Individual differences in executive function and central coherence predict developmental changes in theory of mind in autism

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Abstract

There is strong evidence to suggest that individuals with autism show atypicalities in multiple cognitive domains, including theory of mind (ToM), executive function (EF), and central coherence (CC). This study investigated the longitudinal relationships between these three aspects of cognition in autism. Thirty-seven cognitively-able children with an autism spectrum condition were assessed on tests targeting ToM (false-belief prediction), EF (planning ability, cognitive flexibility and inhibitory control), and CC (local processing) at intake and again 3 years later. Time 1 EF and CC skills were longitudinally predictive of change in children's ToM test performance, independent of age, language, nonverbal intelligence, and early ToM skills. Predictive relations in the opposite direction were not significant, and there were no developmental links between EF and CC. Rather than viewing problems in ToM, EF and CC as co-occurring and independent atypicalities in autism, these findings suggest that early domain-general skills play a critical role in shaping the developmental trajectory of children's ToM.

Keywords: autism, development, longitudinal, theory of mind, executive function, central coherence

Considerable research efforts have been directed towards elucidating the neurocognitive atypicalities underpinning the defining behaviors of autism, including the profound difficulties in social reciprocity and communication and stereotyped, repetitive interests and activities (APA, 1994). In deriving hypotheses concerning the nature of the cognitive deficit(s) in autism, researchers have oscillated between postulating atypicalities in a single domain-specific or domain-general mechanism. Proponents of the theory of mind (ToM) hypothesis have claimed that autism is caused primarily by a specific inability to impute mental states to oneself and to others (Baron-Cohen, Leslie, & Frith, 1985; see Tager-Flusberg, 2007, for review). Alternatively, others have proposed that the behavioral features of autism emerge from more pervasive problems either in executive function (EF) – those higher-order cognitive processes that underlie purposeful, goal-directed behavior (Hughes & Russell, 1993; Ozonoff, Pennington, & Rogers, 1991; see Hill, 2004, and Russo et al., 2007, for review), or in central coherence (CC) – the natural propensity for processing information in context (Frith, 1989; Frith & Happé, 1994; see Happé & Booth, 2008, for review; see also Mottron & Burack, 2001, and Plaisted, 2001, for related accounts).

Both sorts of hypotheses pose challenges: those that posit primary problems in specific domains have been criticized for being too narrow, failing to address the full range of autistic symptoms, while those that propose more general information processing difficulties are faced with the problem of casting the net too wide, thereby failing to account for the strengths that are also characteristic of autism (Happé, 2001; see also Rajendran & Mitchell, 2007, for review). The shortcomings of such hypotheses on their own, together with the possibility that each hypothesis could explain well *some* of the distinct features of autism led Happé, Ronald, and Plomin (2006) to propose that a combination of cognitive risk factors (i.e., poor ToM and EF, and weak CC) gives rise to the core aspects of the behavioral phenotype. There is now strong evidence that individuals with autism show atypicalities across *multiple* cognitive domains (Pellicano, Maybery, Durkin, & Maley, 2006).

Happé et al. (2006) proposed further that these atypicalities are largely *independent* of each other both at the phenotypic and genetic levels. On this view, then, autism is the result of multiple, *primary* cognitive atypicalities. There are good reasons, however, to suspect that atypicalities in core aspects of cognition in autism might not be independent but should be linked throughout development. First, developmental approaches (e.g., Bishop, 1997; Karmiloff-Smith, 1998, 2009; Pennington, 2006) emphasize the dynamic nature of developing systems, where interactions between domains are likely to be the norm and where a selective impairment at an early point during development is likely to have substantial knock-on effects on the emergence of other cognitive functions (see also Oliver, Johnson, Karmiloff-Smith, & Pennington, 2000). Second, numerous studies of young typically developing children have highlighted functional relations between certain abilities, particularly ToM and EF, and have further characterized the nature of this relationship during the course of development.

Knowledge of these interactions between core cognitive functions in typical children should inform and advance our understanding of the possible developmental relations between cognitive atypicalities in children with autism. Yet pinpointing the nature of the developmental relations between cognitive domains in autism necessitates the use of longitudinal studies of which there are strikingly few. This article presents the findings of the first longitudinal study designed to examine potential relations between ToM, EF, and CC in a group of cognitively-able children with an autism spectrum disorder (ASD) over a 3-year period. School-age typically developing children perform at ceiling on some commonly-used cognitive measures. This study therefore focused upon individual differences across key aspects of cognition in the ASD sample alone. The article begins, though, by considering the longitudinal relations between ToM and EF in typical children in order to derive hypotheses regarding the potential (albeit maladaptive) pattern of interactions between these domains in autism. Attention is then directed to the notion of weak CC in autism, and the possibility that it might operate as a potentiating factor, which impinges upon the subsequent development of ToM and/or EF.

Relationship between ToM and EF

In direct contrast to Happé et al.'s (2006) suggestion, research on the typical development of ToM and EF has consistently demonstrated a robust relationship between individual differences in tasks tapping ToM and tasks tapping several components of EF, including mental flexibility, inhibitory control, and working memory (but not planning ability), independent of age and IQ, in preschoolers (Carlson & Moses, 2001; Carlson, Moses, & Breton, 2002; Carlson, Moses, & Claxton, 2004b; Frye, Zelazo, & Palfai, 1995; Hughes, 1998a, 1998b), and toddlers (Carlson, Mandell, & Williams, 2004a; Hughes & Ensor, 2007).

The most straightforward explanation of this association is that false-belief tasks used to index ToM impose executive demands and hence, EF effects the *expression* of ToM (Carlson & Moses, 2001; Leslie, 1994; Leslie & Polizzi, 1998; Moses, 2001; Russell et al., 1991). Several theorists, however, have contended that exists a more fundamental relationship between these two cognitive domains, where functioning in one domain is critical to the *emergence* of functioning in the other. Perner (1998; Perner & Lang, 1999) maintained that the metarepresentational capacity underlying ToM must be attained before children can regulate their own behavior. Alternatively, Russell (1996; see also Moses, 2001) proposed a causal relationship in the opposite direction, suggesting that the abilities to monitor one's actions and to act with volition are critical for reflecting on the mental states of self and others. Longitudinal investigations of the ontogenetic relations between ToM and EF in typical children strongly support the latter view. Hughes (1998b) found that, independent of age, verbal ability, and earlier ToM scores, performance on an EF measure (tapping inhibitory control) at age 4 predicted performance on false-belief measures at age 5, *but not vice versa* (see also Flynn, 2007; Flynn, O'Malley, & Wood, 2004). This finding has been extended to toddlers across 1-year (Carlson et al., 2004a) and 2-year (Hughes & Ensor, 2007) periods using tasks tapping early milestones in ToM and EF. These longitudinal findings provide compelling evidence of a functional relationship in one direction only: that early EF plays a critical role in the emergence of ToM in typical development.

In autism, there is ample empirical support for the presence of ToM and executive problems in most (though not all) children with autism compared to comparison children of similar age and ability (e.g., Ozonoff et al., 1991; Pellicano, 2007; but see Liss et al., 2001), and indeed, the very co-occurrence of difficulties in ToM and EF is suggestive of a link between these domains. Significant ToM-EF correlations have been documented, independent of age, verbal ability and nonverbal ability (Colvert, Custance, & Swettenham, 2002; Joseph & Tager-Flusberg, 2004; Ozonoff et al., 1991; Pellicano, 2007) but the nature of the relation in autism is not well understood. Two studies hint at the possibility that the developmental course of the ToM-EF relation in autism might follow a similar pathway to that of typical development. One cross-sectional study examined the extent of “impairments” within each cognitive domain in a group of young children with autism (Pellicano, 2007). No child showing impaired EF also possessed intact ToM, suggesting that intact EF is a necessary, but not sufficient, condition for the development of ToM in autism. Converging support for this conclusion comes from the only longitudinal study to date. Tager-Flusberg and Joseph (2005a) tested children with ASD (n=45) on numerous ToM and EF tasks at intake and re-evaluated their ToM skills one year later. Children’s early executive skills predicted later performance on ToM tasks independent of language and initial ToM scores. Both studies provide preliminary evidence that in autism, like in typically developing children, a certain level of executive control is critical for the emergence of ToM. Tager-Flusberg & Joseph (2005a) did not, however, assess children’s EF skills at follow-up rendering it uncertain whether longitudinal relations also existed in the reverse direction (early ToM → later EF), which would provide evidence of a bidirectional relationship between these functions (cf. Ozonoff et al., 1991; see also Mundy, 2003).

