CORTEX 49 (2013) 1435–1440

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Journal homepage: www.elsevier.com/locate/cortex

Note

Superior numerical abilities following early visual deprivation

Julie Castronovo [a,*] *and Jean-François Delvenne* [b]

[a] *Department of Psychology, University of Hull, Hull, United Kingdom*
[b] *Institute of Psychological Sciences, University of Leeds, Leeds, United Kingdom*

ARTICLE INFO

Article history:
Received 13 June 2012
Reviewed 28 July 2012
Revised 20 December 2012
Accepted 28 December 2012
Action editor Carlo UmiltÃ
Published online 17 January 2013

Keywords:
Blindness
Numerical estimation

ABSTRACT

In numerical cognition vision has been assumed to play a predominant role in the elaboration of the numerical representations and skills. However, this view has been recently challenged by the discovery that people with early visual deprivation not only have a semantic numerical representation that shares the same spatial properties with that in sighted people, but also have better numerical estimation skills. Here, we show that blind people's superior numerical abilities can be found in different numerical contexts, whether they are familiar or more general. In particular, we found that blind participants demonstrated better numerical estimation abilities than sighted participants in both an ecologic footstep and an unfamiliar oral verbal production task. Blind participants also tend to show greater working memory skills compared to sighted participants. These findings support the notion that vision is not necessary in the development of numerical cognition and indicate that early visual deprivation may even lead to a general enhancement in numerical estimation abilities. Moreover, they further suggest that blind people's greater numerical skills might be accounted by enhanced high-level cognitive processes, such as working memory.

1. Introduction

Vision has for a long time been suggested to be central in numerical cognition for several reasons. Firstly, vision constitutes a predominant sensory modality in humans with significant advantages over other sensory modalities, notably in accessing numerical information. Vision allows greater amount of information to be processed, greater precision, easier access to distant objects, and greater attentional modulations (i.e., sharp focus, easy capture) (Thinus-Blanc and Gaunet, 1997). Secondly, vision allows numerical information to be processed simultaneously, while other senses mainly involve sequential processing, which has been found to be more complex than simultaneous numerical processing in children (Mix, 1999), adults (Tokita and Ishiguchi, 2012) and animals (Nieder et al., 2006). Thirdly, vision has predominantly been used in research on numerical cognition, particularly in the study of subitizing (i.e., rapid and accurate process of up to three or four items). For example, in the "object-file model", subitizing corresponds to a visual pre-attentive non-numerical process foundational to the acquisition of numerical cognition, with the later acquisition of numerical skills following the development of visuo-spatial cerebral circuits (Simon, 1997, 1999; Trick and Pylyshynm, 1994). Finally, the number sense, which

* *Corresponding author*. Department of Psychology, University of Hull, Hull HU6 7RX, United Kingdom.
E-mail address: J.Castronovo@hull.ac.uk (J. Castronovo).
0010-9452/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.cortex.2012.12.018

corresponds to humans' innate approximate intuition about numerosities and largely considered as constituting the foundations of numerical cognition (see Piazza, 2010, for a review), has been labelled as visual (Burr and Ross, 2008; Ross and Burr, 2010; Stoianov and Zorzi, 2012). Following the observation that the perceived numerosity of a set of objects can be modified by adaptation similarly to other primary visual properties (e.g., colour), Burr and Ross (2008) conceptualised "the visual number sense". Their conclusion is that numerosity can be seen as a primary visual attribute and that the primary visual system entails the capacity to approximate numerosities. The idea of a "visual number sense" has been further supported by Stoianov and Zorzi's (2012) hierarchical generative model, showing that visual numerosities constitute invariants, which can be extracted and coded independently from other visual attributes.

