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Review

Interaction between domain-specific and domain-general abilities in math´s competence

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Sandra Torresi[1]

[1] Universidad Favaloro.
Buenos Aires (Argentina)

Abstract

This article is an approach to some viewpoints about interactions between domain-specific and general cognitive tools involved in the development of mathematical competence. Many studies report positive correlations between the acuity of the numerical approximation system and formal mathematical performance, while another important group of investigations have found no evidence of a direct connection between non-symbolic and symbolic numerical representations. The challenge for future research will be to focus on correlations and possible causalities between non-symbolic and symbolic arithmetic skills and general domain cognitive skills in order to identify stable precursors of mathematical competence.

Keywords*:* Numerical cognition; cognitive development; approximate number system; working memory

Interacción entre habilidades de dominio específico y dominio general en la competencia matemática

Resumen

Este artículo es una aproximación a diferentes puntos de vista acerca de la interacción entre las habilidades cognitivas de dominio específico y general involucradas en el desarrollo de la competencia matemática. Muchos estudios reportan correlaciones positivas entre la agudeza del sistema de aproximación numérica y el desempeño matemático formal, mientras que otro grupo importante de investigaciones no han hallado evidencias de una conexión directa entre las representaciones numéricas no simbólicas y las simbólicas. El desafío para las futuras investigaciones será focalizar en correlaciones y posibles causalidades entre las habilidades aritméticas no simbólicas, las simbólicas y las habilidades cognitivas de dominio general con el propósito de identificar precursores estables de la competencia matemática.

Palabras clave: Cognición numérica; desarrollo cognitivo; sistema de aproximación numérica; memoria de trabajo; precursores

Correspondence:

Sandra Torresi
Universidad de Favaloro.
Buenos Aires (Argentina)
E mail: sptorresi@gmail.com

Introduction

Natural numbers are a critical tool for almost all human cultural achievements, they are everywhere and we deeply depend on them so, a central question for science is how they arise in our lives… which are the foundations that support numerical thinking.

Cognitive development depends on two types of essential tools, domain-specific and domain-general processes (Butterworth, 2019) and the way these abilities co-develop is crucial for understanding learning in general, and math learning in particular.

Domain-specific representations guide and constraint the cultural acquisition of novel representations (Carey, 2009; Piazza & Izard, 2009). The core knowledge systems are universally shared independently of formal education and engaged throughout lifetime (Spelke, 2017). For numbers, the neurocognitive startup tool are two preverbal and non-symbolic systems for numerical quantification to of the environment: the *Approximate Number System* (ANS) and the *Object Tracking System* (OTS) (Piazza & Izard, 2009; Piazza, 2010). But this nonverbal number sense may not be enough to develop verbal and exact math competencies and domain-general abilities could be involved.

Domain-general cognitive tools are necessary in a wide variety of tasks and refer to higher order cognitive variables that can predict the performance of several competencies (Fritz, Haase & Räsänen, 2019), for instance, Working Memory (WM) (Blankenship, Keith, Calkins & Bell, 2018) and Processing Speed (PS) (Clark, Nelson, Garza, Sheffield, Wiebe & Espy, 2014) or language (Butterworth, 2019).

Domain-specific tools: ANS and OTS

The Approximate Number System (ANS) enables humans to represent and manipulate quantities in an approximate manner, it means that encodes an imprecise estimate of the numerical magnitude of a set (Nieder & Dehane, 2009; Nieder, 2019). This ancient and evolutionary number sense is shared with non-human animals and primates (Cantlon & Brannon, 2007) and is present from the very beginning, long before the acquisition of symbolic number.

Newborns are sensitive to the abstract numerical attributes of the environment and reacts to the cardinal values of sets presented in all sensory modalities, auditory or tactile, not only in a visual way (Anobile, Cicchini & Burr, 2016; Izard, Sann, Spelke & Streri, 2009) and they are able to discriminate between sets irrespective of the physical properties: surface area, density or contour length (Matejko & Ansari, 2016).

ANS increases in acuity through childhood until around 30 years old (Halberda, Ly, Wilmer, Naiman & Germine, 2012) and varies across individuals (Piazza & Izard, 2009). ANS acuity is assessed with simple approximation number tasks of comparison of two sets, the performance depends on the ratio between the quantities. Because of ANS imprecision close quantities are more difficult to discriminate.