Relationship between CC and other functions

One additional feature implicated in the pathogenesis of autism (cf. Happé et al., 2006) could complicate this picture further. While children with autism show difficulties in EF and ToM, they also show an especially weak form of CC (Frith, 1989; Frith & Happé, 1994; Happé, 1999): a tendency for processing local elements at the expense of global meaning. This peculiarity in information processing has been shown to manifest as superior performance on visuospatial tasks, like the Embedded Figures Test (EFT; Witkin, Oltman, Raskin, & Karp, 1971; see below), for which analysis of local information is advantageous. Indeed, children with autism have been shown repeatedly to outperform typical children of similar age and ability on this task, with very large effect sizes (Cohen's $d>1.3$; e.g., see Morgan, Maybery, & Durkin, 2003; Pellicano et al., 2006). Furthermore, the development of these skills takes different courses in autism and typical development, with especially weak CC being early-emerging and initially accelerated in autism (Pellicano, in press).

It is plausible, then, that the very presence of weak CC early in development – a vulnerability that is not present in typical children to the same extent as in autism – could alter significantly the emergence of other functions, especially ToM and EF. Indeed, Frith's (1989) original account proposed that the social *and* nonsocial (behavioral) symptoms could be viewed as manifestations of weak CC. Without a strong drive for coherence, a child with autism is unable to integrate seemingly disparate information to make sense of his/her social interactions, resulting in "an incoherent world of fragmented experience" (Frith, 1989, p. 93).

Building on Frith's (1989) argument, Jarrold et al. (2000) maintained that early-emerging ToM behaviors, such as joint attention, rely on the coordination or *integration* of verbal and nonverbal cues, including eye-gaze, body posture, and pointing gestures. Accordingly, early manifestations of weak CC therefore could severely limit the extent to which the child could integrate these visual cues to achieve a shared focus of attention. Joint-attention skills are considered "precursors" to later ToM development in typically developing children (Charman et al. 2000) rendering it plausible that fundamental problems in CC could have deleterious effects on the developing ability to reason about others' mental states.

There is indeed some support for a link between ToM and CC in autism. Baron-Cohen and Hammer (1997a, b) showed that fast times on the Embedded Figures Test (EFT), indexing weak CC, were related to poor performance on an advanced ToM task in adults with autism. Similarly, in children with autism, Jarrold et al. (2000) found significant inverse relationships between ToM abilities and performance on two visuospatial CC measures, though only once developmental differences in chronological age and verbal ability had been accounted for. Other empirical work, however, has failed to find significant associations between ToM and CC (Burnette et al., 2005; Happé, 1994, 1997, Morgan, Maybery, & Durkin, 2003; Pellicano et al., 2006). These findings instead find favor with Happé et al.'s (2006) most recent explanatory account, that poor ToM and weak CC are coexisting and independent atypicalities in autism. All of the studies examining a ToM-CC relation, however, have been cross-sectional in nature, and therefore the possibility of a truly developmental relationship between CC and ToM (i.e., whether poor ToM *emerges* from weak CC; Frith, 1989; Jarrold et al., 2000) remains untested.

Akin to Frith (1989), some have suggested a possible link between CC and EF. Individuals with autism might have difficulty on global processing tasks *because* the tasks themselves require intact executive skills (Mottron et al., 1999; Rinehart et al., 2000). For example, the absence of a global processing bias on a test of hierarchically-constructed figures could be attributable to problems shifting attention between global and local levels rather than poor global processing per se (Rinehart et al., 2000; also see Mann & Walker, 2003). Beyond the executive demands of CC tasks, others have proposed a maladaptive ontogenetic relationship in which poor EF is held to be one of the consequences of early manifestations of weak CC (Pennington et al., 1997; Bennetto, Pennington, & Rogers, 1996). On this account, persons with autism have problems producing flexible, goal-directed behavior precisely because it requires the integration of multiple units of information with peripheral or contextual cues. The empirical evidence for a CC-EF relation in cross-sectional studies of children and adults with autism, however, has been mixed (Booth et al., 2003; Pellicano et al., 2006; Teunisse, Cools, van Spaendonck, Aerts, & Berger, 2001). Nevertheless, a potential *developmental* link between CC and EF is intriguing, and requires analysis of longitudinal data.

The present study

Greater clarification is required concerning the developmental links between cognitive processes in autism. Although current accounts postulate multiple co-occurring risk factors in autism (e.g., Happé et al., 2006), this is a less parsimonious view than an emergence account which proposes instead that initial problems in certain domains in autism could be primary and could be causally related to the atypical development of other key functions. Existing findings in the autism literature point largely towards possible “online” associations between areas of functioning, and are therefore silent on developmental causal links between cognitive domains.

The current study addressed these hitherto unexplored questions by investigating longitudinally the developmental relations between ToM, EF, and CC in autism. Children with ASD, aged 4 – 7 years, seen initially as part of Pellicano et al.’s (2006) study, were re-evaluated three years later on developmentally-appropriate measures tapping key components of each domain. Since several tasks were used to assess each cognitive domain, one preliminary aim was to examine the validity of the constructs at each time-point, in addition to determining the stability of individual differences within each domain. One should expect some degree of temporal stability in these functions as evidenced in typical children (e.g., see Hughes, 1998b; Hughes & Ensor, 2007), although it is possible that such stability may not be characteristic of children who follow atypical developmental trajectories.

The primary goal of this study was to establish the underlying nature of the relationship between ToM, EF and CC in autism. In light of the specific direction of the functional link between ToM and EF in typically developing children – that the development of ToM is dependent on EF – one might expect the extent and nature of the link to be similar in autism.

Accordingly, individual differences in early EF skills should be longitudinally linked to change in autistic children's ToM skills but earlier ToM skills should not be predictive of progress in children's EF. It is also conceivable, however, that the presence of weak CC, alongside problems in ToM and EF, could modify the developmental trajectories of one or both of these functions, and could change also the very nature of the developmental course of the ToM-EF relation. To test these possibilities, a series of hierarchical regression analyses was performed, which examined whether individual differences in initial scores in one domain would predict progress in another domain over the 3-year period, independent of the potentially confounding effects of chronological age, verbal ability, and nonverbal ability.

Method

Participants

Forty-five children with an ASD (40 boys) aged between 4 and 7 years (*M* = 67.2 months; *SD* = 10.51) participated in the initial study (Time 1; see Pellicano et al., 2006, for details). These children had received a diagnosis of either autism (*n* = 31), PDD-NOS (*n* = 12), or Asperger syndrome (*n* = 2), according to DSM-IV criteria (APA, 1994) from an experienced panel of independent clinicians and met, or scored 1 point below, the diagnostic cutoff for autism on the Autism Diagnostic Interview – Revised (ADI-R; Lord et al., 1994). All children were considered to be "cognitively-able", obtaining verbal and nonverbal IQ scores above 80 (see below for measures used). Children with autism were recruited through community contacts in the south-west region of Western Australia, including early intervention agencies, speech and language therapists, pediatricians, and parent support groups. The majority of children were White, and the parents were of mixed socioeconomic backgrounds, although specific data on socioeconomic status and educational attainment levels were not recorded. All children spoke English as their first language.

