Abstract Analogical Reasoning in High-Functioning Children with Autism Spectrum Disorders

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Children with autism spectrum disorders (ASD) exhibit a deficit in spontaneously recognizing abstract similarities that are crucial for generalizing learning to new situations. This may contribute to deficits in the development of appropriate schemas for navigating novel situations, including social interactions. Analogical reasoning is the central cognitive mechanism that enables typically developing children to understand abstract similarities between different situations. Intriguingly, studies of high-functioning children with ASD point to a relative cognitive strength in basic, nonabstract forms of analogical reasoning. If this analogical reasoning ability extends to abstract analogical reasoning (i.e., between superficially dissimilar situations), it may provide a bridge between a cognitive capability and core ASD deficits in areas such as generalization and categorization. This study tested whether preserved analogical reasoning abilities in ASD can be extended to abstract analogical reasoning, using photographs of real-world items and situations. Abstractness of the analogies was determined via a quantitative measure of semantic distance derived from latent semantic analysis. Children with ASD performed as well as typically developing children at identifying abstract analogical similarities when explicitly instructed to apply analogical reasoning. Individual differences in abstract analogical reasoning ability predicted individual differences in a measure of social function in the ASD group. Preliminary analyses indicated that children with ASD, but not typically developing children, showed an effect of age on abstract analogical reasoning. These results provide new evidence that children with ASD are capable of identifying abstract similarities through analogical reasoning, pointing to abstract analogical reasoning as a potential lever for improving generalization skills and social function in ASD. ***Autism Res*** *2014, 7: 677–686.* © 2014 International Society for Autism Research, Wiley Periodicals, Inc.

Keywords: autism spectrum disorders; analogical reasoning; development; social cognition

Introduction

The experience of a child is often haphazard. Developing the ability to see the abstract similarities between situations that are superficially different is crucial to social, practical, and scholastic learning [Gentner & Medina, 1998; Goswami, 1991; Landau, Meier, & Keefer, 2010; Liu, Pham, & Holyoak, 1997; Read, 1987; Richland & Burchinal, 2013; Smith, 1984]. Children with autism spectrum disorders (ASD) often demonstrate a bias toward processing stimuli details without processing more abstract and global meaning [Frith, 1989; Happe & Frith, 2006], and therefore may experience difficulties with seeing abstract similarities in the absence of literal or surface-level similarities. Putatively, this detail-focused processing style could leave children and adults with ASD at a disadvantage in all of the unfamiliar environments they encounter as they grow up: from school, to family outings, to extracurricular activities, to the workplace. For example, not understanding the abstract similarities between visits to different restaurants can make each family outing a new and confusing experience, and that may be one (of several) reasons that leads individuals with ASD to eat the same meal(s) at the same restaurant(s). Enabling children to see meaningful similarities between superficially disparate items and situations (e.g., different restaurants, menus, and meal times) is a central role of analogical reasoning in typical development [Gentner & Medina, 1998; Goswami, 1991].

Intriguingly, higher-functioning children with ASD often do have core cognitive strengths for categorizing verbal information and visuospatial reasoning on highly structured tasks, *similarities and matrix reasoning*, where children and adults with ASD show no differences in comparison with normative data or age and IQ matched controls [Mayes & Calhoun, 2008; Oliveras-Rentas, Kenworthy, Roberson, Martin, & Wallace, 2012]. Visuospatial matrix reasoning ability appears to be stronger than standard IQ test performance [Bolte, Dziobek, & Poustka, 2009; Dawson, Soulieres, Gernsbacher, &

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Mottron, 2007]. These skills may support abstract analogical reasoning in which a semantic relationship is inferred between two items and then applied to a separate pair of items that have an abstractly similar semantic relationship. Furthermore, there is some evidence that children with ASD are capable of concrete forms of analogical reasoning [Morsanyi & Holyoak, 2010; Scott & Baron-Cohen, 1996]. However, children with ASD demonstrate impaired performance compared with matched controls on abstract nonanalogical forms of reasoning, such as conditional reasoning [Lawrence et al., 2012; Morsanyi and Handley, 2012], matrix reasoning that involves internal manipulation of information [Shulman, Yirmiya, & Greenbaum, 1995], and deductive reasoning about abstract categorical content [Alderson-Day & McGonigle-Chalmers, 2011]. Therefore, the literature not only provides reason to predict that children with ASD may be capable of *abstract* analogical reasoning, but also suggests reasons to doubt that they have this capability. This unresolved empirical question is of particular significance given the key role of analogical reasoning in supporting the typical development of abilities that are impaired in ASD.

