Neuropsychologia 49 (2011) 924–936

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Spatial and numerical abilities without a complete natural language

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ARTICLE INFO

Article history:
Received 3 June 2010
Received in revised form 8 November 2010
Accepted 13 December 2010
Available online 17 December 2010

Keywords:
Symbol use
Reorientation
Geometry
Counting
Deaf

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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doi:10.1016/j.neuropsychologia.2010.12.017

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