Approximately three years later, all 45 families were invited to participate in the follow-up study (Time 2), 37 of whom consented to take part (82% of original sample). Of the

8 families unavailable for reassessment, 6 families were untraceable, and 2 had relocated. The 37 children with ASD (33 boys) in the follow-up group did not differ in terms of chronological age, $F(1, 44) = .28$, $p = .60$, verbal ability, $F(1, 44) = .63$, $p = .43$, nonverbal ability, $F(1, 44) = 1.27$, $p = .27$, or total ADI-R algorithm score, $F(1, 44) = 1.90$, $p = .18$, from those who were not re-evaluated ($n = 8$).

The follow-up group consisted of 26 children with autism, 9 children with PDD-NOS, and 2 children with Asperger syndrome. At Time 1, these children ranged in age from 4 years 1 month to 7 years 4 months (*M* = 5 years 8 months; *SD* = 10 months). At Time 2, children were approximately 3 years older (*M* = 8 years 5 months; *SD* = 11 months). The majority of these children ($n = 34$) were attending regular, mainstream classrooms.

Measures of general cognitive ability

At both time-points, the Peabody Picture Vocabulary Test – Third Edition (PPVT-III; Dunn & Dunn, 1997) was used to assess children's receptive vocabulary and four subtests (Matching, Associated Pairs, Forward Memory, and Attention Sustained) of the Leiter International Performance Scale – Revised version (Leiter-R; Roid & Miller, 1997) were used to index nonverbal ability (see Pellicano et al., 2006, for details). Standard scores are reported in Table 1. Raw scores are used in subsequent correlational and regression analyses since such scores have not been adjusted for age, and therefore are more sensitive to developmental change.

ToM measures

Three standard false-belief tasks were administered to index ToM at each time-point, and involved children predicting an action based on an attributed false belief. Children were rated as successful only if they gave a correct response to the false-belief test question and corresponding memory and reality control questions.

First-order unexpected-contents task (Perner, Leekam, & Wimmer, 1987). Children received three trials of this task. On each trial, children were shown a familiar box (e.g., egg carton) and asked what they thought was inside. The actual, unexpected contents of the box (e.g., cotton wool) were then revealed. Following the replacement of the lid, children were asked the critical own-belief test question: “Before you looked inside, what did you think was in the box?” They were then asked to predict the belief of another individual who was unaware of the unexpected contents (“If I show this box to Mum, what will she think is inside?), and a reality control question (“What is in the box really?”). Children received one point for each correctly-reported false-belief for both own-belief and other-belief test trials (maximum score=6). During administration of this task at follow-up, no child indicated an awareness that the boxes contained unusual contents from their initial assessment.

First-order unexpected-transfer task (Baron-Cohen et al., 1985). Children were shown six scenarios in which one actor either displaced or substituted another actor’s object. These scenarios were presented via CD-ROM. In a displacement trial, children witnessed the protagonist (e.g., Sarah) leave an object (e.g., an apple) in one location (e.g., backpack) and then leave the scene. While Sarah was absent, another actor (e.g., Andy) shifted the object to a different location (e.g., lunchbox). Upon the protagonist’s return, children were asked to predict his/her false belief (e.g., “Where will Sarah look for her apple?”), and to answer corresponding control questions (e.g., “Where did Sarah put the apple in the beginning?” and “Where is the apple really?”). One point was given for each correct response to the false-belief question for the three displacement and three substitution scenarios (maximum score=6).

Second-order unexpected-transfer task (Perner & Wimmer, 1985). Children were shown two scenarios, each lasting ~1 min, in which one actor (e.g., Jane) placed an object (e.g., a book) in a particular location (e.g., a drawer) and left the room. Another actor (e.g., Tom) moved the object to a different location (e.g., backpack), unaware that the protagonist was watching the transfer through a window. For each scenario, children were asked to attribute a mistaken belief about a belief to a character (e.g., “Where will Tom think that Jane will look for her book?”), and answer two control questions (e.g., “Where is the book really?” and “Where did Jane put the book in the beginning?”). Children received 1 point for each correct response to the false-belief question (maximum score=2). One child failed the control questions for one trial at Time 2. To avoid loss of data, he was given a score of 0 on this task.

EF measures

Four EF measures were administered at Time 1: two targeted children's planning ability (Tower of London and Mazes tasks), one tested children's cognitive flexibility (Set-shifting task), and one tested inhibitory control (Luria's hand-game). At Time 2, a developmentally-appropriate measure tapping cognitive flexibility was administered alongside the Tower of London task. Luria's hand-game and the Mazes tasks were administered only at Time 1, as initial testing at Time 2 revealed that children's performance was at ceiling on both tasks.

Tower of London task (based on Shallice, 1982; see also Hughes, 1998a). This test of higher-order planning ability was administered to children at both time-points. Children were presented with a wooden peg-board consisting of 3 vertical pegs of increasing size (small, medium, big) and given 3 colored beads (red, white, black), which they arranged in a particular configuration (start state). They were then shown a picture of the beads in a different configuration (goal state). Children were instructed to move the beads from the start state to the goal state in as few moves as possible (shown clearly on the bottom of each picture) while obeying the following rules: (1) only move one bead at a time and (2) beads must not be placed on the table. Children completed three initial practice trials, which ensured that children understood the rules of the game, which were followed by problem sets of increasing difficulty, including 4 trials of 1-, 2-, 3-, and 4-move problems. At Time 2, an additional set of 5-move problems were included to increase task difficulty. If a child failed all of the problems within a problem set, testing ceased. The number of moves taken and rule violations (two beads moved at once, bead placed on table) were recorded for each trial. Children were given one point for each trial if they reached the goal state within the minimum number of moves and without violating any rules (Time 1: maximum score=16; Time 2: maximum score=20). Successful performance on this task required children to identify the sequence of steps required to solve a novel problem, and to execute these steps while inhibiting the prepotent tendency to move two beads at a time. High scores therefore reflect good planning ability.

Set-shifting task. One task measuring cognitive flexibility was given to children at each time-point. At Time 1, children with autism were administered Hughes's (1998a) *teddy-bear set-shifting task*, a developmentally-appropriate measure of cognitive flexibility similar to the traditional Wisconsin Card Sorting Test (Heaton, 1981). To begin, children were presented with a teddy-bear and one of three decks of cards, which varied in terms of color (green vs. pink, blue vs. red, or yellow vs. purple), picture shown (hearts vs. diamonds, squares vs. moons, or stars vs. happy faces), and size of picture (small vs. large). Children were told that they were to uncover which cards Teddy like best. On each trial, children were shown a card taken randomly from one deck, and asked, "Is this card one of Teddy's favorites?" They immediately were given feedback (e.g., "Yes, that is one of Teddy's favorite cards" or "No, actually, that isn't one of Teddy's favorite cards"). Three rules (color, shape, and size) were used the order of which was counterbalanced across children. The sorting rule changed either when the child had successfully sorted six cards consecutively, or when a maximum of 20 trials had been presented. At this point, he/she was presented with a new teddy-bear and new deck of cards. Set-shifting performance was rated by the proportion of errors committed following the first sort to criterion.

At Time 2, a more difficult *computerized set-shifting task* (Comerford, Maybery, & Whitehouse, 2008) was administered. To begin, children saw one (target) card at the top of the computer screen, and four (response) cards at the bottom of the screen. The 24 cards differed on three attributes (color, form, and background). All cards shared only one attribute with three out of the four response cards, which ensured that each card could be sorted according to three rules (color, form, or background). Children were asked to select which one of the four response cards matched the target card. Following the child's response, the words 'correct' or 'incorrect' would appear in centre-screen. Cards were selected at random. Once the child had sorted 6 consecutive cards correctly, the rule changed (e.g., from color to form) without warning, and the child was required to shift to sort the cards according to the new (unspoken) rule. Testing continued until the set of 24 cards had been presented twice (48 trials in total). Similar to the earlier set-shifting task, the main variable of interest was the proportion of errors committed following the first sort to criterion. Importantly, both tasks assessed the ability to switch flexibly between sorting categories in response to feedback. A low score (i.e., minimal errors) therefore indicates good cognitive flexibility.