An influential theory of cognition in ASD, *weak central coherence theory*, holds that people with ASD have difficulty identifying abstract similarities because they focus on the details that differ between items and situations (i.e., processing local information rather than global information) [Happe & Frith, 2006]. However, children with ASD are also capable of overcoming their bias to detail if their attention is explicitly directed to global information [Goswami, 1991; Happe & Frith, 2006]. Children with ASD performed well in global processing tasks in studies of divided attention [Plaisted, Swettenham, & Rees, 1999] and letter string discrimination [Plaisted, Saksida, Alcantara, & Weisblatt, 2003] after their attention was explicitly directed toward the global information in these tasks. Ten-year-old children with ASD are much less likely than typically developing children to spontaneously report seeing both forms in an ambiguous figure (e.g., rabbit/duck), but they do report both forms with explicit instructions [Sobel, Capps, & Gopnik, 2005]. These findings suggest an intriguing possibility that explicit instruction in abstract analogical reasoning skills could improve the ability of children with ASD to identify abstract similarities in the real world. If strengths in abstract analogical reasoning on a structured explicit task can be demonstrated, then intervention strategies might be developed that explicitly teach analogical reasoning skills as generalization tools to enhance the ability of children with ASD to learn from their experiences.

The present study probes abstract analogical reasoning in children and adolescents from 8 to 17 years of age. This range represents a developmental stage subsequent to a key transition in the development of analogical reasoning in typically developing children. This transition, called the "relational shift," is characterized by an increased ability to understand semantically distant analogies (i.e., more-abstract analogies that are based on structural similarities) as opposed to primarily focusing on superficial/concrete similarities in analogical reasoning [Gentner, 1988; Rattermann & Gentner, 1998]. The relational shift generally occurs by around age 6 years in typical development. This range also marks the start of a period when children with ASD fall further behind their typically developing peers in the areas of cognitive control, social memory and attention [Luna, Doll, Hegedus, Minshew, & Sweeney, 2007; O'Hearn, Asato, Ordaz, & Luna, 2008; Rosenthal et al., 2013]. Virtually nothing is known about the time course of development of analogical reasoning in ASD. It may be that, even if children with ASD are capable of abstract analogical reasoning, this ability develops on a different time course from typical development. The present study's age range enables us to conduct a preliminary exploratory analysis of this novel question and investigate whether children with ASD develop a mature mastery of abstract analogical reasoning.

Beyond asking whether children with ASD can understand abstract analogies in general, we sought to determine whether the level of abstractness (as a continuous rather than binary variable) affects analogical reasoning in ASD. To measure the level of abstractness in the analogies that children processed, we used an index of semantic distance. Semantic distance is a numerical measure of the difference in superficial meaning between two items or sets of items, calculated using latent semantic analysis (LSA) [Landauer & Dumais, 1997; Landauer, Foltz, & Laham, 1998]. The greater the semantic distance between items or situations, the more abstract the similarity between them. Thus, semantic distance provides a quantifiable measure of the level of abstractness that an individual understands. Semantically distant analogies represent abstract analogical reasoning, but note that the abstractness of these analogies does not refer to the use of abstract symbols as stimuli as in visuospatial relational reasoning tasks such as Raven's progressive matrices [Raven, 1965]. Rather, semantically distant analogies are abstract because they require understanding abstract, rather than concrete, similarities (analogical mappings) between items or situations that may appear different and/or unrelated. Thus, although our stimuli were photographs of actual, concrete objects, the analogical mappings required to perform the task successfully were frequently abstract, and their abstractness increased as a function of semantic distance. Using a quantified measure of abstract understanding (i.e., LSA) is appealing for quantifying abilities along a common, continuous scale to develop consistent, objective yardsticks for therapy-related progress [Committee, 2012] within and

across interventions. Previously, we have found that increasing or decreasing semantic distance has important effects on the cognitive and neural processes of analogical reasoning [Green, Cohen, Kim, & Gray, 2012; Green, Fugelsang, Kraemer, & Dunbar, 2008; Green, Kraemer, Fugelsang, Gray, & Dunbar, 2010, 2012].

