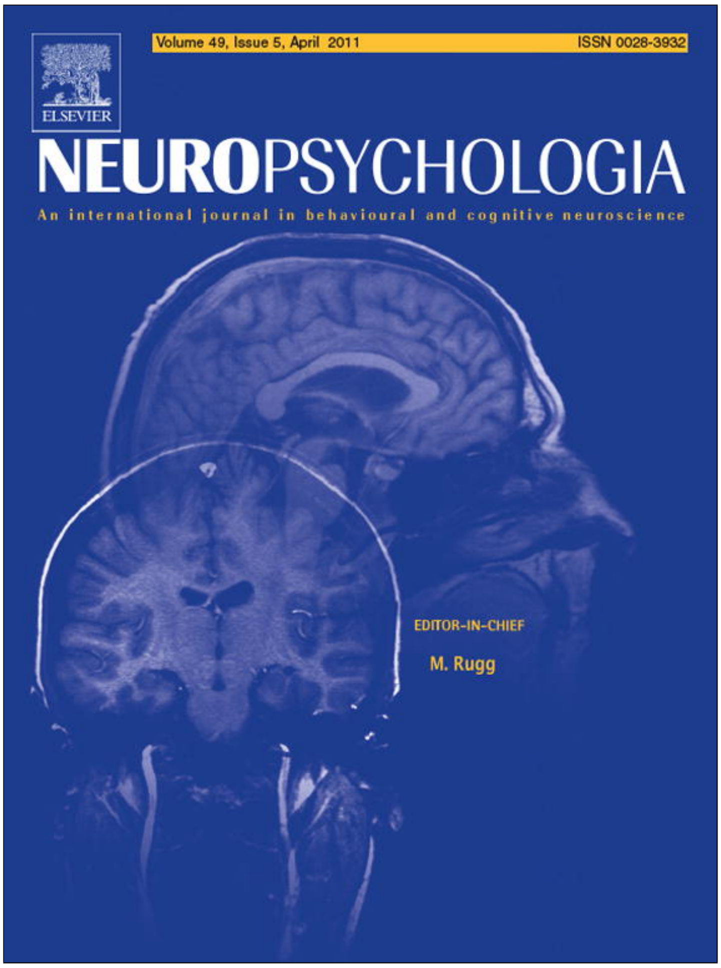
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Spatial and numerical abilities without a complete natural language

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ABSTRACT

We studied the cognitive abilities of a 13-year-old deaf child, deprived of most linguistic input from late infancy, in a battery of tests designed to reveal the nature of numerical and geometrical abilities in the absence of a full linguistic system. Tests revealed widespread proficiency in basic symbolic and non-symbolic numerical computations involving the use of both exact and approximate numbers. Tests of spatial and geometrical abilities revealed an interesting patchwork of age-typical strengths and localized deficits. In particular, the child performed extremely well on navigation tasks involving geometrical or landmark information presented in isolation, but very poorly on otherwise similar tasks that required the combination of the two types of spatial information. Tests of number- and space-specific language revealed proficiency in the use of number words and deficits in the use of spatial terms. This case suggests that a full linguistic system is not necessary to reap the benefits of linguistic vocabulary on basic numerical tasks. Furthermore, it suggests that language plays an important role in the combination of mental representations of space.

1. Introduction

Numerical and geometric abilities are arguably among the pinnacles of human progress. Interestingly, however, humans are not the only animal with such capacities. Research shows that humans possess numerical and geometric abilities that are innate, cross culturally universal, and shared with many non-human animals (see Cheng & Newcombe, 2005; Feigenson, Dehaene, & Spelke, 2004 for reviews). What then, allows humans to build upon and go beyond our core mental abilities to entertain more advanced mathematical and numerical concepts?

Some have proposed that language allows humans to expand upon fundamental abilities (Carruthers, 2002; Hermer-Vazquez, Moffet, & Munkholm, 2001; Hermer-Vazquez, Spelke, & Katsnelson, 1999; Landau & Lakusta, 2009; Shusterman & Spelke, 2005; Spelke, 2000, 2003; Spelke & Tsivkin, 2001; see also Gentner & Goldin-Meadow, 2003; Levinson, 2003). Consistent with this view, some research shows that the development of more advanced numerical and spatial capacities is tightly correlated with the acquisition of spatial and numerical language (Condry & Spelke, 2008; Hermer-Vazquez et al., 2001; Wynn, 1990, 1992). For example, before children learn the meaning of the verbal count list, they can only reliably distinguish between non-symbolic numerical sets approximately, with a ratio limit on precision, and they cannot accurately identify or produce a given number of objects (Wynn, 1990, 1992; Xu & Spelke, 2000). After learning verbal counting, however, children reliably produce or identify sets of objects on the basis of exact cardinal value (Condry & Spelke, 2008; Le Corre, Brannon, Van de Walle, & Carey, 2006; Le Corre, & Carey, 2007; Wynn, 1990, 1992). Similarly, adults discriminate between pairs of arrays of dots or sequences of sounds or actions with only approximate accuracy when the arrays are presented under conditions that do not allow verbal counting (e.g. Barth, Kanwisher, & Spelke, 2003; Cordes, Gelman, Gallistel, & Whalen, 2001; Izard & Dehaene, 2008). These findings suggest that number words and the verbal counting routine contribute to the development of large, exact numerical concepts. Because maturation and other forms of learning covary with language experience in these studies, however, they are open to a host of alternative interpretations.

Other evidence for a role of language in numerical cognition comes from the study of peoples whose language lacks specific numerical vocabulary. For example, the Pirahã and the Mundurucu of the Brazilian Amazon have few number words (no words for exact cardinal values in the former language and a lexicon restricted to 1–5 with some expressions for combining these terms in the latter), despite having an otherwise complex natural language (Everett, 2005; Frank, Everett, Fedorenko, & Gibson, 2008; Gordon, 2004; Pica, Lemer, Izard, & Dehaene, 2004). Interestingly, Pirahã and Mundurucu adults perform strikingly like educated adults in Europe and the U.S. in a variety of tasks that tap approximate

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numerical abilities, but fail at many tasks requiring representations of exact quantity beyond their vocabulary (Frank et al., 2008; Gordon, 2004; Izard, Pica, Spelke, & Dehaene, 2008; Pica et al., 2004). For example, Pirahã and Mundurucu subjects routinely fail to provide the exact number of items to accurately match the number of items in a sample array under conditions involving occlusion or otherwise requiring an exact numerical answer from memory. The only condition in which they succeed at matching the number of items to the sample is when the items are continually visible such that matching can proceed by one-to-one correspondence (Frank et al., 2008). These studies show that a natural language alone is not sufficient to acquire exact number concepts. Other studies of monolingual children who speak Willowra or Angurugu, two Australian languages with limited numerical vocabularies, show no effects of number language on exact numerical competency when compared to monolingual English-speaking children from the same region (Butterworth, Reeve, Reynolds, & Lloyd, 2008). Because members of these groups have a fully developed natural language, however, it is possible that aspects of language other than number words support their large, exact numerical abilities. Still unanswered is the question of whether a complete natural language is necessary to have large, exact number concepts.

Some studies of children also suggest that language influences performance in the spatial domain. Before children learn the spatial terms for left and right, they primarily navigate both by the shape of the surrounding surface layout and by the locations and features of objects, but they often fail to integrate these two sources of information (see Spelke, Lee, & Izard, 2010, for review). For example, in studies using a reorientation paradigm (see Cheng & Newcombe, 2005 for a review), children are led into a testing room where they see an experimenter hide an item, are then blindfolded and disoriented, and are then asked to reorient themselves to find the hidden item. Children use the shape (geometry) of the room to reorient themselves in cases where the room is rectangular with no distinctive features (no landmark condition). This leads them to search equally in the correct corner where the object was hidden and the geometrically equivalent, opposite corner (Hermer & Spelke, 1996). Even when provided with additional landmark information (one wall of a distinctive color), young children still search equally at the correct and geometrically equivalent corners. Adults and older children with linguistic terms for left/right relations, however, use the featural information provided by the colored wall to disambiguate between the two geometrically congruent corners and accurately reorient to locate the hidden item. The importance of language in solving this task is further suggested by the fact that adults can be made to perform like young children who lack terms for left and right by engaging working memory through a verbal interference task (Hermer & Spelke, 1996; Hermer-Vazquez et al., 1999; Huttenlocher & Lourenco, 2007; Learmonth, Newcombe, Sheridan, & Jones, 2008). Moreover, the acquisition of spatial terms for left/right relations in typically developing children correlates with performance on tasks requiring the combination of featural (landmark) and geometrical information (Hermer-Vazquez et al., 2001).