To solve an everyday decision making anytime counting is not possible, ANS representation is activated during both non-symbolic and symbolic approximations (Libertus, Odic, Feigenson & Halberda, 2020), the two systems remain intimately linked and mutually interact with each other.

The second core tool involved in number processing is the Object Tracking System, OTS (Dehaene, 2011), a visuospatial object-based attention system that allows a quick, effortless apprehension up to 4 items called *subitizing* (Ashkenazi, Mark-Zigdon & Henik, 2013). This is a mechanism to enumerate the number of sets at a glance and with high accuracy (Butterworth, 2019; Revkin, Piazza, Izard, Cohen & Dehaene, 2008) without counting. Similar to ANS, OTS varies across individuals and develops in a short period of time and babies reach the adult (like limit of 3-4 items in the first year of life). It´s most important constraint is that it´s limited to a small set (Piazza, 2010), for larger sets exact and serial but slower counting is the only possible mechanism because larger numbers can´t be tracked (Nieder, 2019). Subitizing is a precursor of counting and symbolic representations and the acquisition of a mental number line spatially left-right organization (Dehaene, 2011*)*.

The approximate number system and subitizing are complementary mechanisms of the number sense. Together, enable the comprehension of cardinality and ordinality (Rapin, 2016). Similar to ANS, OTS varies across individuals and develops in a short period of time and babies reach the adult (like limit of 3-4 items in the first year of life). Around 4 years old, are assembled and children understand that sets may have a precise number, so 15 is a different concept from 13 (Dehaene, 2011).

The relation between ANS acuity and mathematical performance has been explored intensively but results remain unclear yet. In fact, several studies have shown that ANS acuity is meaningfully related to mathematical achievement and have also suggested that individual differences in this non-symbolic system predict symbolic mathematical skills (Libertus, Feigenson & Halberda, 2011; Bonny & Lourenco, 2013). For instance, on magnitude comparison tasks typical development children outperforming math learning disabilities children (Desoete, Ceulemans, De Weerdt & Pieters, 2012). So, ANS acuity may be helpful in designing diagnostic and intervention tools (Park & Branon, 2014).

ANS and the symbolic number system rely on each other in a sort of continuity of both representations, the way to acquire the meaning of symbolic numbers is linking with the preexisting innate representations of numbers. So, ANS may constitute the semantic foundation for the symbolic numbers (Dehaene, 2011; Mazzocco, Feigenson & Halberda, 2011).

Three meta-analyses confirm the positive relation between non-symbolic number acuity and math ability (Chen & Li, 2014; Fazio, Bailey, Thompson & Siegler, 2014; Schneider et al., 2016); however, many others studies failed to identify the relation between them (Chu, vanMarle & Geary, 2015; Vanbinst, Ghesquiere & Smedt, 2012; Zhou, Wei, Zhang, Cui & Chen, 2015).

Bugden & Ansari (2011) suggest that ANS acuity wouldn't be the foundation for early mathematical development but the basic symbolic competencies, numerals, number words and the relations among them. The notion of a direct link from non-symbolic to symbolic is challenged by the hypothesis that number symbols are not necessarily inextricably tied to non-symbolic quantities. Resents findings indicate that symbolic and non-symbolic abilities show different developmental trajectories in the first year of schooling but not a unidirectional relationship (Matejko & Ansari, 2016) and even divergent patterns of representation at the neural level (Goffin & Vogel, Slipenkyj & Ansari, 2020).

Possibly, both ANS acuity and the understanding of number symbols independently contribute to math learning (Fazio et al., 2014). ANS may facilitate children's explicit understanding of cardinal value and indirectly may influence early mathematical learning (Chu et al., 2015).

Undoubtedly, the experience with numbers and arithmetic of formal education enhanced the accuracy in the development of ANS (Lindskog, Winman & Juslin, 2014). For instance, there´s evidence of higher ANS acuity in individuals who had formal education experience than without formal education or after ANS training (Nys et al., 2013; Honoré & Noel, 2016). Indeed, what it´s relevant for teaching math is that ANS is refined through practice with the symbolic number system (Matejko & Ansari, 2016) and that acuity facilitates the acquisition of cardinal principle (Nieder, 2019), the core concept of succession of natural numbers.