Finally, we sought to test whether abstract (semantically distant) analogical reasoning ability in ASD is related to better social function. Analogical reasoning is an important mechanism for understanding social situations and interactions (e.g., learning from one interaction and applying it to another), and is thus a driver of healthy social function in typically developing children and adults [Landau et al., 2010; Liu et al., 1997; Read, 1987; Smith, 1984]. Here, we employed the Social Responsiveness Scale (SRS; [Constantino & Gruber, 2005]) as our quantitative measure of social function. The SRS was selected because it is a normed measure that is sensitive to social deficits in ASD, and it is independent from the measures we used to confirm the ASD diagnosis.

We expected to confirm and extend previous findings that children with ASD have intact abilities to make concrete analogies, using stimuli based on real-world images. Furthermore, we predicted novel findings of intact abstract analogical reasoning abilities in ASD, as well as preliminary evidence of age-related differences in the attainment of these abilities. Finally, we predicted that better abstract analogical reasoning supports better social function in ASD, as measured by the SRS.

Methods

Participants

Thirty-three children with an ASD diagnosis and 22 typically developing control (TDC) children were recruited for this study (see Table 1 for participant demographics). Children were recruited through the local community via advertisements and a hospital's outpatient clinics in the surrounding metropolitan area. All children were between the ages of 8 and 17 years and were required to have a general conceptual ability (i.e., full-scale IQ ≥ 60), as measured by the Differential Ability Scales, Second Edition [Elliott, 2007]. Two children (1 ASD; 1 TDC) received Wechsler Intelligence Scale tests (Wechsler Intelligence Scale for Children–4th Edition, or Wechsler Abbreviated Scale of Intelligence; [Wechsler, 1999, 2003]) within the last year and so these prior IQ score were included. Written informed consent from parents of children and assent from children were obtained according to Institutional Review Board guidelines.

Children with ASD received a clinical diagnosis based on *Diagnostic and Statistical Manual of Mental Disorders–Fourth Edition–Text Revised* criteria [APA, 2000]. ASD diagnoses were confirmed with the Autism Diagnostic Observation Schedule [Lord et al., 2000] and the Autism Diagnostic Interview-Revised [Lord, Rutter, & Le Couteur, 1994] by research-reliable clinicians. Children with ASD were screened through a parent phone interview and excluded if their legal guardians reported any history of known genetic, psychiatric, or neurological disorders (e.g., Fragile X syndrome or Tourette's syndrome). Stimulant medications were withheld at least 24 hr prior to testing ($n = 5$), while other medications were not withheld (selective serotonin reuptake inhibitors $n = 8$; selective norepinephrine reuptake inhibitors $n = 3$; alpha 2A agonists $n = 2$). Two children were exposed to alcohol in utero, and one child was born prematurely (within 32–36 weeks), and one child had a hemihypertrophia scar. TDC children were screened and excluded if they or a first-degree relative had developmental, language, learning, neurological, psychiatric disorders, medical disorders affecting cognition, or psychiatric medication usage, or if the child met the clinical criteria for a childhood disorder on the Child Symptom Inventory—Fourth Edition or Child and Adolescent Symptom Inventory [Gadow & Sprafkin, 2000, 2010]. Three children were enrolled but removed from analyses. One TDC child was enrolled but excluded due to the presence of a significant sleep disorder discovered during testing. One ASD and one TDC participant were removed from analysis because of extremely short response time (M < 3000 ms) indicating a

Table 1. Participant Demographics

	TDC	ASD	
Total *N*	22	33	*P*-value
Chronological age (years)			
M (SD)	13.43 (2.24)	13.17 (2.12)	0.66
Range	9.15–17.25	8.83–17.47	
Full-scale IQ[a]			
M (SD)	112.55 (16.17)	102.79 (18.94)	0.05
Range	92–149	67–154	
Gender (male/female)	21/1	29/4	0.34
ADI-R			
Social			
M (SD)		18.06 (5.91)	
Range		1–27	
Communication			
M(SD)		13.88 (5.54)	
Range		0–22	
Repetitive behaviors			
M(SD)		5.24 (1.99)	
Range		0–9	
ADOS			
Social + communication			
M (SD)		10.44 (3.58)	
Range		5–21	

[a]Differential Abilities Scale—Second Edition, Wechsler Intelligence Scale for Children—4th Edition or Wechsler Abbreviated Scale of Intelligence.