In contrast, other studies show that manipulating variables such as size of the testing area, the salience of the landmark information, or the relation of the target location to the landmark, enable young children to use both landmark and geometrical information at the same age they fail in other testing environments (Learmonth, Nadel, & Newcombe, 2002; Learmonth et al., 2008; Lourenco, Addy, & Huttenlocher, 2009; Ratliff & Newcombe, 2005; see Cheng & Newcombe, 2005, for review). These results suggest that situational factors can lead young children to use both types of information without the necessary language to describe the situation. The influence of situational factors has led some to suggest that spatial experience rather than language drives success on such tasks (e.g. Twyman & Newcombe, 2010). As in the case of number, however, developmental investigations comparing children before and after the acquisition of relevant language are limited because they confound language learning with nonlinguistic experience and maturational factors that could allow children's numerical, spatial, and linguistic abilities to emerge in parallel.

In summary, considerable evidence suggests that language is important for expanding numerical and geometrical abilities, but the role of language is still unclear. We turned to a natural case of linguistic deprivation to investigate the influence of language on numerical and spatial cognition.

While it would be unethical to experimentally manipulate exposure to language, occasionally (and unfortunately) economic, societal, or biological factors result in a natural case of language deprivation. The most well-known modern case of linguistic deprivation is that of Genie, a female deprived of linguistic and social interaction for most of her childhood due to abuse (see Curtiss, 1977; Jones, 1995). In the case of Genie and in other similar cases, the extremely impoverished and abusive conditions under which development occurred confound the cognitive conclusions that can be made (Bishop & Mogford, 1993). Natural language deprivation also occurs when a deaf child is born to hearing parents in circumstances in which no schools for the deaf, or access to a deaf community, are available. In such situations, children often fail to acquire a verbal language but do develop their own form of gestural communication or "home-sign" with some, but not all, of the properties of a natural language despite little or no formal linguistic input (e.g. Feldman, Goldin-Meadow, & Gleitman, 1978; Goldin-Meadow, 2003; Goldin-Meadow & Feldman, 1977). The development of rudimentary gestural-linguistic systems has been similarly studied at the group level in a Nicaraguan deaf community where there was no educational system or official sign language for deaf children until about 25 years ago, resulting in an entire cohort of homesigners (e.g. Senghas & Coppola, 2001). Once an official school for the deaf was established, homesigners began to interact and a common language (Nicaraguan Sign Language, or NSL) began to emerge. Interestingly, NSL became increasingly more structured with successive cohorts, suggesting that its systematization developed primarily through innovations by younger cohorts composed of children (<10 years) on the linguistic basis provided by older cohorts (Senghas & Coppola, 2001). One recent study of deaf adult NSL speakers found that individuals who learned an earlier and less complex version of emerging NSL performed worse on spatially-guided search tasks compared to a cohort who had learned a more recent and more complex version of NSL (Pyers, Shusterman, Senghas, Spelke, & Emmorey, 2010). Across the group, moreover, a significant correlation was observed between consistent use of spatial left/right terms and performance on the search tasks.

With the exception of this study, numerical and spatial abilities have not been extensively investigated in the reported cases of language deprivation. Accordingly, we studied the spatial and numerical abilities of an adolescent subject (IC) deprived of linguistic input from infancy due to deafness and lack of formal linguistic sign-language training until early adolescence. This natural case of language deprivation allowed us to ask how numerical and spatial abilities develop in the mature (or maturing) mind in the absence of a complete natural language and little to no formal instruction.

2. Method and results

2.1. Subject information

IC is a 13 year old male (at the time of testing) with a history notable for bilateral hearing loss from infancy (~0 years; 6 months of age). As a result of living in an underdeveloped country, he received little formal schooling, sign language instruction, or other therapeutic intervention until the age of 13 when he immigrated permanently to the United States.

2.1.1. Subject background

IC was born to a 19 year old mother following an uncomplicated pregnancy. His neonatal history was unremarkable. During early infancy he was noted to orient to his mother's voice; however, around 6 months he suffered a febrile illness of unknown etiology, and after that time no longer responded to voice. He babbled at about 1 year and walked independently around 2 years. Shortly after the age of 2 years he suffered a second febrile illness, reportedly meningitis, and was hospitalized for 3 months. After his recovery from this illness he returned to his previous developmental baseline, and was able to run and jump by the age of 3 years. His mother was not aware of any subsequent gross motor, fine motor, or social delays, though he continued to babble and did not produce words. At around age 3 years he moved with his mother from a small African country to the United States, but moved back to Africa to live with his grandmother 6 months later. He was enrolled in a regular school beginning at age 5, but stopped attending school after 1 year because he was often left by himself and was not given any specific support or instruction in sign language. From age 5 to 10 he spent most of his time at home with his grandmother, occasionally leaving the home to play with his younger half-brother and other friends. Beginning at 10 years of age, he received 1 hour per day of instruction in Portuguese Sign Language (PSR). At the age of 13 he moved to the United States with his mother, grandmother, and half-brother. Shortly after he was referred to a local hospital in an attempt to address his educational needs and subsequently enrolled in a residential school for the deaf.

2.1.2. Subject's behavioral profile

IC is a very expressive and social child. When he is at home he spends much of his time with friends, often staying out of the house until late in the evening, and has no difficulty with urban navigation. He enjoys playing on the computer and playing basketball. Per parental report, he is sometimes defiant and can be frustrated when he is unable to communicate. However, his mother reports no specific concerns about hyperactive or impulsive behavior.

IC communicates his thoughts and feelings mostly through facial expression and emotion. He formally communicates with his family members, especially his younger brother, by a home sign gestural system they developed. His use of signs in general was very limited on his first visit to the lab. On subsequent visits, following enrollment in the residential program for deaf children, he increasingly used more signs, specifically ASL.

2.2. Medical background

2.2.1. Audiology report

Two independent audiology reports show IC has bilateral profound sensorineural hearing loss in the range of typical human speech, most likely originating from peripheral auditory nerve damage after his exposure to meningitis during infancy. Some residual hearing was observed in frequencies outside of speech. Informal otoscopy revealed clear ear canals with visualization of the tympanic membrane in both ears. Tympanometry was consistent with normal middle ear function and a limited CT scan focused on the auditory system (ear canals through the brainstem) revealed no structural abnormalities in the brain regions relevant to hearing.

2.2.2. Cognitive and linguistic abilites

A full psychological report, including standardized cognitive and linguistic testing, was conducted by a certified pediatric psychologists approximately 7 months after IC was seen in our lab. Both doctors were experienced at testing deaf children and were fluent in American Sign Language (ASL). During the gap of time between our testing sessions and the psychological evaluation, IC had been living in a residential school of the deaf where he received daily academic and ASL instruction.

At the time of the psychological evaluation, IC was rapidly acquiring ASL, preferred communication through ASL over other modes, and reportedly forgot his family-created home sign system. A full battery of standardized cognitive and linguistic tests was administered to IC over two different sessions: the Wechsler Intelligence Scale for Children (WISC-IV), Wechsler Nonverbal Scale of Intelligence (WNV), Delis-Kaplan Executive Functioning System (D-KEFS), Rey-Osterrieth Complex Figure Tasks, Scales of Independent Behavior-Revised (SIB-R), Wide Range Achievement Test (WRAT-4), and the Sentence Completion Test. However, many of these tests were difficult to administer given IC's language deficit. IC did not have enough language to reach a basal score on the verbal or working memory portions of the WISC-IV, and so a full scale IQ score was not able to be obtained. On the language relevant subtests in which a score was obtained, such as the Similarities (4) and Vocabulary (2) subtests of the WISC-IV, scores continually fell severely below the average range (average 10, ± 3). On the other hand, IC consistently fell within the average range on other cognitive tasks that either did not involve language or required little verbal instruction, such as scores on executive control (e.g. D-KEFS, inhibition = 9, switching = 9), visual-spatial processing, and perceptual reasoning (e.g. WISC-IV block design = 10, picture concepts = 9, matrix reasoning = 7, picture completion = 12). Speed of processing (WISC-IV composite score = 65; average 100 ± 15) and working memory (scores on Copy and Immediate Recall of the Rey Osterrieth Complex Figure Tasks were both significantly below normal limits) performance was found to be below average, possibly mediated by his linguistic limitations.

Qualitatively, IC has a pervasive and severe language deficit likely due to his late introduction to language and lack of early language models. In particular, he shows significant problems with language development, language comprehension, language production, linguistic reasoning, and some aspects of general cognition that may be compromised by his language deficits. However, IC is solidly average on perceptual and cognitive tasks that require little or no language or linguistic instruction.

2.2.3. Neurological profile

No relevant structural imaging of the brain was available (besides a limited CT scan of the auditory system). However, IC has no history of neurologic problems (e.g. epilepsy), a neurologic examination revealed no concerns, and his cognitive testing (aside from language-based tests mentioned above) was in the average range. Together these data suggest that cognitive and linguistic deficits are not likely the result of brain damage.

3. Current experiment

IC participated in three testing sessions at our laboratory in Cambridge, MA over a 9 week period. Each session was separated by about three weeks. IRB approval was obtained for all tasks by the Harvard University Committee for Use of Human Subjects. In addition, we obtained data on a majority of the same tests in 5 typically-developing, hearing control subjects between the ages of 12 and 14 participated (1-Asian, 2-Hispanic, and 3 White). No information on socio-economic status was obtained for any of the subjects and therefore is unknown. Given the extensive nature of this battery and resources involved in testing, we were only able to obtain a modest group of controls. Informed consent was obtained from a parent and assent was obtained from the child at the begin-

Table 1
Gestural configurations produced for numbers 1–12 during testing session one.