The concept of a "visual number sense" implies a central role of vision in the development of numerical representations and skills. However, recent studies on numerical cognition and blindness have challenged this view. A growing set of data has indicated that early blindness does not preclude the elaboration of a semantic numerical representation (SNR) with similar spatial properties to those postulated in sighted people: a mental continuum oriented from left to right (Dehaene, 1997; Dehaene et al., 1993; Fias et al., 1996; Zorzi et al., 2006). Compared to sighted people, congenitally blind people show similar: distance, size and SNARC effects when submitted to numerical comparison (Castronovo and Seron, 2007a; Szücs and Csépe, 2005) and parity judgement tasks (Castronovo and Seron, 2007a); pseudoneglect (leftward bias) in numerical bisection task (Cattaneo et al., 2011); numerical spatial attentional shift in detection tasks (Salillas et al., 2009) and physical line bisection tasks (Cattaneo et al., 2010). Regarding the third property of SNR, its obedience to Weber's law (i.e., approximate numerical processing with increasing numerosity), congenitally blind participants' performances in numerical estimation tasks present as expected the signature to Weber's law [i.e., constant coefficients of variation (CV) across target size] (Castronovo and Seron, 2007b; Ferrand et al., 2010).

Altogether, those data clearly indicate that vision is not essential in the development of SNR with similar properties as in sighted people. More importantly and surprisingly, early blindness might even have a positive impact on numerical abilities. Indeed, congenitally blind participants demonstrate greater estimation skills than sighted participants, especially when submitted to numerical estimation tasks involving touch and proprioception: smaller variability and greater accuracy in their estimates in a small (up to 9) (Ferrand et al., 2010) and large numerical range (up to 64) (Castronovo and Seron, 2007b). These high numerical performances in blind people suggest that early blindness and its consecutive experience in accessing and processing numerical information might lead to greater mapping abilities between symbolic numerical representations (verbal numerals) and their corresponding magnitudes. They could also reflect the use in blind people when performing numerical tasks of enhanced high-level cognitive resources, such as working memory (WM) (Salillas et al., 2009; Szücs and Csépe, 2005), since: (1) WM and numerical skills appear to be linked (De Smedt et al., 2009a, 2009b; Simmons et al., 2012), (2) blind children present greater WM skills than sighted children (Hull and Mason, 1995; Lee Swanson and Luxenberg, 2009), (3) compared to sighted children, blind children seem to rely on WM rather than on finger counting when submitted to counting task (Crollen et al., 2011a), (4) neuroimaging (event-related brain potentials) data suggest that blind people apply high-cognitive resources (cognitive P300 component), such as WM, when processing numerical information (Salillas et al., 2009; Szücs and Csépe, 2005).

Here, we extend our previous findings by showing that congenitally blind people's great estimation skills are not tied to a particular modality (i.e., tactile) in which they might have greater acuity (Goldreich and Kanics, 2003), neither to particular numerical contexts close to their daily life experience in using numerical information (i.e., locomotion involving quantitative judgements through proprioception), but can also be extended to more general unfamiliar numerical contexts requiring verbal, non-tactile numerical processing. Moreover, we provide further support to the assumption that blind people's greater numerical skills might also be accounted by enhanced high-level cognitive processes, such as WM.

2. Methods

2.1. Participants

We tested a group of congenitally blind participants and a group of sighted participants matched in age and sex. All participants gave informed consent.

Blind participants were 11 volunteers (eight men, nine right-handed), presenting different levels of education (eight high school level, three university level) and different histories of visual impairment: prematurity, retinoblastoma, glaucoma, Leber's congenital amaurosis and septo optic hypoplasia. All were proficient Braille readers since childhood, aged between 24 and 65 [mean age = 43, standard deviation (*SD*) = 13].

Sighted participants were 11 volunteers (eight men, 10 right-handed), aged between 25 and 61 (mean age = 43, *SD* = 12). All sighted participants had university education level. They were blindfolded to perform the different tasks.

2.2. Tasks and procedure

All participants were submitted to two numerical production tasks: a footstep production (FP) task and an oral verbal production (OVP) task. They also undertook three WM tasks: forward-digit, backward-digit and word span tests. The tasks were conducted through two sessions, in which both estimation tasks were undertaken twice. The digit span tests ran in the first session, the word span test in the second session.

In both production tasks, the same target numbers as in Castronovo and Seron (2007b) ranging from 5 to 64 were used. Each target number was presented 16 times across eight blocks in each production task (two presentations/block, four blocks/session) according to a fixed pseudo-random order (no consecutive repetition of the same target number). The two tasks were inter-mixed within each session, with half of the participants in each group starting with the FP task, while the other half started with the OVP task. Each task had eight practice trials.