ADI-R, Autism Diagnostic Interview—Revised; ADOS, Autism Diagnostic Observation Schedule—Module 3; ASD, autism spectrum disorder; *SD*, standard deviation; TDC, typically developing control.

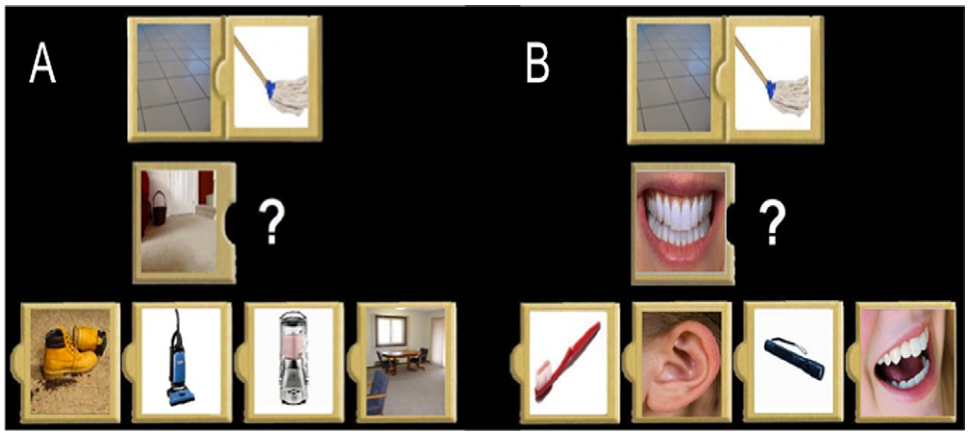

Figure 1. Analogical reasoning trials involving (A) low semantic distance and (B) high semantic distance.

lack of effort/engagement during the task. All analyses were conducted with the four children in the ASD group with medical comorbidities excluded, and the significant findings remained. Therefore, we reported analyses from the full sample.

Procedure

All participants were administered a set of 40 pictorial analogy trials viewed on a computer screen. Each trial was an analogical reasoning problem of the form, "A is to B as C is to ?" (Fig. 1). The A and B items were two linked puzzle pieces at the top of the screen. The C item was an unlinked puzzle piece below the A term. Participants selected the best D item from a menu of four puzzle pieces at the bottom of the screen. Participants were explicitly instructed to look for the answer that completed the analogy. Before completing test trials, all participants were explicitly taught how to apply analogical reasoning, and then they completed four practice trials with additional explicit feedback from the experimenter. Trials were designed in pairs that shared the A and B items, as in Figure 1. One trial in each pair involved relatively low semantic distance, and the other involved relatively high semantic distance. Each trial included an incorrect (lure) answer choice that was a semantic associate of item C and another lure that was similar in appearance to item C. These lures ensured that relying on semantic association or physical similarity as in a "matching-to-sample" task could not lead to the correct answer. Rather, responding above chance required children to identify the abstract analogical connections between relationships. Stimuli were presented in a fixed, pseudorandomized order with the constraint that paired items were not presented consecutively.

To confirm the validity of the analogy stimuli, a pilot group of 96 adult subjects in the United States performed the analogical reasoning task via Amazon Mechanical Turk (Amazon.com, Seattle, WA, USA). Accuracy was high in this cohort (overall: $M = 92.12\%$, standard deviation (SD) = 8.73%; semantically proximate: $M = 95.52\%$, $SD = 2.66\%$; semantically distant $M = 88.54$, $SD = 11.27\%$). One high semantic distance trial was removed from our analyses because accuracy among the pilot cohort was less than two times greater than the chance rate of 25%.

Semantic distance values for each stimulus item were obtained using LSA [Landauer et al., 1998]. Because the stimuli were pictures, semantic distance values were generated using the word pairs that correspond to the picture pairs in each trial (e.g., Mop : Tiles :: Toothbrush : Teeth) as we have described previously [Green et al., 2010, 2012]. Supplementary Table S1 provides the word pairs and LSA-derived semantic distance values for the set of stimuli. In brief, the LSA application (http://lsa.colorado.edu) calculates the similarity between the contextual-usage meanings of words as measured by the cosine of the included angle between vectors assigned to those words within a very high-dimensional "semantic space," comprising extensive corpora of English texts. A vector is added for multiword inputs such as the word pairs representing our pictorial analogy stimuli.