Number	Fingers raised[a]	Fingers raised[a]	Used left hand	Used right hand
1	oIooo		20%	80%
2	oIIoo		17%	83%
3	IIIoo		33%	67%
4	oIIII		67%	33%
5	IIIII		33%	67%
6	IIIII	oIooo	67%[b]	33%[b]
7	IIIII	oIIoo	67%[b]	33%[b]
8	IIIII	ooIII	50%[b]	50%[b]
9	IIIII	oIIII	67%[b]	33%[b]
10	IIIII	IIIII	100%[c]	100%[c]
11	IIIII (x 2)	oIooo		100%[c]
12	IIIII (x 2)	oIIoo		100%[c]

[a] I = fingers raised, o = finger not raised: positions start with thumb and move right to last finger.
[b] Percentage of trials where all digits on this hand were extended to represent five of the total units
[c] IC used all fingers on both hands to represent 10 and then the right hand to represent the additional units on numbers greater than 10.

ning of each testing session. Families were reimbursed for travel expenses and were paid 100 dollars per session for their time.

IC was tested by a team of experimenters experienced in the administration of the reported tasks. One assistant fluent in ASL was continually present to aid the experimental explanation. In addition, IC's brother, the only other "fluent" speaker of IC's homegrown sign language, was present during all testing sessions and aided in task explanation. Importantly, a majority of the tasks presented required little or no verbal instruction and could be explained by behavioral modeling. All coding of gestural communication was done in collaboration with fluent speakers of ASL.

In cases where applicable, IC's performance was tested against chance performance using non-parametric statistics, and IC's performance was compared to age-matched controls using a modified paired-samples t-test for comparing individual performance on non-standardized tests to control groups (Crawford & Garthwaite, 2002). Single case studies and control samples of this size typically violate the assumptions of commonly used statistics, often increase Type I error rate, and, in turn, overestimate the experimental subject's level of abnormality relative to controls (Crawford & Garthwaite, 2002; Crawford & Garthwaite, 2006a, 2006b; Crawford, Garthwaite, & Howell, 2009). The modified test allowed us to assess performance of IC more reliably and accurately, while reducing the Type I error rate by accounting for the modest sample size of the control group (Crawford & Garthwaite, 2002).

4. Linguistic abilities

4.1. Numerical language assessment

4.1.1. Session 1

4.1.1.1. What's on this card? (WOC). This task was based on Gelman's classic counting assessment task (see Gelman, 1993; Le Corre & Carey, 2007; Le Corre et al., 2006; Wynn, 1992) and tests for the presence of linguistic terms for exact quantities. IC was shown a series of computer images containing different quantities of the same items (e.g. 3 dogs) and was prompted to indicate by gesture the number of items contained in the image. The image was left in view until a final response was given. IC was given positive feedback for each answer provided regardless of whether the answer was right or wrong. Three blocks were presented using different items in each block (houses, dogs, motorcycles). The numbers 1–12 were tested in each block.

IC responded without hesitation, with gestural configurations that were consistent and transparent. Small numbers (1–5) were signed with one hand; larger numbers (6–10) were signed with two hands. Fingers were generally pointed upward or slightly sideways and hand orientation varied between numbers (palm or back of hand facing experimenter). When a number surpassed 10, he first showed 2 full hands and then an isolated number of fingers. The specific fingers raised to indicate each number were stable despite some changes in which hand was used to sign the number (see Table 1). The hand used to represent the remainder of numbers greater than 5 was consistent (see Table 1). With these gestures, IC performed almost perfectly on this task. He correctly indicated the number of items on 90% (27/30) of trials. The three mistakes made were with the larger number trials (showing 11 fingers for 10, 12 fingers for 10, 9 fingers for 8).

In 69% (25/36) of the trials IC produced a noun corresponding to the items as well as the number. Signs for the nouns were consistent across different trials. The noun was generally placed before the number (Noun-Number: 23 trials). However, in one trial the noun was produced together with number using two hands simultaneously and in another trial IC produced a bracketed expression (number-noun-number), with phrasing suggesting that he first produced the number in isolation and then produced a noun-number phrase.

4.1.2. Session 2

4.1.2.1. WOC with events (WOCe). In this session, the same basic concept was assessed in a WOC task, except stimuli were purposefully made to be more complex in an attempt to elicit more language. Computer images were again presented to IC, but this time different numbers of actors (horse, dog, cat, monkey) were portrayed performing 4 different actions (eating, sleeping, jumping, running) (see Fig. 1a). Again, images were left visible until a final response was given. First, IC practiced with 8 slides aimed at eliciting the corresponding label or action, then 16 different slides showing several (similar) actors performing the same action so as to elicit sentences like: "Four dogs are sleeping." The numbers 2, 3, 6, 8, 10, 12, 20, and 27 were presented two times each for a total of 16 trials.

IC began on the first trial by signing the number; on the second trial he also began writing the Arabic response himself on the coding sheet. This time all numbers were signed in ASL, which includes signs that are not transparent with respect to how many fingers are raised. This switch from home-sign to ASL most likely reflected new skills acquired at his residential school entered between the first two sessions. On some trials, his counting procedure was transparent; he touched his thumb to his fingers sequentially while scanning the objects. His counting was very quick and for the most part accurate (13/16, 81% correct). Two of the three errors were made on the largest test trial (27). The final 4 trials were not signed, but written only in Arabic form and they were correct (6, 2, 8, 3).

In most cases, he did not produce a sequence of signs, and did not refer to the type of animal or the action. Only in 38% of the trials (6/16) did he produce additional signs to describe the picture. The order of the sign sequences produced were: Verb-Actor (2), Actor-Verb (2), Verb-Actor-Number (1), Verb-Actor-Verb-Number (1). These sequences were consistent with the productions of session 1; the number was systematically placed at the end of the phrase.

4.1.2.2. Elicitation using Arabic numerals. This task was designed to assess basic recognition of Arabic digits and the subsequent ability to produce labels for them (e.g. Gilmore, McCarthy, & Spelke, 2010). In this task IC was presented with an Arabic digit on the computer screen as asked to give the appropriate sign (3, 5, 7, 10, 12, 16, 23, 29, 47, 53, 100, 106, 120, 300, 341, 1000). Numerals were left on the computer screen until a final response was provided.

IC signed the numbers in ASL without hesitation or mistake. He used transparent signs (as in ASL) for small numbers (3,5), showing

Table 2
Comparison of IC to controls across all tasks.

Test	Task	IC (% correct) * = lenient coding	Controls (% correct)	Comparison Statistics	Difference between IC and controls?
Numerical language	What's on this card? (WOC)	90%	100%	n/a ceiling effect	Yes (?)
	WOC w/events	81%	100%	n/a ceiling effect	Yes (?)
	Elicitation with numerals	100%	100%	n/a ceiling effect	No
Numerical abilities	Sample matching	100%	100%	n/a ceiling effect	No
	Simple Numeral comparison	100%	100%	n/a ceiling effect	No
	Difficult Numeral Comparison (multiple-digit)	97%	99%	No difference $p > .25$	No
	Approx. addition (1- & 2-digit)	79%above chance	98% above chance	Sig. difference $p < .01$	Yes
	Exact addition (1- & 2-digit)	46% below chance	85% above chance	Sig. difference $p < .05$	Yes
	Subtraction (1-digit)	67% below change	100% above chance	n/a ceiling effect	Yes
	Multiplication (1-digit)	42% below chance	100% above chance	n/a ceiling effect	Yes
Spatial language	Elicitation w/real objects: top/under	Prompted: 0%	Unprompted: 100%	n/a ceiling effect	Yes
	Elicitation w/real objects: left/right	Prompted: 0%	Unprompted: 0% Prompted: 100%	n/a ceiling effect	Yes
	Spatial WOC w/o prompting: top/under	Unprompted: 19%* Prompted: 81%*	Unprompted: 100% Prompted: 100%	n/a ceiling effect	Yes
	Spatial WOC w/o prompting: left/right	Unprompted: 0% Prompted: 6%*	Unprompted: 10% Prompted: 100%	n/a ceiling effect	Yes
Spatial abilities	Reorientation: no-landmark	75%	Not tested	–	–
	Reorientation: landmark	75%	Not tested	–	–
	Oriented search: no landmark	88%	40%	No difference $p > .1$	No
	Oriented search: landmark (hidden in unique)	100%	100%	n/a ceiling effect	No
	Oriented search: landmark (hidden in non-unique)	12%	98%	Sig. difference $p < .001$	Yes
	Map Task: Hidden in unique	100%	100%	n/a ceiling effect	No
	Map Task: Hidden in non-unique	79%	91%	Sig. difference, $p < .05$	Yes

3 and 5 fingers. For numbers 7–16, IC used single ASL symbols that are not transparent (ex: 12 signed as index + middle fingers successively raised and lowered). Starting at number 29, he successively signed the digits as symbols (a single, non-transparent symbol for digits 6–9), which is an acceptable way to sign these large numbers in ASL.

