (24.3)
Age at MRI (<i>M</i> , <i>SD</i>)	45.8 (30.5)	43.9 (24.5)
External cause of TBI (<i>n</i>)		
Fall	9	9
Vehicle collision	0	9
Vehicle/pedestrian	0	2
Sports/play	1	6
Gender (<i>n</i>)		
<i>F</i>	2	12
<i>M</i>	8	14
Socioeconomic status		
Low	1	7
Middle	8	17
High	1	2
Glasgow Coma Scale score (<i>n</i>) ^{<i>a</i>}		
3–8	0	9
9–12	0	3
13–15	10	14
Days impaired consciousness (<i>M</i> , <i>SD</i>) ^{<i>b</i>}	0	1.3 (4.1)
IQ ⁺	95.3 (9.7)	87.6 (14.1)

Note: group effect.

^{*a*} Chi square, $p < 0.05$.^{*b*} *t*-test $p < 0.05$.

Table 2

Social communication behaviors of young children with mild and moderate–severe TBI.

Least squares means (SE)	Severity of TBI	
	Mild (<i>n</i> = 10)	Moderate–severe (<i>n</i> = 26)
Social response		
Joint Attention	0.77 (0.11)	0.74 (0.07)
Gestures	0.10 (0.06)	0.16 (0.04)
Words	1.71 (0.33)	1.71 (0.21)
Social initiation		
Joint attention	0.13 (0.11)	0.28 (0.07)
Gestures	0.06 (0.13)	0.35 (0.08)
Words	2.65 (0.45)	2.24 (0.28)

Table 3

Effect of age and severity of brain injury on social communication scores.

Social domain	Age effect		Group effect			
	<i>F</i> (1,33)	Parameter estimate	Effect size (<i>R</i> ²)	<i>F</i> (1,33)	Parameter estimate	Effect size (<i>R</i> ²)
Social response						
Joint Attention	0.60	0.0017	0.018	0.09	0.038	0.003
Gestures	6.23 *	0.0033	0.155	0.84	−0.0681	0.021
Words	72.30**	0.0585	0.686	0.00	−0.0045	0.000
Social initiation						
Joint attention	1.69	0.0029	0.047	1.26	−0.1442	0.035
Gestures	0.02	−0.0004	0.001	3.57 *	−0.2919	0.098
Words	62.35**	0.0739	0.651	0.61	0.4148	0.006

*
 $p < 0.05$ **
 $p < 0.001$.

Table 4

Surface area of callosal regions by severity of brain injury.

Least squares means (SE)	Severity of TBI	
	Mild (<i>n</i> = 10)	Moderate-severe (<i>n</i> = 26)
Total CC	1.372 (0.078)	1.269 (0.043)
Rostrum	0.038 (0.005)	0.038 (0.003)
Genu	0.357 (0.030)	0.340 (0.018)
Rostral body	0.201 (0.015)	0.204 (0.009)
Anterior midbody	0.152 (0.011)	0.148 (0.007)
Posterior midbody	0.134 (0.010)	0.126 (0.006)
Isthmus	0.121 (0.008)	0.104 (0.005)
Splenium	0.388 (0.025)	0.387 (0.016)

Table 5

Effect of age and severity of brain injury on regional callosal surface area.

Callosal area	Age effect		Group effect		
	<i>F</i> (1,33)	Parameter estimate	Effect size (<i>R</i> ²)	Parameter estimate	Effect size (<i>R</i> ²)
Rostrum	0.79	0.0001	0.023	0.01	0.0006
Genu	12.84**	0.0021	0.278	0.24	0.0172
Rostral Body	13.79**	0.0011	0.295	0.02	-0.0022
Anterior midbody	17.83**	0.0010	0.350	0.08	0.0037
Posterior midbody	11.18**	0.0006	0.249	0.49	0.0078
Isthmus	18.55**	0.0007	0.335	3.36*	0.0170
Splenium	15.38**	0.0021	0.318	0.00	0.0004

* *p* < 0.05** *p* < 0.001.