Luria's hand-game. This task was used by Hughes (1996) to assess inhibition in children with autism, and stemmed originally from Luria, Pribram, and Homskaya's (1964) work with pre-frontal patients. Following Hughes's (1996, 1998a) procedure, two conditions were administered at Time 1 only. In the first, imitation (control) condition, the experimenter performed a hand movement (e.g., made a fist or pointed a finger), and the child was asked to mimic the movement. In the second, conflict (test) condition, the child was required to execute the *opposite* action to that of the experimenter; that is, when she made a fist, children had to point their finger, and when she pointed her finger, children had to make a fist. Feedback was provided after every trial. There were five 'fist' and five 'finger' trials for each condition presented in a randomized order. Children received 1 point if they executed immediately the correct hand movement, yielding a total score out of 10 for each condition. This task required children to hold in mind an arbitrary rule and inhibit a prepotent response to perform a rule-governed motor act. High scores in the conflict condition reflect good inhibitory control.

Mazes task (taken from the Wechsler Pre-Primary Scales of Intelligence – Revised; Wechsler, 1989). This planning task, administered at Time 1 only, required children to complete a series of increasingly more complex mazes. Successful performance demanded that children plan their route ahead to reach the opening of the maze without deviating from the correct path. The number of errors made (i.e., path deviations) was recorded for each trial. If children failed two consecutive mazes (i.e., completed the mazes but with several errors), testing ceased. Standard scoring procedures were used (see Wechsler, 1989). High scores indicate good planning ability (maximum score=26).

CC measures

Three measures of visuospatial CC (cf. Happé, 1999) were given at Time 1, including versions of the Embedded Figures Test, the Pattern Construction task, and the Figure-Ground task. At Time 2, children were administered all but the latter task to avoid ceiling effects. For all measures, a local processing bias (i.e., weak CC) was advantageous to task performance.

Embedded Figures Test (EFT). Children received versions of the EFT at each time-point, which assessed their ability to disembed a local element from a global image. At Time 1, children received both the Preschool version of the EFT (PEFT; Coates, 1972), and Set A of the Children's EFT (CEFT; Witkin et al., 1971). In the PEFT, the child was shown a picture of the target figure (a triangle) and asked to locate the same triangle hidden within a larger black-and-white figure (e.g., a clock) as quickly as possible. Children completed 24 test trials in total, in addition to three initial practice trials. In Set A of the CEFT, children were shown a cardboard cut-out of a triangle, and asked to find quickly the triangle embedded in a larger colored figure. Children completed 2 practice trials, followed by 11 test trials. Six trials from the PEFT were also present in the CEFT; the order of presentation of these tasks therefore was counterbalanced across participants. A composite score was created by averaging the mean times for the two tasks (see Pellicano et al., 2006, for details).

At Time 2, children received the full CEFT (Sets A and B). In Set B, the target figure was a house. Children completed 14 trials. Following standard procedures (see Witkin et al., 1971), Set A always preceded Set B. For each version of the EFT, children's accuracy and response latency were recorded for each trial. Children were given a maximum of 30 s to locate the target stimulus on each trial. One point was given for each trial on which they successfully located the hidden target. If the triangle was not located within 30 seconds, then an error was recorded, and the maximum time (30 s) was given for that trial. The dependent variable of interest was time taken to find the hidden figure. Children with autism typically perform well on this task purportedly because they are not captured by the global image, allowing them to focus on the individual elements and find quickly the hidden target (Shah & Frith, 1983). As such, fast times on the EFT reflect good local processing (i.e., weak CC).

Pattern Construction task (from the Differential Ability Scales; Elliott, 1990). This block construction task is similar in nature to Wechsler's (1999) Block Design subtest but contains a larger range of items (2-, 4-, and 9- block patterns), and can be administered to children of a wider age range (3–17 years). Children were shown a series of two-dimensional patterns composed of black and yellow segments, and were required to re-construct each pattern using three-dimensional blocks (whose surfaces were yellow, black, or half-yellow and half-black) as quickly as possible. Following standard discontinue rules (Elliot, 1990), testing discontinued if children failed to reconstruct correctly the pattern or exceeded the time limit on 4 out of 5 consecutive trials. Individual item scores, based on both accuracy and speed, were converted to ability scores using tables in the test Manual. In autism, heightened performance on block construction tasks has been attributed to a superior facility for segmentation (Shah & Frith, 1993). High scores therefore indicate good local processing (i.e., weak CC).

Figure-Ground task (from the Developmental Test of Visual Perception – 2nd Edition; Hammill, Pearson, & Voress, 1993). This task, administered at Time 1 only, required children to identify a number of stimulus figures embedded in a complex background, and was similar in nature to the EFT. Children were shown a target shape (e.g., triangle, square, circle) and asked to find as many of the figures hidden within a complex confusing background. Children were awarded one point for locating all of the hidden figures on a given trial for a maximum of 18 trials (maximum score=18). High scores reflect good local processing (i.e., weak CC).

General procedure

At each time-point, children were assessed individually, either at the family home or at the University. Children were seen twice within the space of two weeks, with each session lasting approximately 1-1.5 hours. Tests of general cognitive ability were always administered first followed by specific cognitive measures. Ethical approval for the initial and follow-up studies was granted by the Human Research Ethics Committee at the University of Western Australia, and informed written consent was obtained from parents prior to participation.

Results

This section begins with preliminary data analysis, which served to establish the validity of each construct. Descriptions of the coherence and temporal stability of each cognitive construct are reported first, followed by the results of principal component analyses. The main body of this section reports the results of a series of hierarchical regression analyses, which addressed the central aim of the study: to examine the longitudinal associations between cognitive domains in autism. Note that developmental changes in children's cognitive scores are reported in detail elsewhere (Pellicano, in press).

Background data analysis

Preliminary data screening revealed one extreme score (±3*SD*s) on the Pattern Construction task at Time 2. Following Wilcox (2002), this score was trimmed by replacing it with the value representing 3*SD*s above the mean score, and subsequent analyses were conducted using the trimmed score for this task. Children's (untrimmed) mean scores on all cognitive measures are presented in Table 1. The distribution of scores of all variables met assumptions of normality, with the exception of the individual ToM measures, which were significantly positively skewed. Logarithmic transformations were unsuccessful in normalizing the data, and therefore Spearman's rho was used to examine interrelationships between individual ToM tasks (see Table 2). Also, for ease of interpretation in analyses, scores on the Set-shifting and EFT measures were reversed so that a high score reflected good cognitive flexibility and good local processing (i.e., weak CC), respectively.

Insert Table 1 about here

Coherence. Table 2 presents a correlation matrix of concurrent and longitudinal associations between individual task scores, and age, verbal ability, and nonverbal ability. In general, significant associations emerged between scores on tasks assessing each cognitive domain, suggestive of good convergent validity for each construct at each time-point. In view of these significant correlations, robust aggregate scores were constructed for each time-point by averaging the standardized scores of individual measures for each domain. Estimates of internal consistency (Cronbach's alpha) were substantial for each aggregate score at Time 1 (ToM: $\alpha = .67$; EF: $\alpha = .77$; CC: $\alpha = .70$) and Time 2 (ToM: $\alpha = .71$; EF: $\alpha = .72$; CC: $\alpha = .76$).

Insert Table 2 about here

Temporal stability. Aggregate scores were used to examine the stability of individual differences within each cognitive domain across the 3-year period (see Table 3). Cross-time correlations revealed that individual differences in autistic children's aggregate scores were moderately stable across time for ToM, EF, and CC, and that this temporal stability was independent of the covarying effects of age, verbal ability, and nonverbal ability.