4.1.2.3. Control subject performance. As expected given the extensive practice with symbolic number, age-matched controls performed perfectly on producing verbal labels for Arabic numerals (average 16/16) and producing the correct number-label-verb sequence (e.g. 5-dogs-running) to describe the WOCe (average 8/8) (Table 2).

4.1.3. Summary of Numerical Language Assessment

IC was proficient in using numerical signs and Arabic digits to express exact natural number concepts. His use of numerical signs changed from a transparent home-sign to non-transparent

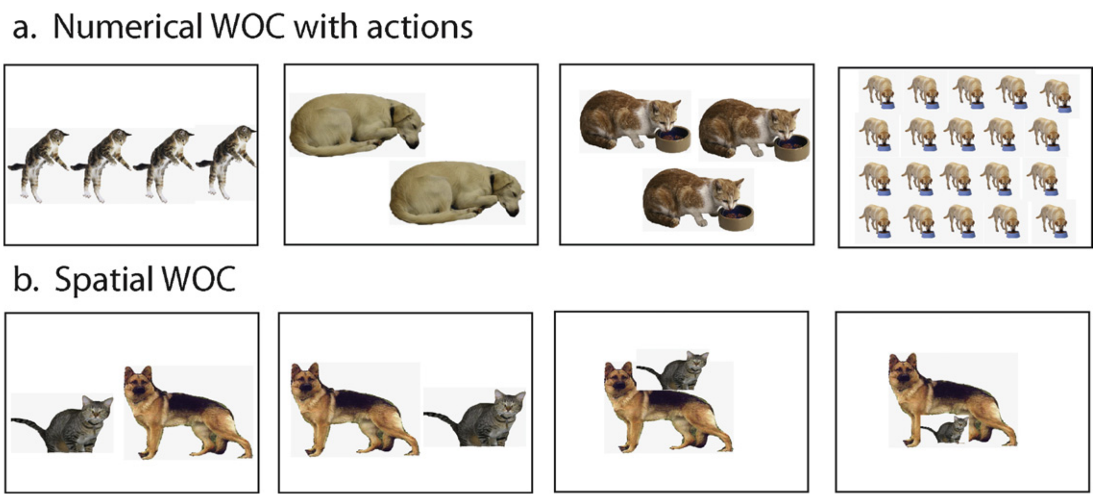

Fig. 1. Sample pictures from the numerical (a) and spatial (b) versions of the "what's on this card?" task (WOC).

ASL over the course of the testing sessions as a result of entering a residential school for the deaf. Nonetheless, even in the first session IC accurately counted and used Arabic symbols to represent exact quantities fairly competently. Thus, it appears that despite the lack of a complete natural language, IC has learned and applied a sophisticated numerical vocabulary.

4.2. Spatial language assessment

A series of tasks was administered over sessions 2 and 3 to probe IC's knowledge and use of spatial language. Specifically, these tasks were devised to assess the functional production of spatial language to describe basic horizontal (left/right) and vertical (above/below) relations. These tasks, based on tests developed by Senghas and Coppola (2001) for assessing gestural spatial language in the deaf, were similar to the *What's On the Card*? number tasks except that the variable manipulated was the spatial relationship between objects rather than the number of objects.

4.2.1. Session 2

4.2.1.1. Elicitation with real objects and prompting in ASL and home-sign. Five manipulable objects (book, toy duck, apple, toy elephant, toy dog) were gathered and presented in pairs in a specific spatial relationship. The same objects were used repeatedly to contrast the spatial relationships of *left*, *right*, *above*, and *below*. The experimenter first placed a pair of objects in front of the child (e.g. apple/duck). Next, the experimenter signed 'object-spatial relationship, other object-spatial relationship' to him. For example, the experimenter would place the duck next to the apple and sign 'duck-left, apple-right', using ASL. Then, the experimenter would switch the relative positions (left-right) of the objects and elicit a response from IC. The same pattern of placement and prompting was used for the above/below relationship. Both left/right and on above/below relationships were tested (e.g. apple on the left/duck on the right; duck on the left/apple on the right). If IC produced no response, the correct response was modeled by the experimenter and a different pairing was then presented. Despite producing labels for the objects 100% of the time during the first 4 trials, IC never produced a spatial term to accompany the object labels. After 4 attempts to elicit spatial terms (2-left/right; 2-above/below), IC stopped signing the labels for the objects and instead fidgeted with the objects while conveying frustration to the experimenter through facial gestures and sounds.

After this failure to elicit any spatial vocabulary from the child, the experimenter turned to IC's younger brother and requested the brother ask IC to describe the spatial relationship between the specific objects as best he could in the child's home-sign. For example, in the case of the duck/apple pair, the experimenter requested the brother tell IC to say the duck is on the right/the apple is on the left. The younger brother prompted IC in a similar manner to the experimenter, although using slightly different, yet highly intuitive spatial signs for left and right. No response was observed to the initial pairing prompt or to the other permutations of the pairings (4 total). Again, IC expressed frustration through facial and hand gestures (throwing hands up in the air) and playing with the objects. From these tests it was not clear whether IC had no sign language for spatial terms or whether he did not understand what was being asked of him. In either case, the contrast between performance in the number-language elicitation and spatial-language elicitation tasks is striking.

Control subjects were presented with the same task without any verbal prompting besides asking, "what is this?" Control subjects spontaneously produced labels for the items 100% (average 4/4) of the time. In addition, they spontaneously produced terms for above and below to describe the spatial relationship between the items 100% (average 2/2) of the time. However, in the absence of prompting, the use of "left/right" was not spontaneously observed in controls (0%, average 0/2). In these cases they simply produced the labels for each of the items without further explanation.

4.2.2. Session 3

4.2.2.1. Spatial WOC without prompting. In an effort to reduce the temptation to play with the objects and make the spatial language testing more similar to other numerical language assessment procedures, testing of spatial language during session three was completely computer-based. Four images pairs were created and presented on a blank white screen (cat-dog, monkey-tree, car-motorcycle, and bed-book). To practice, each item was presented individually and a sign for each object was elicited. IC successfully produced distinctive labels for all of the items. After successfully identifying each of the pictures, IC was then presented with 4 trials for each pair conveying the spatial relationships of *left-right* and *above-below*. For example, the child first saw a picture of the dog on the right and the cat on the left (see Fig. 1b.). The experimenter elicited an explanation of the picture as had been done in the number language elicitation tasks.

IC produced the signs for the objects 100% (16/16) of the time. However, only in 19% (3/16) of the cases did he produce signs in addition to the item labels. The first case was of a monkey on top of a tree, IC produced signs for "monkey" and "tree" and the additional sign of "sit". We interpreted this sequence as "the monkey is sitting in the tree". The second case was the monkey sitting underneath the tree. For this picture IC produced signs for "monkey" and "tree" followed by a different sign of hands together suggesting "sitting" or "crouching". We interpreted this sign sequence as "the monkey is sitting/crouching by or under the tree". The contrasting "sitting" signs produced suggested differential description of the two pictures. The third case was of the book under the bed. IC produced signs for "bed" and "book" followed by a sign extending the hands forward in what seemed to be a sign for "off of" or "in front". While this was not the intention of the picture, this response seemed to be a relatively accurate description. A loose interpretation of these three cases grants IC some vocabulary to talk about relationships between objects. However, he produced these responses in less than half (3/8) of the above/below contrasts. The cases in which he did produce additional signs were also the most natural cases in which words like "sitting" could replace spatial terms. Critically, no additional signs were produced in the left/right cases (0/8). No significant difference was observed between the proportion of trials IC produced spatial terms for above/below compared to the proportion of trials IC produced spatial terms for left/right relations (Wilcoxon $Z = -1.73$, $p = .08$).

In contrast, control subjects without prompting spontaneously produced labels on 100% of the trials and the spatial terms for above/below on 100% of the trials (average 8/8), but left/right terms only on 10% of trials (average 0.8/8). Again, in the majority of left/right cases, controls only produced labels for the objects. Controls spontaneously produced significantly fewer spatial terms for left/right compared to terms for on top/underneath relations (Wilcoxon $Z = -2.12$, $p = .03$). Even with a lenient coding of IC's responses, a significant difference in the production of unprompted spatial terms was observed, where IC produced significantly less spatial terms than controls ($t = -2.939$, $p = .04$) (Table 2).

4.2.2.2. Spatial WOC with prompting. To maximize the chance that IC would produce spatial signs and ensure that he understood the terms we were trying to elicit, we repeated the spatial WOC task during the same session with the same pictures, but with ASL prompting. The procedure was similar to the first testing block except that if IC did not produce additional signs beyond item labels the experimenter would prompt him by producing the item labels combined with the correct spatial terms. For example, in the first case (dog-left/cat-right) IC produced labels "dog/cat". The experimenter then prompted him by signing "dog on the left/cat on the right" in ASL, and then moved on to the next case. Prompting occurred for every case in which IC did not produce additional signs.

