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Experimental Evidence From Newborn Chicks Enriches Our Knowledge on Human Spatial–Numerical Associations

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Abstract

Núñez and Fias raised concerns on whether our results demonstrate a linear number-space mapping. Patro and Nuerk urge caution on the use of animal models to understand the origin (cultural vs. biological) of the orientation of spatial–numerical association. Here, we discuss why both objections are unfounded.

Keywords: Number cognition; Spatial–numerical association; Mental number line; Spatial cognition; Domestic chicks (*Gallus gallus*)

Núñez and Fias (2015) criticized our study (Rugani, Vallortigara, Priftis, & Regolin, 2015a) for failing to (1) provide a mathematical definition of linear mapping; (2) to demonstrate a linear number-space mapping. Our goal, however, was not to define the structure of chicks' number-space mapping but to investigate the existence of spatial numerical associations (SNAs) in the absence of language or cultural experience. Moreover, Núñez and Fias (2015) claimed that our results may depend on spatial biases due to brain asymmetry, and particularly on an asymmetrical processing of novel stimuli experienced at test. They argued that because of the logarithmic compression of the mental number line (MNL), which makes large numbers harder to discriminate from one another, large numbers would be perceived as more similar (less novel); vice-versa for small numbers (more novel). Indeed, many behavioral asymmetries have been demonstrated in birds (Rogers, Vallortigara, & Andrew, 2013), but our chicks' performance lacked any asymmetry; it was symmetrical around chance level (50%), being equally distributed across experiments and across small versus large number trials (Rugani, Vallortigara, Priftis, &

Regolin, 2015b). Asymmetries in novelty processing could also not explain our data. If we assume that the right hemisphere processes novelty, this would explain chicks' association of small numbers with the left space, but not that of large numbers with the right space (unless "less novelty" is processed by the left hemisphere! For a detailed discussion see Rugani, Vallortigara, Priftis, & Regolin, 2016a). Concerning our analyses, we refer readers to our subsequent paper (Rugani et al., 2015b), in which we argue that these were actually appropriate.

Patro and Nuerk (2016) favored evidence supporting the role of culture in the orientation of the MNL. Although culture does affect the direction of the MNL, it is difficult to deny the increasing bulk of evidence showing that SNA occurs in non-verbal subjects (Adachi, 2014; Bulf, de Hevia, & Macchi-Cassia, 2015; De Hevia & Spelke, 2009, 2010; Drucker & Brannon, 2014; Lourenco & Longo, 2010; for a review, see Rugani & de Hevia, 2016).

Concerning the criticism about number-space coding in ordinal tasks, in previous studies we found that birds, trained to identify a target element (e.g., the 4th) in a sagittal series of identical elements (e.g., 10), whenever required to respond on a left/right oriented series, localized the target mainly starting from the left end (Rugani, Kelly, Szelest, Regolin, & Vallortigara, 2010; Rugani, Regolin, & Vallortigara, 2007; Rugani, Vallortigara, Vallini, & Regolin, 2011). We recently showed that this left bias could be a consequence of a right-hemisphere dominance, resulting in the left visual hemifield controlling birds' behavior (Rugani, Vallortigara, & Regolin, 2016b). Patro and Nuerk (2016) believe, as we also do, that the explanation for the bias observed in chicks (Rugani et al., 2007, 2011), Clark's nutcrackers (Rugani et al., 2010), and monkeys (Drucker & Brannon, 2014), in tasks involving purely sequential coding, cannot be easily transferred to the SNA. In the first case, an explanation in terms of selective attending to the left hemifield (i.e., pseudoneglect) as a result of a right-hemisphere activation can account for the biases. In contrast, in the SNA task (Rugani et al., 2015a), chicks did not show a generic left bias. The direction depended on the relative magnitude judgments: left bias for small magnitudes, right bias for large magnitudes. We suggested that a right hemispheric dominance prompts the SNA to be left-to-right (rather than right-to-left) oriented. This possibility is not confined to the avian brain. In fact, it is well attested that lateralization is a widespread phenomenon which, although stronger (Vallortigara & Versace, 2017), is certainly not limited to those taxonomic groups lacking a corpus callosum (Rogers et al., 2013). Lateralization shares the same biological basis (the genes involved in the NODAL signaling pathway; Concha, Bianco, & Wilson, 2012; Ocklenburg & Güntürkün, 2012) in all vertebrate classes (including mammals, Rogers et al., 2013). Vertebrates also share the key features of the non-verbal numerical system (i.e., size and distance effects, review in Vallortigara, 2014, 2017). Overall, this constitutes a strong evidence for basic homology for both lateralization and approximate number system in vertebrates.

We agree with Patro and Nuerk's (2016) cautions concerning the generalization of conclusions from one species to a very distant one (though we found rather bizarre their example of transferring to humans the female spider's habit of eating its partner). Yet we regard similarities in behavior and brain (whether based on common ancestor or on

convergent evolution' Bolhuis & Wynne, 2009) as an invaluable source of insight into the nature of cognitive processes (Tinbergen, 1963; Versace & Vallortigara, 2015). In the present case, after conceding all the possibilities for society and culture to modulate number-space mapping (Zebian, 2005), evidence in non-human species suggests that, indeed, a biological root is there for SNA. It is of course a matter of taste to be more interested in the modulatory effect of culture and society on a psychological phenomenon or in its biological basis. We are mainly concerned with the biological basis and believe that comparative methods and animal models provide a privileged road for such an investigation. Disentangling between homology versus analogy in evolution of the SNA was not the aim of our study. Future investigations on the genetic basis will shed light on this aspect of SNA.

In sum, our study constitutes a step forward that shows a cultural-independent association between numbers and space. Our paradigm could also be used to test infants and to better understand the phylogenetic versus ontogenetic origin of this aspect of numerical cognition.

A crucial challenge will be understanding how and where number magnitude is represented in the brain. Comparative studies on numerical processing have suggested that numerical knowledge constitutes a domain-specific cognitive ability (Cantlon, 2012; Pepperberg & Carey, 2012; Scarf, Hayne, & Colombo, 2011; Wang, Uhrig, Jarraya, & Dehaene, 2015) with a dedicated neural substrate (Dehaene, 2011; Nieder, Freedman, & Miller, 2002; Vallentin & Nieder, 2008) and a topographical organization (humans; Harvey, Klein, Petridou, & Dumoulin, 2013). Recently, neurons selective to numbers have been found in the brain association area (*nidopallium caudolaterale*, NCL) of crows (Ditz & Neider, 2015). This allows future investigations of the neural basis of spatial–numerical associations to explain how neural codes of space and number can determine an association of small numbers with the left space and of large numbers with the right space.

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