The SRS [Constantino & Gruber, 2005] was administered to the parents of all children participating in the study. The SRS is an informant-report, 65-item questionnaire that assesses behavioral characteristics of ASD, covering interpersonal, communicative, and repetitive/stereotypic behaviors rated on a 4-point Likert Scale (0–3 points). Higher scores indicate more social deficits. We used the SRS total score to examine the relationship between analogical reasoning ability and adaptive social functioning.

Results

Participants showed a high degree of accuracy (Table 2). Accuracy was high overall for the total set of

Table 2. Group Accuracy by Semantic Distance of Analogical Reasoning

	TDC (%)	ASD (%)
Semantically proximate		
Mean	92.72	90.76
Standard deviation	9.47	11.73
Semantically distant		
Mean	88.04	84.53
Standard deviation	12.39	13.35

ASD, autism spectrum disorder; TDC, typically developing control.

analogies ($M = 88.81\%$, $SD = 11.7\%$), and for both semantically proximate analogies ($M = 91.55\%$, $SD = 10.84\%$) and semantically distant analogies ($M = 85.93\%$, $SD = 12.97\%$). Consistent with our main hypothesis, accuracy for the ASD group did not differ from the TDC group overall ($t(53) = 0.88$, $P = 0.38$, Cohen's $d = 0.24$), for semantically proximate analogies ($t(53) = 0.66$, $P = 0.514$, Cohen's $d = 0.18$) or, most notably, for semantically distant analogies ($t(53) = 0.98$, $P = 0.33$, Cohen's $d = 0.27$). RTs (overall: $M = 10245$ ms, $SD = 37984$ ms; semantically proximate: $M = 10308$ ms; $SD = 38726$ ms; semantically distant: $M = 10182$ ms, $SD = 37207$ ms) also did not differ between ASD and TDC groups overall ($t(53) = 0.87$, $P = 0.39$, Cohen's $d = 0.24$), or for semantically proximate ($t(53) = 0.87$, $P = 0.39$, Cohen's $d = 0.24$), or semantically distant analogies ($t(53) = 0.87$, $P = 0.39$, Cohen's $d = 0.24$). Neither accuracy nor RT was significantly correlated with semantic distance in either group of subjects (all $P > 0.4$). Including IQ as a covariate in each of the foregoing contrasts did not result in any significant group differences at the $\alpha = 0.05$ level. Accuracy was significantly higher for semantically proximate analogies than semantically distant analogies for both the ASD group ($t(32) = 4.35$, $P < 0.01$) and the TDC group ($t(21) = 2.54$, $P = 0.019$). RT did not differ between semantically proximate and semantically distant analogies for either group (both $P > 0.4$).

To test our second major a priori hypothesis, we investigated the relationship of analogical reasoning ability to social function in ASD as measures by the SRS. SRS total scores were higher in the ASD group ($M = 77.09$, $SD = 13.24$) than in the TDC group ($M = 40.86$, $SD = 4.70$; $t(53) = 12.29$, $P < 0.01$, Cohen's $d = 3.65$). Consistent with our prediction concerning the relationship between abstract analogical reasoning and social function, SRS total score in the ASD group was significantly negatively associated with accuracy for semantically distant analogical reasoning ($\beta = -0.38$, $P = 0.04$; Fig. 2). This relationship was not significant for semantically proximate analogical reasoning ($\beta = -0.25$, $P = 0.17$), although a weak trend was apparent, consistent with the prediction that analogical reasoning ability, and especially abstract analogical reasoning, supports better understanding of social situations and interactions to guide social behavior.