Using this procedure, IC produced signs in addition to the item labels on 81% (13/16) of trials. In the above/below cases, he made more effort to explain the pictures using appropriate signs like "patting his back" after seeing the cat was on top of the dog. However, in very few if any cases did he describe a picture in a manner that allowed the spatial relationship to be unambiguously interpreted. That is, from his signs it was unclear whether the cat was on top of the dog or the dog was on top of the cat. Nonetheless, in all the above/below cases, IC produced additional signs in an attempt to elaborate on the pictures.

The same was not true for the left/right relationships. In 5 of the 8 left/right cases IC produced additional signs. However, none of these additional signs identified left/right relationships. Instead, they seem to signify other terms to explain the situations. For example, in car/motorcycle left right conditions IC produced a sign that suggested "beside" or "next to" as the same sign was used to explain the contrasting conditions (car-left/motorcycle-right; motorcycle-left/car-right). A similar case was used for the monkey/tree-left/right pairings. IC produced the same sign for "looking" on the left side of his body in both cases even though the monkey was on the opposite sides in the two pictures. Interestingly, these were the only two cases in which a sign was produced in an obviously asymmetrical body space suggesting a left/right distinction. However, in only one of the two cases the sign actually described the direction of the monkey's gaze (looking left), suggesting no true left/right distinction was being made. This was the only case (1/16) in which IC provided a spatial sign that accurately described the left/right spatial relations of the picture.

Control subjects with prompting again produced object labels on 100% of the trials, terms for above/below on 100% of trials, and quickly corrected themselves by adding left/right terms to their description of the pictures upon the first prompting and all subsequent promptings (100%, 8/8). The flawless rate of prompted use of spatial terms in controls was strikingly different from that produced by IC (Table 2).

4.2.3. Summary of spatial language assessment

IC produced no spatial terms on our first attempt using real objects despite prompting and modeling in ASL by the experimenter and in home-sign by the child's brother. However, it is unclear if IC understood what was being asked of him. The second day of spatial language testing yielded interpretable findings suggesting the child may have some basic vocabulary that can be used to describe specific relationships between items (e.g. monkey sitting in tree). However, this vocabulary failed to describe spatial relationships between those items accurately and unambiguously. IC provided additional descriptions of the above/below contrasts in 12/16 cases presented. Only 3 of these cases actually involved specific spatial signs of below (twice) and above (once) and in none of the cases did his description unambiguously describe the picture. That is, from his description, one would not know which item was in which spatial location. In the left/right cases he showed even less evidence of a sign vocabulary to explain the spatial relationships. In only 6 of the 16 left/right trials did IC produce any additional signs besides item labels and out of the 6 instances of additional signing only 1 of them accurately described the spatial relationship of the item signed to the other item. All other descriptions were ambiguous as to the relationship between items.

IC's spatial language performance stands in contrast to the performance of control subjects who produced unambiguous spatial terms to describe the above/below relationships 100% of the time without being prompted and produced unambiguous spatial terms for left/right relationships 100% of the trials after only 1 prompting by the experimenter. The lack of spontaneous use of left/right spatial terms in the conditions without prompting in controls suggests that disambiguating left/right relations may not be naturally intuitive even to older children with clear mastery of the language. Nonetheless, the lack of descriptive power of IC's spatial vocabulary reveals specific and focused deficits in IC's spatial language, in stark contrast to his relatively sophisticated knowledge of numerical language tested using a similar procedure and performance of age-matched controls on the same tasks.

5. Numerical abilities

5.1. Numerical abilities

All tests of numerical abilities were conducted in a quiet room either on a laptop computer or with objects on the desktop.

5.1.1. Session 1

5.1.1.1. Sample matching. This task was similar to those used in many field research studies on numerical cognition to assess basic exact number concepts (e.g. Frank et al., 2008; Gordon, 2004; Pica et al., 2004). For this test the experimenter placed a certain number of stones in front of the child and requested that the child reproduce the same number of stones. This was first modeled with practice trials on 1, 2, and then 5 stones. Seven different quantities were used (1, 2, 3, 4, 7, 10). The child successfully produced the correct number of stones on 100% of the trials. IC produced sets with a random configuration, without trying to align the stones in one-to-one correspondence with the experimenter's stones.

Another variation of this task was run in which the experimenter tapped on the child's shoulder a given number of times and then prompted the child to tap back that same number of times. Multiple blocks in different conditions were planned, but the child quickly figured that he could just read Arabic numbers from the coding sheet and began "cheating". He completed 3 blocks with 7 trials each (numbers 1, 2, 3, 4, 5, 7, 10; proceeded by training trials with numbers 1, 2, 5). All the responses were correct.

Control subjects ($n = 4$) also produced correct responses 100% of the time on both versions of the sample matching tasks.

5.1.1.2. Arabic numeral comparison. This task was designed to assess basic understanding of Arabic digits and their ordinal relationship to one another. It is similar to classic tests of numerical magnitude comparison (e.g. Dehaene, 1989, 1996; Dehaene, Dupoux, & Mehler, 1990). In this task the child was presented with pairs of Arabic digits and was asked to choose the larger number. One block of 1-digit number comparisons, 1 block with 2-digit number comparisons, one block with 3-digit number and 4-digit number comparisons, and one block of 2-digit vs. 3-digit number comparisons. All responses were correct (36/36) and for the most part very fast (mean reaction time for all trials = 1418 ms). His performance of 100% correct was significantly above that predicted by chance (binomial $P < .001$). Controls were not tested on this task.

5.1.2. Session 3

5.1.2.1. Difficult Arabic numeral comparison. In the final session, the Arabic numeral comparisons were made more difficult. These included numbers with up to 4 digits and in many cases only differed by the place value of two numbers (920 vs. 902). IC performed nearly perfectly (35/36; 97% correct). He performed perfectly on the subset of the comparison trials that contained the same digits but required representing the left to right ordinal relationship between those digits to determine which was greater (e.g. 920 vs. 902 or 37 vs. 73) (100%, 24/24). The only mistake he made (89 vs. 91) appeared to be due to pushing the wrong button by accident.

Again, his overall performance was well above chance (97% correct, binomial $P < .001$) and not significantly different ($t = -1.340$, $p > .25$) from average control performance (99%, 35.75/36).

5.1.2.2. Basic arithmetic. These tasks were designed to assess approximate and exact arithmetic abilities (after Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999). In these tasks, IC was presented with a simple arithmetic problem on the right side of the screen and another numeral on the left side of the screen. He was instructed to choose the side of the screen that was more (e.g. 1 + 1 or 4). The problems were presented in four blocks that became progressively harder. Blocks either required an approximate answer (1 + 1 or 6) or an exact answer (3 + 2 or 6) to be solved. The first two blocks were 1-digit addition problems and the second two blocks were two-digit addition problems. On the approximate 1-digit addition problems IC answered correctly 92% of the time (11/12). On the exact 1-digit addition problems IC correctly answered 67% of the time (8/12). On the approximate 2-digit addition problems IC answered 67% of the problems correctly (8/12). Finally, on the exact 2-digit addition problems IC only answered 25% of the problems correctly (3/12). Collapsing across digit number, IC performed correctly 79% of the time with approximate problems and 46% of the time with exact problems. Statistics confirmed that performance on approximate addition problems exceeded chance performance (binomial $P = .007$) but performance on exact addition did not exceed chance (binomial $P = .839$). A comparison of performance between approximate and exact addition tasks showed significantly better performance on approximate addition (Wilcoxon $Z = -2.83$, $p < .01$).

Approximate 1-digit subtraction and multiplication problems were also presented in the same format as the addition problems. IC correctly answered 1-digit approximate subtraction problems 67% of the time (8/12) and 1-digit approximate multiplication problems 42% of the time (5/12). Neither subtraction (binomial $P = .388$) nor multiplication (binomial $P = .774$) performance exceeded chance. IC's performance on 1-digit approximate subtraction was not significantly different from that of 1-digit addition (Wilcoxon $Z = -1.73$, $p > .08$; multiplication), but performance on 1-digit multiplication was significantly worse than performance on 1-digit addition (Wilcoxon $Z = -2.45$, $p < .05$).

Control subjects ($n = 4$) performed perfectly on the approximate 1-digit addition (average 12/12), answered 88% correct on the exact 1-digit addition (average 10.5/12), answered 96% correct on the 2-digit approximate addition (average 11.5/12), answered 81% correct on the 2-digit exact addition problems (average 9.75/12), answered 100% correct on 1-digit approximate subtraction problems (average 12/12), and 100% on the 1-digit approximate multiplication problems (average 12/12).

A comparison of IC's performance on basic arithmetic tasks to that of controls revealed a significant difference in performance on approximate ($t = -7.022$, $p < .01$) and exact addition problems ($t = -4.352$, $p < .05$). A clear difference was observed between the perfect performance of controls on multiplication and subtraction and the sub-chance performance of IC on the same tasks (Table 2).