Two concepts must be defined to avoid confusions: *cardinality* refers to set size, the last number produced when counting the set: 1, 2, 3, 4… 5 (Szkudlarek & Brannon, 2017), *symbolic number* includes the Arabic code and verbal code representations: 5 and five.

Domain-general tools: the case of WM

According to Carey (2009) and Szkudlarek & Brannon (2017) improving math depends on a multifaceted approach so, ANS acuity is a foundational skill but insufficient. Many studies focused on different domain general abilities as predictors of children individual mathematical achievement: fluid intelligence and working memory (Blankenship et al., 2018; Geary, 2011; Xenidou-Dervou et al., 2018), processing speed (Clark et al., 2014; Kuzmina, Tikhomirova, Lysenkova & Malykh, 2020), vocabulary and word recall (Purpura & Ganley, 2014), inhibitory control (Gilmore et al., 2013) or in a combination of three: intelligence, central executive and reading achievement in a seven-year longitudinal study (Geary, Nicholas, Li & Sun, 2017).

Working Memory (WM) has shown to be a strong longitudinal predictor of various mathematical skills (Hornung, Schiltz, Brunner & Martin, 2014; Xenidou-Dervou et al., 2018). According to Baddeley (2012), WM is an attention-driven multicomponent cognitive construct, an active system for temporal storing and processing information in an online manner at service of complex cognitive tasks. The system includes four components: a) Central Executive (CE), the most complex, an attentional system which monitors, controls and regulates the workings of the others and is activated when visual, spatial or phonological elements need to be manipulated, b) a Buffer Store (BS) for integrating information from a range of sources into a multidimensional code, c) a Phonological Loop (PL) a brief store of phonological elements together with a means of maintaining information by vocal or subvocal rehearsal, and d) a Visuospatial Sketchpad (VSSP) for storing spatial and visual information.

WM span is considered essential to math skill but this seems to be content-specific: visuospatial rather than verbal WM skills correlate with math achievement (Clearman, Klinger & Szücs, 2017). In a recent systematic review, Allen, Higgins & Adams (2019) confirmed an evident positive effect of visuospatial WM on mathematics attainments and suggested to take into consideration the type of VSSP involved. It is possible to identify the individual contribution of each component of the WM underlying different tasks (Fanari, Meloni & Massida, 2019), for instance, CE will be necessary in counting backward in twos from a certain number, whereas simply repeating the same number would not because it´s related to another component, the PL. In the case of atypical math development, researchers found difficulties in spatial WM tasks performance but not in visual tasks (Mammarella, Caviola, Giofrè & Szücs, 2018).

CONCLUSIONS

In a way of reconciling discrepant findings about precursors of math competence, research proposes that interventions should focus on domain-specific skills but also general cognitive abilities (Träff, Östergren & Skagerlund, 2020) as apparently, they contribute to distinct aspects during math growth. Indeed, both are implied and interact in the early numeracy (LeFevre et al., 2010) with different weights and in different moments and perhaps different resources for similar tasks (Fanari et al., 2019; Hornung et al., 2014).

Siemmann & Petermann (2018) suggested an integral model that could help understanding learning math and identifying children at risk of struggling with mathematics. They describe three factors for arithmetic development: a domain-specific number sense, the *foundation* on which arithmetic development rest, a *scaffold* of domain-general skills that assist in linking abstract numerosity with symbolic representation, and *tools,* the early number competencies: ordinality, cardinality, counting that are involved in arithmetic.

This body of novel concepts from cognitive neuroscience on precursors of math development should be considered a valuable contribution for educational interventions (Hellstrand, Korhonen, Räsänen, Linnanmaki & Aunio, 2020). It´s extremely important that educators improve their knowledge about factors related to healthy math competence. Teachers need this evidence-based guidance to make educational decisions about what to teach, why, how and when.

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Sandra Torresi: Degree in Social Sciences (Universidad de Buenos Aires, Buenos Aires)