In addition to our primary, a priori hypotheses, described above, we sought to explore the additional possibility of different developmental trajectories for analogical reasoning. We investigated the relationship of age to performance in the ASD and TDC groups. These analyses suggest intriguing possibilities about the development of analogical reasoning in ASD, but are presented only as preliminary findings here (e.g., nominal significance is reported, without correction for multiple comparison). Notably, age appeared to predict accuracy in the ASD group for semantically distant analogies ($\beta = 0.37$, $P = 0.037$). The ASD group showed an association between age and accuracy overall ($\beta = 0.34$, $P = 0.05$), but not for semantically proximate analogies ($\beta = 0.28$, $P = 0.11$), indicating that the overall effect was driven by the semantically distant analogies. The TDC group did not show effects of age on accuracy for semantically distant analogies or for overall accuracy or accuracy on semantically proximate analogies (all $P > 0.4$). The effect of age on accuracy for semantically distant analogies in ASD led us to further explore whether children with ASD became more accurate at the higher ranges of semantic distance with increasing age. Closer examination revealed that this effect appeared to be largely driven by lower performance among 8–10 year olds in the ASD group ($M = 67.11$, $SD = 13.16$) as compared with the TDC group ($M = 92.98$, $SD = 3.04$; $t(5) = 3.27$, $P = 0.022$, Cohen's $d = 2.92$). Performance by children older than 10 years was very similar between the ASD group ($M = 86.93$, $SD = 11.65$) and TDC group (87.26, 13.17; $t(46) = 0.09$, $P = 0.93$). The age-accuracy association did not show any trend by semantic distance in the TDC group. No such trend was observed for RT in either group (all $P > 0.4$). While these preliminary findings are intriguing, it is important to note that the 8- to 10-year-old age groups were small in our sample (4 ASD; 3 TDC), so future research will be important to provide clearer understanding of putative age effects on analogical reasoning in ASD.

To investigate whether analogical reasoning performance was related to cognitive ability, we correlated full-scale IQ with accuracy and RT in the semantically distant analogies condition. Full-scale IQ was a significant predictor of accuracy for semantically distant analogies ($\beta = 0.44$, $P = 0.010$) in the ASD group and was also marginally predictive in the TDC group ($\beta = 0.44$, $P = 0.046$). Notably, the effect of age on accuracy for semantically distant analogy in the ASD group was significant when IQ was included in the regression ($\beta = 0.42$, $P = 0.007$).

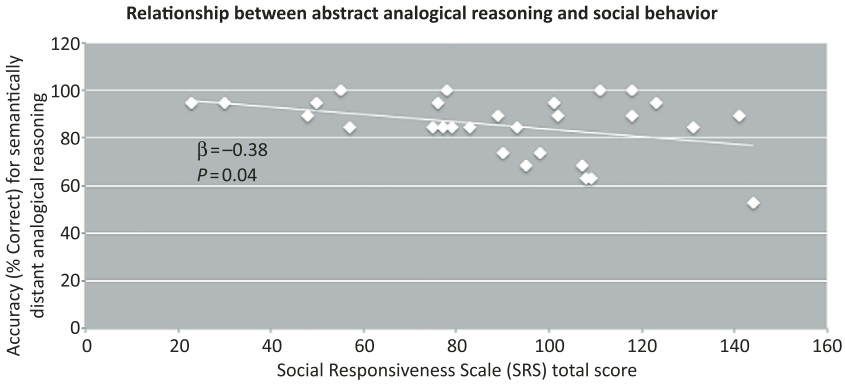

Figure 2. Accuracy for abstract (semantically distant) analogical reasoning trials was associated with adaptive social functioning as measured by the SRS. The negative association reflects the fact that lower SRS scores mark better adaptive social function.

Discussion

Analogical reasoning that connects semantically distant situations is essential for typical development [Gentner & Medina, 1998; Goswami, 1991; Richland & Burchinal, 2013], but has been largely unexplored in children with ASD. Here, we found new evidence that children with ASD are capable of identifying abstract similarities through analogical reasoning and that analogical reasoning ability correlates negatively with social deficits. The significant effect of age on accuracy for semantically distant analogical reasoning in ASD but not TDC children in the present study provides an indication that semantically distant analogical reasoning may develop on a lagging trajectory in ASD relative to TDC.

Analogical Reasoning in ASD

A challenge for ASD research is to find ways to channel the strengths that are already present in ASD to address core deficits. Children with ASD, particularly higher-functioning children, often have relative strengths in categorizing and nonverbal reasoning with highly structured cognitive tasks that have explicit instructions [Mayes & Calhoun, 2008; Oliveras-Rentas et al., 2012]. Analogical reasoning, a form of inductive relational reasoning, is a core mechanism for understanding abstract similarity [Green, Fugelsang, & Dunbar, 2006; Green et al., 2010, 2012; Landau et al., 2010; Liu et al., 1997; Read, 1987; Smith, 1984] and is related to social function in typically developing individuals [Landau et al., 2010; Liu et al., 1997; Read, 1987; Smith, 1984]. Our finding of intact analogical reasoning on a structured task that explicitly cues individuals to generate abstract analogies provides new and encouraging evidence that children with ASD can understand similarities between items and situations that are not physically similar (i.e., abstract similarity). This extends prior analogical reasoning studies in ASD that demonstrated intact concrete analogical reasoning with simple line drawings representing elementary analogies between superficially similar objects [Morsanyi & Holyoak, 2010; Scott & Baron-Cohen, 1996]. Importantly, the negative correlation between semantically distant analogical reasoning items and social function also confirms that abstract analogical reasoning is related to social function in ASD, presenting a potential bridge from cognitive strength to social weakness.