5.1.3. Summary of numerical abilities

IC appears to have acquired a sophisticated, systematic system of exact number representation that goes beyond the core numerical ability to assess approximate quantity. He is relatively proficient in using Arabic digits, as well as using his sign language vocabulary to represent and communicate numbers. It is unclear whether the few mistakes made truly reflect errors in his cognitive system or are simply a result of a few careless mistakes. He does seem to grasp the basic concept of the simple arithmetic operations of addition. However, the preciseness of these skills is lacking. He does not appear to yet understand multiplication or subtraction. It is unclear from his educational history exactly how he has acquired these exact, symbolic numerical skills. It is possible that symbolic numerical abilities were learned as a result of direct teaching and instruction or may have arisen naturally through experience with a cultural system(s) based on concepts of exact cardinal values like monetary units.

6. Spatial and geometric abilities

A series of tests were administered to assess IC's spatial and geometric abilities. These tests involved two main tasks: reorientation and oriented search.

6.1. Search tasks

6.1.1. Session 1

6.1.1.1. Reorientation. This task, widely used with young children, patient populations, and non-human animals (see Cheng & Newcombe, 2005 or Lee & Spelke, 2010 for reviews), was used to assess the use of geometrical and featural information for navigation under conditions of disorientation. IC was brought into a completely circular room that contained no obvious geometric cues as to the location of a hidden door. The room contained a symmetrical lighting system, hidden sound system, and an embedded video camera in the middle of the ceiling (see Lee, Shusterman, & Spelke, 2006 or Lee & Spelke, 2008 for more details on method and setup). Then he was further led into a large rectangular enclosure (6 ft. high × 4 ft. wide × 8 ft. long) that had been constructed in the center of the circular room. Small boxes had been placed in each of the four corners of the inside of the rectangular enclosure before the child entered. IC observed the experimenter place a small toy in one of the corner boxes, and then he was blindfolded and turned around 2–3 times in one direction and then 2–3 times in the other direction. This process was repeated until he had been turned at least 10 times. The experimenter then positioned himself behind IC and removed the blindfold. The wall at which he was facing when removing the blindfold was varied randomly between trials. The child was then encouraged to find the toy. No training trials were provided, as the purpose of this task was very intuitive.

Two different types of trials were presented. In the no-landmark trials all the walls were a uniform color minimizing the available information for potential use in reorienting and finding the toy. In the landmark trials a red piece of fabric was hung and covered one of the short walls. This provided an additional cue to the child as to where the toy was hidden.

IC correctly located the hidden item 75% of the time (6/8 times) in the no-landmark condition (see Fig. 2). His performance exceeded absolute chance of 25% (binomial $P = .004$). His errors were made in the rotationally equivalent corner suggesting that he was in fact using the geometry of the room to reorient (100% geometrically-correct performance, 8/8). His performance was not above chance, however, when deciding between the two rotationally equivalent responses (binomial $P = .289$). In the landmark condition, his performance closely resembled performance in the no-landmark condition: he correctly chose the correct hiding place 75% of the time (3/4) and his error was again to the rotationally equivalent corner, suggesting he was using geometric information to solve the task (see Fig. 2). This rate of performance again showed reliable use of the room's geometry (100% geometrically-correct performance, 4/4), chance performance at distinguishing between geometrically equivalent corners only (binomial $P = .625$), and no enhancement of performance by introduction of the red wall (75% in both conditions; 0% advantage).

Interestingly, IC approached the reorientation task differently than most children and adults previously tested in the lab. Rather

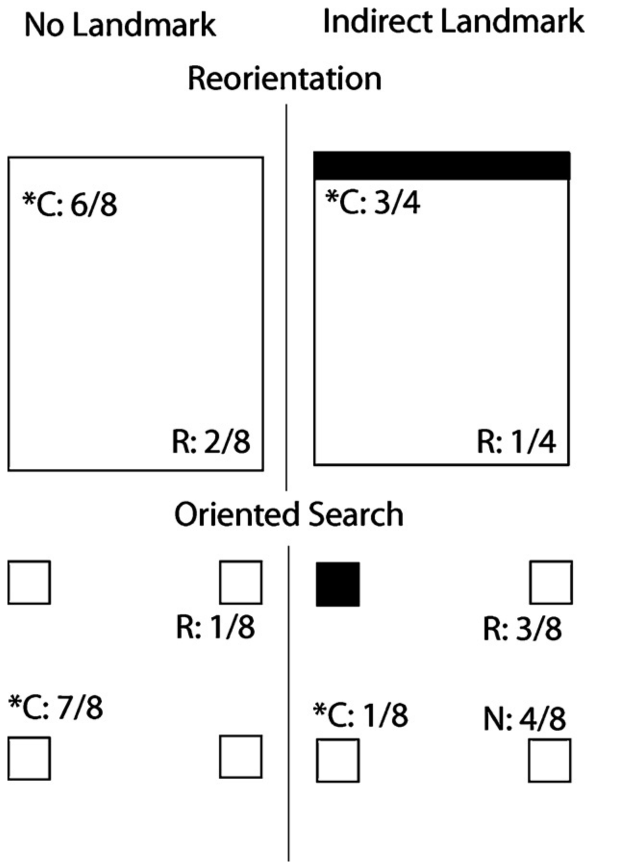

Fig. 2. IC's performance on reorientation and oriented search tasks. C = correct response, R = rotational error, N = nearest error.

than relying only on the geometry of the layout or even the obvious red wall in the landmark trials, he seemed to be reorienting based on a cue from the ceiling. After the blindfold was removed, he would look up at the ceiling. After a few seconds he seemed to gain some insight into the correct orientation and he would go immediately to where he calculated the hiding place to be based on this ceiling cue. From this observation it is unclear whether IC's pattern of responses, consistent with the use of geometry, were derived solely from the geometric properties of the enclosure, through other cues such as the "ceiling cue" that might have been used in isolation to calculate the hiding place based on something like a heading angle, or some combination geometry and additional cues. Given this availability of this alternative strategy, we did not do further reorientation testing and we did not test control subjects on the reorientation task.

6.1.2. Sessions 2 and 3

6.1.2.1. Oriented search. IC's unusual pattern of performance on the reorientation task prompted the creation of a task that eliminated the additional possible cues (such as the ceiling cue) to finding the hidden item. This new task, oriented search, was based on similar tasks used to probe spatial memory and representation in young children (see Lourenco & Huttenlocher, 2006). The purpose of this task was to test for the use of featural and geometrical cues in a different paradigm that eliminated the use of extraneous cues to finding the hidden item. The oriented search task was devised so only geometry and/or task-specific landmarks jointly served to specify a hidden object's location. The child was brought into the circular room where four small boxes were arranged in a rectangular pattern on the floor. While the child was watching, the experimenter placed a small piece of candy in one of the boxes and confirmed with the child that he had seen the hiding location. The child was then lead out of the room and two other experimenters entered the room and closed the door. These two experimenters rotated the rectangular array either 90, 180, or 270 degrees as well as switched the individual boxes so that certain features of a particular box (e.g. small scratch on a particular box) would not be indicative of the hiding location. The child was then lead back into the room and encouraged to search for the candy. The main experimenter was blind to the amount of rotation and upon entering walked to the far side of the array and looked back in the direction of door.

In the no-landmark condition all the boxes were uniform in color and shape. The box where the toy was hidden was counterbalanced across trials. In this case the child was left only with geometric information. The child would have to remember something like "the toy is hidden in the corner with a large distance between boxes on the left and a small distance between boxes on the right (sense and distance information)" in order to solve the task. However, this information only eliminates 2 of the 4 possible hiding locations, leaving the subject to choose at random between the two rotationally-equivalent corners. In the landmark condition, one of the boxes was a different color and shape than the other three boxes that made up the rectangle. This provided an extra "landmark" cue to the location of the hidden candy in both cases where the object was hidden in the unique landmark container or in one of the non-unique containers. In this case the task can be successfully solved by using the geometric information in conjunction with the landmark information. On some trials the item was hidden in the unique box and on other trials the item was hidden in one of the non-unique boxes. Furthermore, across trials the relationship of the box where the item was hidden to the unique box was varied and counterbalanced.

In the no-landmark condition, IC correctly located the hiding place 7/8 times and the only error he made was to the rotationally equivalent box (see Fig. 2). This rate of success was higher than predicted by absolute chance (binomial $P < .001$), but not above chance when restricted to the two geometrically equivalent corners (binomial $P = .07$). In the landmark condition, the child successfully located the hidden object 100% of the time when it was hidden in the unique container (8/8, binomial $P < .001$). However, in stark contrast, IC correctly located the hidden object only 12% (1/8) of the time when it was hidden in one of the non-unique containers (1/8 in the correct location; 3/8 in the rotationally equivalent container; 4/8 times in the container closest to the correct box, see Fig. 2). This performance was well below absolute chance (binomial $P = .367$). Furthermore, it did not appear that the child was using geometric cues effectively as he only choose either the correct location or the rotationally-equivalent non-unique corner 50% (4/8) of the time. Rather, it appeared the child knew it was not in the unique container and was choosing randomly between non-unique containers when the item was hidden in any location besides the unique container.