Insert Table 3 about here

Concurrent relationships between cognitive domains

Each cognitive construct showed good internal consistency and temporal stability. Table 3 also shows that were clear concurrent relations *between* domains, especially ToM and EF, both at intake and follow-up. To assess further the validity of the constructs, principal components analyses with varimax orthogonal rotation (n = 37) were carried out on all individual ToM, EF and CC variables, with the effects of age, verbal ability, and nonverbal ability removed (by entering the partial correlations into the principal components analysis). The analysis of Time 1 variables yielded not three, but four factors with an eigenvalue greater than 1.00, which together explained 70.3% of the variance in the data (see Table 4). All three ToM variables loaded on to the first factor (with rotated factor loadings ≥ .67), and all three CC variables loaded on to the second factor (loadings ≥ .51). The EF variables were divided among the two remaining factors: one which could be interpreted as a planning factor (since Mazes and Tower of London variables loaded on to this factor; loadings ≥ .66) and one as a shifting/working memory factor (with Luria's hand-game and the Set-shifting task loaded on to this factor; loadings ≥ .63). This fractionating of the EF construct is not unexpected as many researchers (e.g., Hughes, 1998a; Hughes & Graham, 2002; Miyake et al., 2000) emphasize the componential nature of EF. Importantly, this analysis suggests that the constructs themselves at Time 1 were separate and distinct from one another.

A similar analysis was conducted for Time 2 variables. Two factors were extracted, which together explained 59.9% of the variance in children's scores (see Table 4). All three ToM variables, the Tower of London task and the Set-shifting task loaded on to the first component (loadings ≥ .61), and the two CC variables loaded on to the second component (loadings ≥ .67), suggesting that ToM and EF were no longer distinct constructs in this sample of children with autism at follow-up.

Insert Table 4 about here

Longitudinal relationships between cognitive domains

The main aim of this study was to determine whether individual differences in early cognitive skills (ToM, EF, CC) were longitudinally associated with emerging skills in other cognitive domains, or whether these skills developed independently (cf. Happé et al., 2006). A series of hierarchical regression analyses was carried out to distinguish between these alternative hypotheses (see Table 3 for cross-time correlations between aggregate scores). Since autistic children's task performance at a particular time-point will be attributable partly to their age and level of concurrent ability (both verbal and nonverbal), and partly to their earlier (Time 1) task performance in that cognitive domain, variation attributable to these factors in children's Time 2 scores in a particular cognitive domain were accounted for by entering concurrent age, verbal ability, nonverbal ability, and earlier task performance in the first step of the regression model. The additional contribution of early cognitive variables, if any, was then tested by entering these variables into subsequent steps of the regression equation. This procedure therefore sought to determine the contribution of early cognitive skills (e.g., EF and CC) to change in children's other skills (e.g., ToM) over the 3-year period; that is, whether certain cognitive skills early on played a role in the development of other cognitive functions in children with autism.

Predicting change in ToM. Table 5 shows the results of regression analyses carried out to determine the contribution of early EF and/or CC scores to variability in children's progress in ToM. Recall that Happé et al.'s (2006) account predicts that ToM skills should be distinct from EF and CC, at least developmentally, while other theorists suggest that early EF (Russell, 1996) or CC (Jarrold et al., 2000) should be longitudinally linked to ToM. To begin, Time 2 age, verbal ability, and nonverbal ability and initial ToM aggregate scores were entered simultaneously as predictors of children's Time 2 ToM aggregate scores. These variables jointly accounted for 45% of the variance in later ToM scores (see Table 5). Time 1 EF aggregate scores were entered in the second step of the analysis. Individual differences in early EF were predictive of change in children's ToM performance, $\Delta R^2 = .15$, $\Delta F(1, 31) = 14.27$, $p = .001$. In the third step, Time 1 CC aggregate scores made an independent contribution to the prediction of ToM, accounting for additional 9% of unique variance in Time 2 ToM scores, $\Delta R^2 = .09$, $\Delta F(1, 31) = 6.00$, $p < .05$. The final model was significant, $F(6, 36) = 11.02$, $p < .001$, $R^2 = .69$. The negative beta value (see Table 5) suggests that good local processing skills (i.e., weak CC) early on predicted poor ToM performance at follow-up, consistent with Jarrold et al. (2000). When the regression analysis was repeated with the order of predictors reversed, by adding CC aggregate scores at the second step and initial EF scores at the third step, both variables continued to predict significant unique variance in children's later ToM scores (CC: $\Delta R^2 = .12$, $\Delta F(1, 31) = 8.50$, $p < .01$; EF: $\Delta R^2 = .12$, $\Delta F(1, 30) = 11.47$, $p < .005$). Together, these analyses show that early EF and CC skills make independent contributions to change in children's ToM skills.

In view of the fractionated EF construct at Time 1, an additional regression analysis was conducted, similar to the one above, except that two Time 1 EF composite scores were computed – one reflecting a planning factor and the other reflecting a shifting/working memory factor – and entered stepwise into the second block. Age, verbal ability, nonverbal ability, and initial ToM scores were entered as background predictors at the first step of the analysis; these predictors accounted for 45% of the variance in children's ToM scores, R^2=.45, $F(4, 32) = 5.56$, $p < .001$. At the second step, scores on the EF planning factor (ß = .62, $p < .001$), but not the EF shifting/working memory factor (ß = .16, $p = .25$), were uniquely related to change in ToM scores, $\Delta R^2 = .13$, $\Delta F(1, 30) = 13.51$, $p < .001$. When CC aggregate scores were entered in the final step, they were negatively related to children's later ToM scores (ß = -.47, $p < .01$), accounting for an additional 12% of unique variance, ΔR^2=.12, $\Delta F(1, 29) = 8.50$, $p < .01$. The final model was significant, $F(6, 36) = 11.81$, $p < .001$, $R^2 = .70$.

Predicting change in EF. A second regression analysis was conducted to elucidate the early predictors of change in EF performance. While Happé et al. (2006) suggest that ToM and local processing skills should be independent from indices of executive control, other authors have proposed that these domains might be overlapping. Specifically, Perner (1999) has argued that ToM is a prerequisite for the later development of EF skills, and Pennington et al. (1997) has suggested that later EF problems in autism develop from an early-emerging weak CC bias. In the first step of the equation, Time 1 developmental variables and initial EF aggregate scores explained 53% of the variance in children's EF scores three years later, $R^2 = .53$, $F(4, 32) = 8.97$, $p < .001$, although only initial EF scores made a unique contribution to the model (ß = .54, $p < .05$) (see Table 5). Next, children's initial ToM aggregate scores were entered at the second step of the equation. The increase in variance accounted for in later EF scores, however, was not significant, $\Delta R^2 = .01$, $\Delta F(1, 31) < 1$. Finally, when children's Time 1 CC aggregate scores were entered in the third step, they failed to account for any additional variation in change in EF scores over and above the effects of age, verbal ability, and nonverbal ability, and initial EF performance, ΔR^2=.01, $\Delta F(1, 30) < 1$.

Predicting CC skills at follow-up. A final regression analysis examined the early predictors of children's CC skills. Analysis at the first step showed that Time 2 age, verbal ability, nonverbal ability, and initial CC aggregate scores jointly explained 64% of the variance in later CC scores, $R^2 = .64$, $F(4, 32) = 14.44$, $p < .001$. Children's initial ToM scores failed to explain a significant amount of unique variance in Time 2 CC scores when entered at the second step, $\Delta R^2 = .02$, $\Delta F(1, 31) = 1.95$, $p = .17$ (see Table 5). Furthermore, when early EF scores were entered at the third and final step, they failed to independently predict children's CC scores at Time 2, $\Delta R^2 = .01$, $\Delta F(1, 30) = 1.20$, $p = .28$.

