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Review

Infants' intermodal numerical knowledge

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ABSTRACT

Two-system theory as the dominant approach in the field of infant numerical representation is characterized by three features: precise representation of small sets of objects, approximate representation of large magnitudes and failure to compare small and large sets. Comparison of single- and multimodal numerical abilities suggests that infants' performance in multimodal conditions is consistent with these three features. Nevertheless, the influence of multimodal stimulation on infants' numerical representation is characterized by preventing the formation of perceptual overlaps across different sensory modalities which can lead to an understanding of numerical values of small sets and also by creating a conceptual overlap about numbers that increases infants' accuracy for discriminating quantities when numerical information is presented bimodally and synchronously. Such multisensory benefits provide numerical capabilities beyond what is depicted by the two-system view.

1. Introduction

Recent studies have revealed that even fetuses are sensitive to the change in numerosity (Schleger et al., 2014), and there is substantial evidence that after birth such sensitivity can be explained by two representational systems: an exact system for small numbers (4 <) and an approximate system for large numbers (< 4) (for reviews, see Cantrell & Smith, 2013; Cordes & Brannon, 2008; de Hevia, 2016; Feigenson, Dehaene, & Spelke, 2004; Hyde, 2011; Mou & vanMarle, 2014). In spite of remarkable advances in infants' numerical cognition, little scientific effort has been devoted to the study of multimodal numerical processing in infancy. In intermodal (or multimodal) numerical tasks, the researchers test infants' abilities to form abstract representations of numerical information which refers to the extraction of numerosity from stimuli that are received by a particular sensory modality, and relate this number to obtained number from another sensory modality in order to find quantitative relationships between two sets. Unlike unimodal studies in which infants' ability for numerical discrimination, ordering and arithmetic operations (addition, subtraction, multiplication, and division) have been properly investigated (see McCrink & Birdsall, 2014), in multimodal studies there is evidence for only two forms of numerical abilities: adding and matching numerical quantities. In this paper, first the evidence (predicted by the two-system view) for infants' intermodal numerical representation will be reviewed. Then the mechanisms involved in unimodal and multimodal numerical tasks will be compared. Finally, we will argue that the multimodal processing can go beyond the limits of the two-system view.

2. Small numbers comparison

In a seminal work, Starkey, Spelke, and Gelman (1983) used intermodal-matching paradigm to test infant numerical abilities. Seven-month-old infants were presented with two visual displays: one containing three and the other two objects. While infants were

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looking at these displays they heard either two or three drumbeats. The results showed that infants hearing two drumbeats looked longer at the display with 2 rather than 3 objects; vice versa, hearing 3 drumbeats was associated with longer looking at 3 objects. The authors concluded that infants can detect numerical information beyond sensory modalities. But due to the complex interaction between intermodal perception and cognition, multiple lines of research interpret infants' performance in different ways (Kirby, 1992; Mix, Levine, & Huttenlocher, 1997; Moore, Benenson, Reznick, Peterson, & Kagan, 1987). For example, some studies attempted to replicate the findings of Starkey et al. (1983), Starkey, Spelke, and Gelman (1990) and reported the opposite result: infants looked longer at the display that was numerically different from the auditory pattern (Mix et al., 1997; Moore et al., 1987). These results were explained by an intensity hypothesis asserting that infants respond to the effective intensity of stimuli which is a function of both the organism states (aroused or quiescent) and the overall amount of physical energy received from different modalities (Lewkowicz et al., 1994; Turkewitz, Lewkowicz, & Gardner, 1983; Turkewitz, Gardner, & Lewkowicz, 1984). Generally two main functions are discussed in this hypothesis: intensity-based equivalence and cross-modal additively and substitutability. The former refers to identical responding to events in terms of the intensity of the inputs and according to the second function infants have a tendency toward a moderate (or optimal) level of stimulation across modalities. For example, Lawson and Turkewitz (1980) presented 1, 4, 6 and 64 cubes to the newborns. Half of the newborns were presented with sound at the same time while the others were the non-sound group. Compared with the non-sound group, the newborns who received sound preferred fewer cubes. In other words, sound presentation leads them to look longer to stimuli with lower intensity because the intensities of visual and auditory stimuli are combined together providing a moderate level of stimulation. Apparently, these results are correspondent with the inconsistent findings as reported by Mix et al. (1997) and Moore et al. (1987). That is, infants who heard two sounds may be driven to seek the more stimulating displays of three objects, whereas infants who heard three sounds are driven to seek the less stimulating displays of two objects.