Control subjects searched successfully only 40% of the time in the no landmark condition (average 3.25/8). In contrast, control subjects searched successfully 100% of the time in the landmark condition when the object was hidden in the unique location (average 4/4) and 98% of the time in the landmark condition when the object was hidden in a non-unique location (average 11.75/12, one error made was to the geometrically equivalent corner).

A comparison of IC's performance to that of controls revealed no significant difference in the no landmark trials ($t = 2.236$, $p > .1$), nor in the landmark condition when the object was hidden in the unique location (both controls and IC were 100%). A significant difference in performance, however, was observed in the landmark condition on the trials that involved finding the object in one of the non-unique locations ($t = -18.334$, $p < .001$). Compared to the hearing children, the deaf child was less able to use spatial relationship of a hiding place to the landmark in order to retrieve the object (Table 2).

6.1.3. Summary of spatial and geometrical performance

Tests of IC's spatial and geometrical abilities showed an interesting patchwork of strengths and focal weaknesses. In both reorientation and oriented search tasks IC readily used geometric information to find a hidden object in experimental conditions where no unique "landmark" object was present and readily used featural information on trials where the item was hidden directly in a unique "landmark" container. Performance, however, diminished significantly in cases where a landmark was present and the item was hidden in one of the non-unique locations. From his pattern of response it appears that he was not even using geometry in these cases. In other words, IC had difficulty on trials that required combining both geometrical information and featural information to find a hidden item.

7. Symbol use and spatial reasoning

7.1. Map task

These tasks, based on earlier studies of symbol understanding in young children and non-human animals (Bluestein & Acredolo, 1979; DeLoache, 1995), assessed the ability to use symbols to represent space (see Dehaene, Izard, Pica, & Spelke, 2006; Shusterman, Lee, & Spelke, 2008). This task was conducted in a rectangle-shaped room with similar lighting and audio-visual equipment as the circular room (see Shusterman et al., 2008 and Dehaene et al., 2006 for more details on method and set-up). In this task, the child was asked to place a ball in one of a number of buckets located inside the room based on a map of the room, whose monochrome circles preserved the geometric relationships between the buckets (for more details see Dehaene et al., 2006). The task began with the child facing the experimenter and with his back to the array. The experimenter then pointed to a specific item on the map, allowing the child to look at the map as long as he wanted. Once the child turned around towards the buckets the experimenter removed the map from view. After the child had placed the ball in a chosen bucket, an additional experimenter removed the ball, praised the child, and returned the child to the starting position. This procedure was modeled first by the child's brother using a simplified map and bucket array (a blue and red bucket placed side by side) and then a few practice trials were completed by the child himself on the simple 2-bucket array. After the child completed four practice trials perfectly, the experimenter moved on to the test trials. During the second and third testing sessions the difficulty of the task was increased by requiring the child to exit the room before viewing the map. Nine different maps/bucket configurations were tested over the three testing sessions. Different test trials required the use of three main types of information for correctly solving the task (landmark information, distance information, and sense information).

Fig. 3 presents IC's performance on each of the configurations tested. Overall, IC produced the correct response 87.5% of the time (70/85), significantly greater than chance in both 3-item (37/45, binomial $P < .001$) and 4-item arrays (33/40, binomial $P < .001$). On trials in which the correct placement was the landmark (or uniquely colored bucket), IC performed perfectly (100%, 14/14), suggesting he understood what was being asked of him. He performed marginally worse (Fisher's exact $p = .05$, one-tailed), although still better than chance, on trials that did not involve placement in the unique, landmark bucket (79% correct; 56/71; 3-item arrays 31/39, binomial $P < .001$; 4-item arrays 25/32, binomial $P < .001$). On the 15 trials in which IC made errors, 93% of his incorrect responses were consistent with left/right sense confusions (14/15). In the two isosceles triangle conditions, identical except for the presence or absence of a landmark (see Fig. 2, # 3 and # 7 isosceles triangles), no significant difference was observed on trials where the correct placement was one of the non-unique containers (or equivalent containers in array containing all non-unique containers) (Wilcoxon $Z = -1.00$, $p = .32$). This suggests that IC was no more likely to use geometrical sense information in cases where a landmark was present compared to cases where a landmark was not present.

On average, control subjects placed the item in the correct location 92.7% of the time (average 71.4/77). Control subjects also performed perfectly when correct placement was the landmark (uniquely colored bucket) (average 100%, 12/12) and well on trials requiring placement in a non-unique container (average 59.4/65, 91.4%). No significant difference was observed between control subjects' performance when the correct placement was at the unique container compared to when correct placement was at the non-unique container (Fisher's exact test, $p = .69$). Like IC, most of the control subjects' errors were consistent with left/right confusions (average 97.1% of errors). While performance of controls was not significantly different from IC's overall performance ($t = -1.606$, $p < .18$), control subjects performed significantly better on non-unique trials compared to IC ($t = -3.302$, $p < .05$) (Table 2). This can be accounted for by the fact that IC made more overall sense (left/right) errors compared to the average control. An analysis of control subjects' performance on non-unique trials of the isosceles triangle revealed no difference between the non-landmark and landmark conditions ($F(1, 4) = 4.57$, $p = .09$; Wilcoxon $Z = -1.63$, $p = .10$), suggesting they were also no more likely to use geometry on the isosceles triangle with a landmark compared to the isosceles triangle with no landmark (averages trend towards more use of geometry on the landmark condition).

7.2. Summary of map performance

Across all 81 mapping trials that tested for sensitivity to three basic properties of maps—landmark/feature information (here, color), relative-distance information and sense information—IC performed at a level far higher than would be expected by chance. This means both that he naturally intuited the symbolic function of the maps, as well as the properties of distance, sense and color that were tested for. He was in many ways "typical" in his map-reading talents. However, he encountered relatively greater difficulty with sense problems.

That IC encountered greater difficulty with trials requiring representing sense relations than controls may suggest that he used a different process for encoding left-right information in the maps. Further evidence for this conjecture comes anecdotally: during the task, IC was often observed attempting to rotate the map or rotate his own perspective relative to the map so as to align the map with the configuration of objects. Importantly, though a certain amount of mental rotation is required for the sense distinction, the notions "left-of" and "right-of" do not require that the configuration match exactly the very perspective from which it was observed.

8. General discussion

IC showed proficiency in numerical tasks despite the lack of a complete natural language. At some point he had learned numerical vocabulary, using canonical numerical signs and demonstrating understanding Arabic digits. Furthermore, he applied this knowledge to count objects accurately over a number of different experimental conditions including those that required short-term memory. IC also demonstrated a keen sense of space. He performed

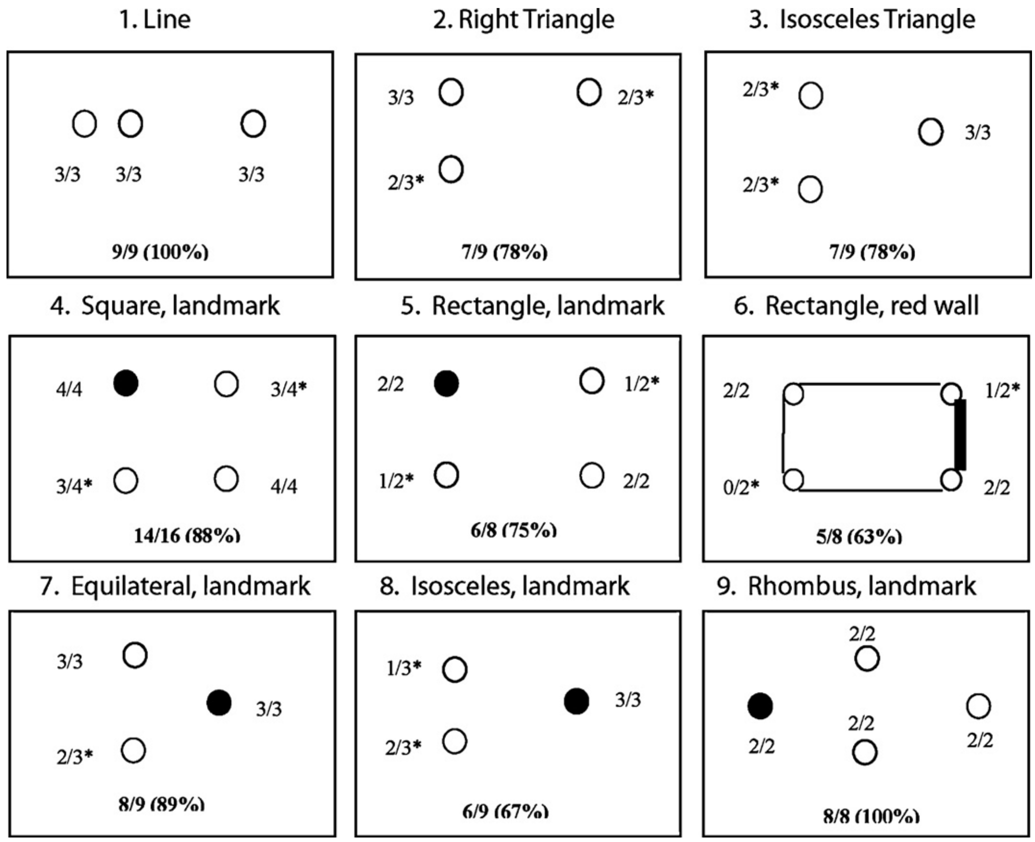

Fig. 3. IC's performance on map tasks 1–9. Numerical ratios presented at each location within each map represent the total number of correct placements over the total number of trials where the experiment pointed to that location. Numerical ratios at the bottom of each map represent the total number of correct placements over the total number of trials for that map.