Insert Table 5 about here

Discussion

Recent theoretical and empirical work emphasizes not a single cognitive atypicality in autism but multiple co-occurring cognitive atypicalities in ToM, EF, and CC (e.g., Bailey & Parr, 2003; Frith, 2003; Happé et al., 2006; Pellicano et al., 2006). This is the first study to investigate the nature of the longitudinal relationships between these domains. Contrary to suggestions that these atypicalities are largely independent in autism (Happé et al., 2006), this study found several key developmental relationships in a group of cognitively-able children with ASD. First, individual differences in early EF predicted change in children's ToM skills over and above variance accounted for by age, verbal ability, nonverbal ability, and children's initial ToM performance. In contrast, there was no independent relationship between children's early ToM skills and later executive control. Second, CC independently and inversely predicted success on ToM tasks: low scores on visuospatial CC tasks (i.e., strong CC) at intake were associated with success on ToM tasks at follow-up. Furthermore, this relationship was asymmetric: early ToM skills did not predict later CC. Finally, no longitudinal links emerged between individual differences in EF and CC, suggesting that these functions might be distinct in autism. These findings demonstrate clear developmental links between early domain-general processes (EF and CC) and autistic children's emerging sociocognitive skills, and highlight the importance of studying autism within a developmental context.

All three cognitive constructs also showed coherence at intake and follow-up: there were significant relationships between individual tasks for each aspect of cognition, independent of concurrent age, verbal ability, and nonverbal ability and individual differences in autistic children's cognitive performance were stable over this 3-year period, and remained so even once individual and developmental differences in general ability were accounted for. The current findings extend those of Tager-Flusberg and Joseph (2005b; see also Steele, Joseph, & Tager-Flusberg, 2003), who found a robust longitudinal relationship between aggregate ToM scores independent of language level over a 1-year period, and suggest that there is temporal stability in individual differences within ToM, EF, *and* CC in children with autism over a longer time-period. The coherence of the constructs and the stability of individual differences in each aspect of cognition support the validity of the constructs. The main aim of this study, however, was to elucidate the longitudinal links *across* cognitive domains and it is that issue which is discussed in depth below.

Developmental relations between ToM and EF

There has been fervent theoretical discussion surrounding the functional relations between ToM and EF in typical and atypical development. The current study found evidence of an asymmetric relationship between ToM and EF in a group of children with autism: children's early-emerging EF skills were longitudinally associated with children's progress in ToM performance over the 3-year period. There was no evidence, however, of a reciprocal link between these functions. This pattern of findings strengthens the preliminary evidence from two earlier studies on autism (Pellicano, 2007; Tager-Flusberg & Joseph, 2005a), which suggested that EF skills might play an important role in autistic children's developing ToM skills. Furthermore, this pattern is entirely consistent with findings from several longitudinal investigations of the development relationship between ToM and EF in typical children (Carlson et al., 2004a; Flynn, 2007; Flynn et al., 2004; Hughes, 1998b; Hughes & Ensor, 2007). Taken together, the current longitudinal data and data from typically developing toddlers and preschoolers provide firm evidence that individual differences in early EF skills influence children's subsequent performance on ToM tasks (specifically, false-belief prediction tasks) for children with *and* without autism. These findings are in line with an expression account of the ToM-EF relation (e.g., Moses, 2001; Russell et al., 1991). Yet the longitudinal nature of these data suggests that the ToM-EF relationship goes deeper than this.

The fact that early ToM failed to predict independently later EF skills speaks against the view that the capacity for metarepresentation (critical for ToM) is a prerequisite for the emergence of executive control (ToM→EF) (Perner, 1998), or that there is a bi-directional relationship between these functions (Ozonoff et al., 1991). Instead, Russell's (1996, 1997; see also Moses, 2001) emergence account, that the child's developing capacity for metarepresentation is dependent on the rudimentary development of executive control (EF→ToM), explains well the asymmetry in the current longitudinal data. Specifically, Russell argues that it is only once a child can monitor his/her actions and act with volition (i.e., demonstrate agency) is he/she able to reflect on other peoples' minds. In autism, then, the root of children's inability to experience self-awareness results from a primary problem in EF.

This view is supported by the only training study to have investigated the potential causal relationships between ToM and EF in autism. Fisher and Happé (2005) trained school-aged children with autism on either EF or ToM and tested both skills immediately following the week-long training program and again 2 months later. ToM training had an immediate and sustained effect on children's ToM skills, yet no concomitant gains were shown in EF. By contrast, although EF training failed to have an effect on children's EF skills at follow-up, it nevertheless produced significant improvements in children's ToM skills two months later.

There is, however, an alternative explanation. Hughes (1998b; see also Luria, 1966, and Lewis & Carpendale, 2009) proposed that developments in EF might contribute *indirectly* to the development of mental-state awareness via social contact. She argued that children's emerging EF skills may serve to facilitate interactions with social partners since effective social interactions require children to monitor their own and others' actions and adjust their behavior. Increased social contact also has positive implications for the child's developing ToM (Ensor & Hughes, 2008; Hughes & Leekam, 2004). This is noteworthy in the current study, as the majority of children attended mainstream schools at follow-up, providing opportunities for them to interact with non-autistic peers. Developments in EF, then, might have bootstrapped the quality and quantity of children's social interactions, leading to progress in ToM. Conversely, early difficulties regulating one's own behavior could have a negative impact on children's social competence, which in turn could disrupt their sociocognitive development. In this way, EF could be an important limiting and enabling factor in the capacity to engage in effective social interactions, indirectly influencing children's developing ToM. Although some studies have examined the distal correlates of individual differences in social cognition in autism (e.g., Slaughter, Peterson, & Macintosh, 2007), no studies have investigated the sources of individual differences in autistic children's developing executive skills. The combination of both experimental and observational measures of child-parent/sibling/peer interactions in future research will be beneficial in teasing apart the direct and indirect effects of EF upon ToM in autism, and to elucidate any (dis)continuities with typical development.

One additional point of interest is that performance on two EF tasks, both tapping planning ability, specifically predicted autistic children's progress in false-belief test performance. Research on typical development has identified that a combination of component skills, including inhibitory control and working memory, may be central to children's developing ToM (Carlson et al., 2002; Carlson et al., 2004b), which, on the face of it, appears incongruous with the current findings. Yet the planning tasks used here, especially the Tower of London task, are multifactorial in nature, and measures not only sustained and focused attention and the generation of goals and sub-goals (Shallice, 1982), but also the ability to shift flexibly between subgoals, to hold a sequence of moves in mind (i.e., working memory), and to inhibit a previously active sub-goal, all of which increase with task difficulty (e.g., Bishop et al., 2001; Bull, Espy, & Senn, 2004; Goel & Grafman, 1995; Hughes, 1998b). Indeed, the latter two processes are precisely those that have been shown to be critical in the emergence of ToM in typical preschoolers suggesting that, overall, the specificity of the developmental relations between ToM and EF in ASD might not be too dissimilar from that of typical development.

Developmental relations between ToM and CC

Executive control was not the only early cognitive skill to predict independently later ToM performance, however. Individual differences in visuospatial CC at intake made a unique contribution to progress in children's ToM skills at follow-up, beyond the shared effects of age, verbal ability, nonverbal ability, initial ToM scores *and* initial EF scores. Furthermore, there was no reciprocal relationship between ToM and CC. Early ToM skills did not predict autistic children's CC performance at follow-up. These findings support cross-sectional data showing that weak CC goes hand-in-hand with poor ToM in individuals with autism once the effects of age and verbal ability have been adjusted for (Baron-Cohen & Hammer, 1997; Jarrold et al., 2000). Crucially, the current longitudinal results provide for the first time evidence of a *developmental* relationship between ToM and CC in autism.