Our finding of intact performance for abstract analogical reasoning in higher-functioning children with ASD conflicts with reports of impaired performance on tasks tapping other complex forms of reasoning, like conditional reasoning [Lawrence et al., 2012; Morsanyi & Handley, 2012]. One distinguishing factor between the analogical reasoning and the conditional reasoning tasks is that the conditional reasoning tasks require sentence comprehension and potentially place greater demands on verbal reasoning. Furthermore, one of the conditional reasoning tasks included fantasy-based content that required ignoring one's own beliefs, and children with ASD tended to respond more in accordance with their beliefs than with valid conclusions [Morsanyi & Handley, 2012]. The analogical reasoning task does not make these demands, as the very basis of analogical reasoning is to extract similarities across items based on known relationships.

Making It Explicit

If children with ASD can perform analogical reasoning, why do they often fail to use this ability to identify abstract similarities? A key distinction is between *spontaneous* vs. *effortful* analogical reasoning [Gick & Holyoak, 1983]. Children with ASD may not use semantically distant analogical reasoning *spontaneously*, and this may contribute to their difficulties with generalizing rote skills

learned in treatment to new situations. Limited generalization of emotion/facial recognition or social skills beyond the walls of the treatment center is an ongoing problem in ASD research (see [Brown & Bebko, 2012] and [Wass & Porayska-Pomsta, 2013] for recent reviews); however, our data indicate that they are capable of using *effortful* analogical reasoning when explicitly instructed and are able to apply their effortful analogical reasoning ability to find abstract similarities. TDCs apply analogical reasoning *spontaneously*, often without conscious awareness [Liu et al., 1997; Read, 1987; Smith, 1984]. However, TDCs can also be trained to use *effortful* analogical reasoning via explicit instruction [Gick & Holyoak, 1983]. An extensive literature of analogical reasoning research in TDCs shows that analogical reasoning reveals the abstract similarities that connect seemingly different situations [Goswami & Brown, 1990; Green et al., 2010, 2012; Holyoak & Thagard, 1995; Rattermann & Gentner, 1998]. This literature further reinforces the potential of analogical reasoning to enable important life skills in ASD and is a crucial target for further investigation. Similarly, our data suggest the hypothesis that effortful analogical reasoning with explicit instruction may be a novel entry point for leveraging a cognitive strength to teaching social skills to children with ASD that can be applied to daily life in a more flexible manner than skills learned through rote memory.

Preliminary Indication of a Lagged Developmental Trajectory

Exploratory analyses suggested an effect of age on analogical reasoning in the ASD group, but not in the TDC group, especially for semantically distant analogies. These data may indicate that the relational shift toward understanding abstract analogical similarities that occurs in typical development around age 6 years may occur several years later in ASD, but that the ASD group eventually reaches similar levels of accuracy as the TDC group. If supported by further research, this pattern of developmental lag, followed by compensatory maturation, would be somewhat notable relative to other high-order cognitive skills in ASD, such as executive function. Executive function is generally not impaired in very young children with ASD compared with chronologically age and/or mental age-matched controls [Dawson, Meltzoff, Osterling, & Rinaldi, 1998; Dawson et al., 2002; Griffith, Pennington, Wehner, & Rogers, 1999; Stahl & Pry, 2002; Yerys, Hepburn, Pennington, & Rogers, 2007]; however, executive function deficits are reported in childhood [McEvoy, Rogers, & Pennington, 1993; Pellicano, 2010; Yerys, Wolff, Moody, Pennington, & Hepburn, 2012] and persist or increase into adolescence and adulthood in visual spatial working memory [Luna et al., 2007; O'Hearn et al., 2008], response inhibition [Luna et al., 2007; O'Hearn et al., 2008], planning [Pellicano, 2010; Wallace, Silvers, Martin, & Kenworthy, 2009], and set shifting [Ozonoff et al., 2004; Rosenthal et al., 2013]; the present study's preliminary observation of a more complete "catch up" to TDCs is therefore potentially interesting. As discussed above, effortful analogical reasoning may provide a cognitive ability to leverage in teaching new skills to adolescents and young adults with ASD to help them cope with the increasing complexity of their social and academic environments. Future research involving a greater number of preadolescent children and especially longitudinal research following a large sample of children from young childhood through adolescence will be important to conclusively characterize the developmental trajectory of abstract reasoning in ASD relative to TDC.