well on tasks that involved complex mental rotation, memory, symbolic map use, and reorientation with direct landmark cues or geometry alone. However, IC showed a focal deficit in spatial tasks that required him to combine geometrical and landmark information to accurately search for a hidden object: to correctly locate an object hidden in a non-distinctive container (in a rectangular array consisting of three identical containers and one distinctive container), he would have needed to use both the features of the target container and its geometric relationship to the other containers. The observed failures cannot be explained by a lack of understanding of the tasks because he performed at ceiling in tasks where objects were hidden directly at the landmark and typically in tasks without landmarks. Also, the failures cannot be due to order or boredom effects because in each instance task conditions were counterbalanced. Finally, we believe the failures are not simply due to the indirect landmark conditions being more difficult than the other conditions because he performed significantly better on the no-landmark trails in which only the geometric relationships among the objects served to distinguish them.

It may be the case that the presence of a landmark reduces, to some extent, the use of geometrical cues. This possibility is supported by map task data from young children, where non-geometrical errors are more prevalent in conditions in which the array contains a landmark and the target location is a non-unique location (e.g. triangle composed of 1 red bucket and 2 white buckets) compared to errors made on the equivalent array with all identical items (e.g. triangle composed of all white buckets) (Shusterman et al., 2008). To a lesser extent, this idea is also supported by data from Mundurucu subjects (Amazon), where a small portion of errors were "non-geometrical" when the correct response was one of the non-unique containers in a triangular array containing a landmark (Dehaene et al., 2006). However, IC's performance cannot be accounted for solely as a result of decreased use of geometry in the presence of a landmark, as IC was marginally below chance (albeit with very few trials) on reorientation tasks and significantly below chance on oriented search tasks requiring the combination of landmark and geometry, in contrast to the Mundurucu that accurately located the target on a majority of such trials. And, neither IC nor age-matched controls performed differently when the correct response was a non-unique container in an isosceles triangle with a landmark compared to the same isosceles triangle without a landmark.

Interestingly, while IC possessed functional vocabulary for numbers he appeared to have an impoverished vocabulary to describe spatial relations. Despite numerous attempts including modeling and prompting in ASL, PSL (Portuguese Sign Language), and by a family member using home-sign, little if any evidence was observed for the basic use of spatial terms. Specifically, terms to describe left/right relations did not appear to be part of his vocabulary and terms to describe above/below relations seemed to be linked to alternative descriptions using action verbs (such as "sit"). Furthermore, the approximations used to describe spatial relations were ambiguous. That is, it was unclear which object/actor held which spatial position with relation to another object/actor. This was not for a lack of perceptual skills to do so, as he was perfect at distinguishing multiple-digit numbers that only differed by their ordinal left/right relations to each other (e.g. 37 vs. 73).

8.1. *Implications for numerical cognition*

The current results suggest that natural number concepts can arise from limited language proficiency, including vocabulary for number words/symbols, objects, and actions, and do not require a complete natural language. It is still debated whether a numerical vocabulary is essential to developing full-blown natural number concepts (Butterworth et al., 2008; Condry & Spelke, 2008; Frank et al., 2008; Gordon, 2004; Izard et al., 2008; Pica et al., 2004). However, these previous studies cannot disentangle the role of numerical vocabulary from the contribution of a complete natural language because all of the groups that have been studied possess a natural language. Here we present exactly the opposite case to those that study populations with natural language but without number words: a case of isolated proficiency with number words, Arabic number symbols, and counting in a child who lacks a conventional natural language. Because the child performed as well as hearing controls on all the numerical tasks except for those tapping arithmetic facts learned in school, his performance provides evidence that mastery of a full, conventional natural language is not necessary for the formation of natural number concepts.

8.2. Implications for spatial/geometrical cognition

These results have four main implications for our understanding of the role of language in the development of spatial thinking. First, spatial left/right relationships may not be intuitive or automatically represented on the presentation of a pair of objects, but rather may be facilitated by the conscious evoking of linguistic terms to call them to mind. This suggestion is supported by the fact that age-matched controls spontaneously produced terms to disambiguate above/below relations between objects, but did not spontaneously produce spatial terms to describe left/right relationships between objects. Upon first prompting with the relevant spatial terms, however, the control subjects produced disambiguating left/right terms on all subsequent elicitation trials.

Second, sensitivity to certain spatial cues or disposition towards "alternative strategies" may be heightened in the absence of a language to accurately describe spatial relations. For example, on most of the reorientation trials where no obvious landmark cue was present, IC seemed to search intently for slight asymmetries or other non-obvious markers within the experimental chamber for use in solving the task. Similar strategies were not observed in informal piloting on adults nor have they appeared to have been used by children in past experiments within the same experimental chamber (e.g. Lee & Spelke, 2008, Lee et al., 2006). Also, the experimenters noted that IC seemed to be using some sort of mental-rotational strategy to approach a subset of the trials of the map task, as he was observed several times making hand motions indicating rotation of the array in the space in front of himself. These strategies may explain his performance on reorientation trials, for example, but cannot explain his performance on oriented search trials which were devoid of such asymmetries or additional cues, yet his ability to locate the hidden object on no-landmark trials was greater than chance (81%). Because the number of trials was small, his high performance may be due to chance factors. This possibility is supported by the fact that a statistical comparison of IC's performance to that of controls on the no-landmark condition showed no significant difference. Nonetheless, his success rate of 81% on no-landmark trials stands in stark contrast to his success rate of 33% on landmark trials with the item hidden in a non-unique location. This contrast suggests that if alternative strategies or additional cues were used in the no-landmark conditions, they were not equally applied in the indirect landmark and the no-landmark conditions.

Third, the correlations between language and spatial abilities observed in previous studies cannot be explained simply by cognitive maturation or non-linguistic experience, in light of IC's performance. IC was a maturing, cognitively-intact adolescent with extensive experience navigating, yet he lacked the ability to solve tasks involving landmarks as indirect cues: tasks that are easily solved by younger children with the appropriate spatial vocabulary as well as by age-matched controls (Hermer-Vazquez et al., 2001).

Fourth, the ability to combine geometrical and indirect landmark cues appears to be impaired without ready access to specific terms for describing spatial relations. With extensive probing in ASL, PSL, and home-sign, IC produced some approximations to describe above/below relations but never produced unambiguous terms for left/right. That is, one could not tell which object/actor was in which spatial relation to the other.

Previous evidence has shown a tight correlation between spatial vocabulary and the ability to use indirect landmarks as cues to reorientation or successful search behavior (Hermer-Vazquez et al., 2001; Pyers et al., 2010). IC's performance in tasks requiring the combination of geometrical and indirect landmark information is consistent with this pattern. His failures on this spatial task cannot be explained by deficits in memory, mental rotation ability, misunderstanding of the task, or in the geometric or landmark representations themselves, as he performed typically on different experimental conditions of the same task that required these types of resources to be used separately (no-landmark condition, or object hidden at landmark). Furthermore, his inability to solve tasks requiring the use of indirect landmark cues and geometry cannot be explained by an overall deficit in cognition as he was extremely proficient in the numerical domain. Additionally, his focal deficits do not appear to be perceptual as he successfully discriminated between multiple-digit numbers that only differed by the arrangement of the digits left to right (e.g. 56 versus 65).

The observed failures suggest that the lack of specific spatial language may be detrimental for the ability to combine mental representations of geometry and landmark cues. This work accords with previous studies that revealed a correlation developmentally between the functional use of left/right terms and success in tasks requiring the combination of geometric and landmark cues (Hermer-Vazquez et al., 2001). The present findings go beyond the developmental evidence by revealing that the ability of humans to combine geometric and landmark cues rapidly and flexibly is not built up by spatial-navigational experience (e.g. Cheng & Newcombe, 2005; Newcombe & Ratliff, 2007). Indeed, IC performed quantitatively and qualitatively differently from age-matched controls on the same tasks in the same testing environment despite both IC and controls having had substantial spatial-navigational experience.

We believe our data add an interesting piece of evidence to this debate through a natural deprivation experiment, showing that a lack of left/right terms correlates with impaired performance on several tasks conceptually tapping the ability to combine geometrical and feature information. These behavioral patterns of strengths and focal deficits allow us to make inferences about the role of experience in the development and function of the brain systems that underlie numerical and spatial abilities. Finally, these results attest to the robust nature of core numerical and geometrical intuitions. Despite deprivation of linguistic input, IC retained, used, and built upon core representations of number, space, and geometry.

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