Frith (1989) described the typical propensity to "pull together large amounts of information" (p. 97) as a way of deriving coherent and meaningful experiences. She argued further that in autism this propensity is especially weakened, writing that "without this type of high-level cohesion, pieces of information would just remain pieces, be they small pieces or large pieces" (p. 98). As a result, autistic information processing is characterized by a persistent preference for processing details combined with an inability to extract a central, coherent representation. As Jarrold et al. (2000) suggested, early-emerging ToM skills, such as joint attention behaviors, rely critically on a certain level of perceptual integration: making sense of a pointing gesture requires combining information about where the person is looking and pointing, what the person is saying, in addition to the social context. Without such perceptual integration, the child may not be able to develop shared intentions, which could seriously hinder the development of children's ability to reflect on goal-directed behavior.

Alternatively, weak CC may interfere with autistic children's developing language skills. Several studies have shown that individuals with autism show difficulties integrating information in context to make inferences (e.g., Jolliffe & Baron-Cohen, 1999, 2000; Norbury & Bishop, 2002), and to resolve lexical ambiguities, such as homographs and idioms (Frith & Snowling, 1983; Happé, 1997; López & Leekam, 2003). In typical development, some theorists have claimed strongly that syntactic development, specifically children's mastery of sentential complements, which requires the ability to extract embedded clauses, is a necessary prerequisite for the development of a representational ToM (de Villiers & de Villiers, 2000; Hale & Tager-Flusberg, 2003; Lohmann & Tomasello, 2003). Problems understanding sentential complements also predict ToM difficulties in autism (Tager-Flusberg & Joseph, 2005b). Early and especially weak CC therefore could disrupt autistic children's syntactic development, which would have negative consequences for ToM development. The current study did not assess children's knowledge of sentential complements or their linguistic CC skills but the link between such skills and ToM could be a worthwhile avenue for future work.

Developmental relations between EF and CC

Several researchers (Mottron et al., 1999; Rinehart et al., 2000) have proposed that autistic children's poor executive skills might hinder their ability to process information at the global level thus forcing them to focus on the local level of analysis. Alternatively, Pennington et al. (1997) considered whether EF problems in autism could be subsumed by weak CC. The current findings found no developmental links between EF and CC in either direction and therefore do not support the notion of either an online or a developmental relationship between these two functions. Instead, these findings are consistent with Happé et al.'s (2006) suggestion that these two domains are independent through development.

It is noteworthy that the current study employed CC measures on which a focus on local detail was advantageous – precisely those tasks at which children with autism should excel. Perhaps significant longitudinal links between EF and CC might have been observed had measures that demanded effective global processing been employed since those are tasks on which autistic children should perform poorly (e.g., Booth et al., 2003). To resolve this issue, future longitudinal work should ideally use multiple CC measures, which place differential demands on local-global processing (Happé & Booth, 2008).

Implications for models of autism

According to Happé et al. (2006), co-occurring atypicalities in ToM, EF, and CC are independent in autism. These authors hint at the possibility that there might be interactions between cognitive functions but do not discuss the extent or nature of potential interactions. This view is sharply contrasted with the developmental approach championed by several authors (Bishop, 1997; Karmiloff-Smith, 2009), which stresses the fluidity of developing systems, where the profile of cognitive atypicalities, and of the associations or dissociations between them, may change over time within individuals with autism. Indeed, the current longitudinal findings suggest that functioning in EF and CC potentially contributes to the *emergence* of autistic children's ToM.

One possibility is that there are not three but two inherited risk factors – poor EF and weak CC – in autism, and that poor ToM emerges as a consequence of early atypical input from EF and CC. The second, albeit less parsimonious, possibility is that all three risk factors are present at birth and shape the defining behaviors of autism, precisely as Happé et al. (2006) claim but that they interact in specific ways, such that both EF and CC modify the subsequent development of ToM. Principal component analyses of the current data suggested that the constructs were clearly distinct at Time 1 yet were linked at a later point in development (at least for ToM and EF), thus supporting the latter view. Caution is warranted here, however, given that such analyses were based on a reasonably small sample size. Notably, on both possible accounts, poorly developed domain-general capacities early on during development are likely to place the child's emerging sociocognitive skills at considerable risk of impairment. In either case, both EF and CC could make promising candidates for interventions.

In sum, this is the first study to investigate the longitudinal relations between three key aspects of cognition in autism – ToM, EF, and CC. Rather than suggesting that there are several co-occurring, independent and largely static atypicalities in autism (cf. Happé et al., 2006), the present results suggest that autistic children's cognitive skills emerge within a dynamic developing system where domain-general skills play a critical role in shaping the developmental trajectories of ToM. These results reinforce the view that that early executive skills are an essential ingredient in children's developing understanding of mind – a pattern common to both typically and atypically developing children. Moreover, these results suggest further that the presence of an additional and especially pronounced atypicality early in development (in this case, weak CC) might have damaging effects on autistic children's ToM. These conclusions are necessarily limited by the absence of a typical comparison group, which would have been helpful in elucidating the parities and disparities between the developmental interactions across cognitive domains in typical development and in autism. It will be particularly important for future work to clarify whether the longitudinal CC-ToM relation is unique to autism or whether it is also a feature of typical development. The conclusions are further restricted by the presence of only two time-points, the reasonably small sample size, and the measurement of receptive vocabulary as the sole index of language ability. Nevertheless, these data represent a first step towards characterizing the developmental interactions of core cognitive functions in autism. Further longitudinal work encompassing multiple time-points is needed to show how core cognitive processes emerge over time and to identify which sorts of child and environmental (e.g., social interactions; cf. Hughes, 1998b) factors might influence children's development trajectories. Studying autism within a distinctly developmental context should lead to a more nuanced theoretical model of the developing cognitive phenotype of autism.

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Table 1. *Mean scores for cognitive measures at intake and follow-up (n=37).*

Variable	**Time 1** *M* (*SD*) Range	**Time 2** *M* (*SD*) Range
General cognitive ability		
Verbal ability [a]	97.08 (11.52) 80 – 122	93.89 (17.88) 62 – 138
Nonverbal ability [a]	113.27 (13.93) 83 – 141	104.35 (12.72) 80 – 135
Theory of Mind		
First-order unexpected-contents (out of 6)	1.92 (2.13) 0 – 6	4.97 (1.99) 0 – 6
First-order unexpected-location (out of 6)	1.78 (1.83) 0 – 6	3.32 (2.62) 0 – 6
Second-order unexpected-location (out of 2)	.08 (.28) 0 – 1	1.00 (0.94) 0 – 2
Executive Function		
Tower of London (# of trials in min. moves)	6.33 (2.80) 2 – 13	11.39 (3.21)[b] 5 – 18
Set-shifting (prop. errors following first sort to criterion)	.32 (.07)[b, c] .18 – .45	.44 (.16)[b, d] .22 – .80
Luria's hand-game (out of 10)	7.00 (1.82) 4 – 10	-
Mazes (out of 26)	14.08 (4.88) 4 – 22	-
Central coherence		
Embedded Figures Test (EFT) (s)[a]	5.61 (2.32)[e] 1.84 – 9.65	6.35 (2.66)[f] 1.56 – 13.58
Pattern Construction (ability score)	132.14 (17.64) 108 – 182	136.81 (20.90) 104 – 211
Figure-ground (out of 18)	13.05 (2.16) 9 – 18	-

Notes. [a] Standard scores are reported here; [b] *n* = 36; [c] Teddy-bear set-shifting task (Hughes, 1998b); [d] Computerized set-shifting task (Comerford et al., 2008); [e] Composite score comprising performance on the Preschool version of the EFT (Coates, 1972) and Set A of the Children's EFT (Witkin et al., 1971); [f] Sets A and B of the Children's EFT (Witkin et al., 1971).