Semantic Distance as a Quantified Measure of Performance

The Interagency Autism Coordinating Committee Strategic Plan for Autism Spectrum Disorders has identified the development of "methods for measuring changes in core symptoms of ASD from treatment" as a top priority for National Institutes of Health-sponsored research. The present research demonstrates a novel application of semantic distance as a quantified measure of abstract similarity. Using semantic distance to measure comprehension of abstract similarity in ASD introduces a new tool to quantify treatment-related changes related to categorization and generalization skills. This metric provides a means by which comprehension of similarities can be assessed based upon a standardized, numerical index of semantic distance as a complement to existing subjective assessments.

Limitations of the Present Study

It is important to note limitations of the present study. First, while our study demonstrates that abstract analogical reasoning is a capability in high-functioning children with ASD, we were not able to compare our explicitly directed implementation of analogical reasoning with a more implicit reasoning or categorization task. Such comparisons will be important in future research to better understand the preserved capacity for abstract analogical reasoning relative to other related abilities and deficits in ASD. Further, our only measure of social function (SRS) captured social deficits rather than emerging social skills, such as the social skills improvement system [Gresham & Elliott, 2008]. Demonstrating a link between better prosocial skills and better abstract analogical reasoning abilities is a clear future direction in this line of work. It is also possible that a link between analogical reasoning ability and social function may be explained by variables not included in our analysis, such as verbal ability, which

future research should consider. Ideally, future experimental investigations of abstract analogical reasoning interventions can be used to help determine a causal relationship between developing this ability and improving social function. The present study is only able to provide correlational observations. In addition, the present study focused mostly on children with cognitive abilities in the average range or higher. Extending this work into children and adults with ASD and lower cognitive abilities is an important future step to determine if abstract analogical reasoning is an appropriate cognitive tool to build upon clinically (see below). While our sample included a child with an IQ below 70, and he performed well above chance (chance = 25% and he performed > 50% in both conditions), future studies are needed to determine whether analogical reasoning can be assessed validly in individuals with cognitive impairments. As noted above, our preliminary analysis of developmental trajectory of abstract analogical reasoning is limited by a small number of younger children in the 8- to 10-year-old age range. A cross-sectional analysis of this sort is also less conclusive than a longitudinal study. Finally, while the ASD group was higher functioning (i.e., mean group IQ > 70), its mean IQ was still significantly lower than that of the TDC group. This did not present a substantial interpretive hazard in this case because the key variable (analogical reasoning performance) was as strong in ASD as in controls. Analyses with and without IQ as a covariate showed the groups performed similarly on the analogical reasoning task. Given concerns with best practices for handling group differences in IQ in studies of neurodevelopment [Dennis et al., 2009], matching participants individually across groups would be informative in future studies.

Laying the Groundwork for Therapeutic Intervention

No prior ASD research has tested analogical reasoning as a tool for understanding abstract similarity. Thus, the empirical foundation for using analogical reasoning therapeutically is currently missing. Interestingly, some therapists for children with ASD have identified the potential utility of analogical reasoning and have begun using analogical reasoning in therapy games (http://www.nationalautismresources.com/analogies-game.html), although no data are yet available to validate or guide this therapeutic approach. A major motivation of the current research and an important goal for future research is to establish the empirical foundation for using analogical reasoning as a therapy tool, maximizing the effectiveness of this approach, and targeting specific cognitive constructs that support analogical reasoning in ASD. The relationship between abstract analogical reasoning and an established measure of social function, which we identified here, is consistent with the prediction that analogical reasoning abilities in ASD support social function and that augmenting existing analogical reasoning abilities in ASD represents a potential training lever for improving social function.

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Supporting information

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

Table S1. List of verbal descriptors for stimuli and LSA-derived semantic distance values.

File S1. Instructions and practice for analogical reasoning task.