Although the results of these early studies are mixed, the subsequent studies using ecologically relevant contexts provide clear evidence that infants are able to detect numerical correspondences between small sets of entities perceived in different sensory modalities. Kobayashi, Hiraki, Mugitani, and Hasegawa (2004) suggested that there was no natural relation between the object and sound in previous studies and such procedure could be difficult for infants. Therefore, they created meaningful relationship between events by using a violation-of-expectation paradigm. Specially, Five-month-old infants were familiarized with two or three dolls dropping on a stage, each doll made a tone upon impacting. At test, participants saw a doll (without tone) and then an opaque screen came up and concealed the doll. Under this condition, when two tones were added, infants were able to anticipate the correct outcome of intermodal addition (1 doll + 2 tones = 3 doll) and looked longer at the incorrect outcome (1 doll + 2 tones = 2doll) when screen was removed. In another study with similar procedure Kobayashi, Hiraki, and Hasegawa (2005) trained six-month-old infants to associate an object with a tone and found that participants recognized numerically mismatched events in (2 vs. 3) condition. Infants who heard three tones looked longer at two dolls, whereas infants who heard two tones looked longer at three dolls. Jordan and Brannon (2006) attempted to invoke infants' spontaneous response to numerosity by using socially relevant stimuli. The authors showed seven-month-old infants two monitors side by side; one of them showed a movie of two women and the other three women, simultaneously mouthing the word "look". While looking at the monitors infants heard two or three female voices concurrently saying "look". In this study each 3 or 2 auditory stimuli simultaneously presented with a single auditory stream, whereas 3 and 2 auditory streams were identical in duration. Therefore, the task was designed to eliminate the role of rate and duration. The results showed that infants spontaneously match the number of voices with the number of faces. For example, infants who heard a soundtrack with three voices looked longer at a dynamic visual display with 3 faces rather than 2 faces. Similar to the research on infants, Coubart, Streri, Marie, and Izard (in revision) reported that neonates successfully matched 1 vs. 2 voices with the corresponding number of faces, but could not do so for 1 vs. 3 faces and voices, suggesting that newborns' representation of small numbers is limited to 2 items and such representational system is available at birth. In another study Farzin, Charles, and Rivera (2009) investigated 6-, 7- and 8-month-old infants' numerical abilities with arbitrarily related stimuli. Infants were initially familiarized with three jump sequences of a doll (e.g., a koala) in one side of the display and two jumps of another doll (e.g. a panda) in the other side. Each jump was presented simultaneously with a tone and the duration of 2 and 3 jump sequences was controlled. At test trials both dolls displayed without movement, infants only heard two or three tones at a novel rate and overall duration from familiarization. The authors found that 6-, 7-, and 8-month-old female and 8-month-old male infants looked longer at the numerically matched side of the display rather than the unmatched. For example, infants who associated three-jump sequences of a koala with three tones during familiarization, looked longer at the side that a koala appeared (left or right) when they were tested with three tones. In all of the above mentioned studies infants discriminated numerical information across the visual and auditory modalities, but Féron, Gentaz, and Streri (2006) reported some evidence of amodal[1] and abstract representation of small numerosity(2 vs. 3)across visuo-tactile modalities in 5-month-old infants. In summary, there is evidence that infants, and even neonates, possess an abstract system for representation of small sets and the capacity of this system increases from 2 items to 3 over the first few months of life (see Table 1).

3. Large numbers comparison

An analog magnitude system (AMS) can support infants' representation for large quantities in which numerical value of items in a set are represented as mental symbols. AMS provides a capacity for processing cardinal values of items. For example, 4 could be represented as '——' and 8 as '————'. Because the magnitude of a mental symbol is not exactly equal with the numerosity of

[1] Amodal properties refer to information that can be extracted by more than one sense modality (e.g., number, intensity, shape, rhythm).