Table 2. *Correlation coefficients between task scores (n = 37).*

	Time 1												Time 2									
Variable	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.	17.	18.	19.	20.	21.	22.	23.
1. T1 age	.59‡	.63‡	.19	.29	.20	.20	.27	.18	.53‡	.38†	.34†	.62‡	.96‡	.23	.28	.02	-.03	-.07	.39†	.32	.34†	.16
2. T1 verbal	-	.70‡	.35†	.43†	.33†	.41†	.50‡	.39†	.65‡	.52‡	.35†	.61‡	.59‡	.75‡	.56‡	.47‡	.28	.36†	.48‡	.56‡	.36†	.45‡
3. T1 nonverbal		-	.38†	.45‡	.25	.38†	.46‡	.48‡	.72‡	.48‡	.50‡	.64‡	.64‡	.65‡	.64‡	.33†	.07	.28	.47‡	.65‡	.47‡	.45‡
4. T1 ToM 1^{st} U-L[a]			-	.62‡	.70‡	.24	.37†	.48‡	.27	.40†	.48†	.38‡	.16	.33†	.43‡	.40†	.24	.54‡	.23	.23	.40†	.35†
5. T1 ToM 1^{st} U-C[a]				-	.53‡	.34†	.36†	.40†	.54‡	.55‡	.45‡	.39†	.31	.52‡	.47‡	.39†	.32†	.51‡	.30	.54‡	.50‡	.59‡
6. T1 ToM 2^{nd} order[a]					-	.27	.44‡	.36†	.18	.35†	.28	.30	.20	.29	.28	.31†	.16	.37†	.14	.18	.22	.27
7. T1 EFT[b]						-	.43‡	.46‡	.36†	.27	.47‡	.31	.23	.43‡	.18	.09	-.04	.02	.31†	.45‡	.19	.17
8. T1 Pattern Con.							-	.44‡	.56‡	.34†	.14	.42‡	.26	.33†	.43‡	.13	-.02	.18	.31†	.55‡	.28	.36†
9. T1 F-G								-	.45‡	.32†	.18	.47‡	.13	.35†	.30	.17	-.04	.31†	.44‡	.51‡	.34*	.28
10. T1 ToL									-	.48‡	.41†	.70‡	.53‡	.57‡	.53‡	.35†	.20	.39†	.48‡	.71‡	.57‡	.52‡
11. T1 set-shifting[b]										-	.54‡	.54‡	.42†	.62‡	.38†	.50‡	.24	.34†	.51‡	.54‡	.52‡	.53‡
12. T1 Luria											-	.48‡	.41†	.46‡	.44‡	.35†	.24	.33†	.50‡	.40†	.33†	.38†
13. T1 mazes												-	.58‡	.50‡	.56‡	.50‡	.11	.40†	.46‡	.49‡	.57‡	.43‡
14. T2 age													-	.26	.39†	.06	-.08	-.07	.48‡	.41†	.35†	.15
15. T2 verbal														-	.55‡	.62‡	.44‡	.52‡	.50‡	.64‡	.43‡	.57‡
16. T2 nonverbal															-	.43‡	.22	.48‡	.44‡	.66‡	.51‡	.42†
17. T1 ToM 1^{st} U-L																-	.45‡	.74‡	.15	.24	.52‡	.63‡
18. T1 ToM 1^{st} U-C																	-	.47‡	.02	.08	.17	.52‡
19. T1 ToM 2^{nd} order[a]																		-	.17	.25	.56‡	.50‡
20. T2 EFT[a]																			-	.61‡	.34†	.24
21. T2 Pattern Con.																				-	.47‡	.49‡
22. T2 ToL																					-	.53‡
23. T2 set-shifting[a]																						-

Notes. Time 1: T1; Time 2: T2; ToM 1^{st} U-C: theory of mind first-order unexpected-contents task; ToM 1^{st} U-L: theory of mind first-order unexpected location task; ToM 2^{nd}: theory of mind second-order task; EFT: embedded figures test; Pattern Con.: Pattern Construction task: F-G: Figure-Ground task; ToL: Tower of London Luria: Luria's hand-game; [a] Spearman rho correlation coefficients (see text for details); [b] Scores on these tasks have been reversed so that high scores are indicative of good performance; †Significant at $p < .05$; ‡Significant at $p < .01$

Table 3. *Pearson correlations between domain aggregate scores (n=37).*

		Time 1			**Time 2**		
		ToM	EF	CC	ToM	EF	CC
Time 1	ToM	-					
	EF	.55** (.37*)	-				
	CC	.53** (.29)	.56** (.24)	-			
Time 2	ToM	.50** (.36*)	.50** (.35*)	.13 (-.22)	-		
	EF	.52** (.28)	.69** (.43**)	.36* (.06)	.66** (.53**)	-	
	CC	.35* (-.05)	.70** (.25)	.60** (.41**)	.20 (-.31)	.50** (.03)	-

Notes. Partial correlations adjusting for concurrent/Time 2 chronological age, verbal ability, and nonverbal ability are shown in parentheses. ToM: theory of mind; EF: executive function; CC: central coherence.
* Significant at the 0.05 level (2-tailed); ** Significant at the 0.01 level (2-tailed).

Table 4. *Factor loadings from the principal components analysis (orthogonal rotation) of scores on theory of mind (ToM), executive function (EF), and central coherence (CC) measures at Time 1 and Time 2 with variation associated with concurrent age, verbal ability, and nonverbal ability removed at each time-point.*

	Factor loadings			
	1	**2**	**3**	**4**
Time 1 variables				
ToM: 1st-order unexpected-contents	.87*	-.03	.20	.08
ToM: 1st-order unexpected-location	.67*	.28	.27	-.00
ToM: 2nd-order unexpected-location	.87*	-.05	.01	.17
EF: Tower of London	-.05	.89*	-.02	.03
EF: Set-shifting	.30	.33	.63*	-.10
EF: Luria's hand-game	.15	.01	.88*	.19
EF: Mazes	.10	.66*	.29	.12
CC: Embedded Figures Test	-.03	-.03	.23	.92*
CC: Pattern Construction	.33	.22	-.38	.51*
CC: Figure-ground	.35	.27	-.14	.58*

Time 2 variables	**1**	**2**
ToM: 1st-order unexpected-contents	.68*	-.38
ToM: 1st-order unexpected-location	.61*	-.05
ToM: 2nd-order unexpected-location	.74*	-.32
EF: Tower of London	.73*	.14
EF: Set-shifting	.74*	.13
CC: Embedded Figures Test	-.04	.67*
CC: Pattern Construction	.05	.87*

* Factor loadings > .4

Table 5. *Summary of hierarchical regression analyses (final models) (n=37).*

	Variable	*B*	*SE B*	*ß*	R^2 or ΔR^2
Predicting ToM	Step 1				.45***
	T2 age	-.05	.01	-.66***	
	T2 verbal ability	.03	.01	.58***	
	T2 nonverbal ability	-.00	.01	-.02	
	T1 ToM aggregate	.38	.13	.39**	
	Step 2				.15***
	T1 EF aggregate	.56	.15	.53***	
	Step 3				.09*
	T1 CC aggregate	-.61	.18	-.58**	
Predicting EF	Step 1				.53***
	T2 age	-.01	.01	-.13	
	T2 verbal ability	.00	.01	.15	
	T2 nonverbal ability	.01	.01	.16	
	T1 EF aggregate	.60	.25	.54*	
	Step 2				.01
	T1 ToM aggregate	.19	.16	.18	
	Step 3				.01
	T1 CC aggregate	-.15	.17	-.14	
Predicting CC	Step 1				.64***
	T2 age	.01	.01	.17	
	T2 verbal ability	.01	.01	.24	
	T2 nonverbal ability	.01	.00	.26	
	T1 CC aggregate	.38	.15	.34*	
	Step 2				.02
	T1 ToM aggregate	-.22	.14	-.22	
	Step 3				.01
	T1 EF aggregate	.24	.22	.21	

Notes. Time 1: T1; Time 2: T2; ToM: theory of mind; EF: executive function; CC: central coherence. *Significant at $p < .05$; **Significant at $p < 0.01$; ***Significant at $p < .001$.