Neuroimaging Contributions to the Understanding of Neuropsychological Cognitive Processing for Numeracy and Mathematics

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Introduction

Numerical and mathematical processing skills have a long history from the ancient classical Greeks Plato, Aristotle Frank, Mendel [1] to the birth of modern psychology, with John Dewey [2], Conant [3], O’Shea [4], suggesting that children learn numerical concepts by reinforcement, not in an abstract way, by identifying similarities, differences of empirical individual units, forming general concepts. This essay follows through the recent evolution of neuroimaging studies debate, sets the theoretical context of three dominant theories that influenced the context of research tools/methods; and how neuroscientific research has contributed uniquely to the understanding of numerosity. The essay concludes with a cogent argument that alternative research tools are necessary, complimentary, and multidisciplinary research generates different types/levels of new hypotheses, ensuing more reliable and valid information which benefits individuals, educationalists and society at large. Numerical processing (referring to arithmetic, mathematics, geometry and advanced computation) is huge. The paper is an eclectic review of the neurotypical findings of general numerical processing only but excludes dyscalculia Menon [5].

Numeracy Importance

The overwhelming research suggest that, numeracy is essential for progress in all aspects of life. Understanding numbers is the basis for developing arithmetic and mathematical skills of all levels and types of applications Dehaene [6], Hurford [7]. Major longitudinal research studies in the UK Bynner, Parsons [8], Donato [9], documented the phenotypic and behavioural outcomes of poor numerical skills and highlight the negative consequences on men’s and women’s, employment opportunities, health outcomes, social-civic involvement and overall quality of life Parsons, Banner [10]. Finding out if specific numerical processing is actually an observable brain process or not, is important to make stronger correlational claims, regarding relationships of numerosity and language.

Theories and Neuroimaging

New neuroimaging tools are used to test existing and emerging new theories and collect data that are impossible with surveys, and experiments. However, without multimethod, multiparadigm comparisons to make valid, reliable and nomological evaluations of competing claims Goya, Pitre [11], Hsee [12], Hsee [13], Hagger [14]. Three theoretical strands attempt to explain the development of number processing, using different research approaches. The first theory suggests that language is innate, culturally constructed and absence impedes learning numerical concepts and knowledge Chomsky [15], Hurford [16], Wiese [17], Spelke [18]. Their position without neuroscientific data, is not supported empirically, of how, when, and where language underpins numerical development. The second theory suggests that children learn numerical concepts as part of lexical acquisition and development of Theory of Mind (TOM) Bloom [19], Clark [20-22]. TOM facilitates multiple perspective taking, conceptual differentiation, through social interactions, enabling nuanced meaning differentiation between words, symbols, and number associations. However, Bloom and Clark, provide weak empirical evidence that brain processing occurs this way, and fail to account for alternative hypotheses.

The third theoretical position postulates a biological, evolutionary, ontogenetic Carey [23], innate ability of ‘number sense’ and processed in distinct brain areas Dehaene [24]. Innate, numerical processing is present in all cultures with and without dedicated number words Pica et al., 2004; Lasne [25]. Dehaene and co-researchers, Dehaene [26], Dehaene & Cohen [27]. Dehaene [28] using neuroimaging data proposed that different numerical formats are processed in different brain regions. First, visual
Arabic numbers are processed by bilateral activity in inferior ventral occipito-temporal areas; secondly, the inferior parietal areas process analogical size, and approximate volume; and thirdly, word numbers are processed in the left perisylvian areas Dehaene [29]. Dehaene and colleagues, during a period of 20 years, carried out extensive neuroscientific research to disentangle the effects of language-dominant or spatial iconic representation of numerical processing and whether there are specific brain regions innately dedicated to non-verbal numerical processing Dehaene [29], Dehaene [28], Pica et al., 2004; Agrillo [30], Lasne [25].

They claim that, innate numerical ability theory is evolutionary Dehaene [28] Pica et al., 2004, and studied systematically using different tasks to understand the conceptual processes of numerical approximation, estimation, and manipulation related to concrete examples, in non-numerically literate (Amazonian Munduruku tribe) and literate western cultures McCrink [31]. To support their theory, that numbers are language-independent representations, Dehaene and colleagues, focused on the dedicated biological brain networks, which are putatively responsible for basic number processing. Their multimethod research produced diverse but supporting evidence of evolutionary innate abilities in animals, infants and adult humans, independent of other abilities. Their neuroscientific research using a range of neuroscientific tools, fMRI, MEG, EEG, and brain legions, suggests that the inferior parietal region is implicated in number processing Dehaene [28]; King & Dehaene, 2014. This level of specificity of explanatory power is only possible with neuroimaging and multimethod approaches. The tripartite model by Dehaene [28] implicating the horizontal segment of IPS, the left AG related to the perisylvian areas, and the bilateral PPS, was further re-tested by Piazza [32], Cohen Kardes [33], using fMRI, fMRA and ERP tools. These multimethod findings have provided convergent validity evidence that the left IPS processes numerical quantities irrespective of format (Arabic, word, and mixed format), but the right IPS processes quantities of Arabic numerals only. Nieder, Jacob [34,35], tested numerical processing of magnitudes and Approximate Number Systems, with primates using single cell-neuron methods and found converging evidence that humans and animals can process numbers without words, but using approximate estimates, activating different populations of neurons bilaterally in the IPS and lateral PFC. Rosenberg-Lee [36], investigated the PPC in detail to identify the specific cytoarchitecture for four calculations (+, -, *, %), and found differences in processing these basic arithmetic tasks by the IPS, SPL and AG. Converging neuroimaging findings using different neuroimaging tools, augment the credibility of prior theoretical positons. Hyde [37], using fNIRS, found that 6 months old babies’ right parietal areas, are specialised for number processing, before language development and that this ability is lateralized with environmental experiences. Artemenko [38] in a longitudinal fNIRS study found that fronto-parietal network brain networks for arithmetic are well established for adolescents. Amalric [39] found that blind mathematicians process advanced mathematics in similar brain networks as sighted without the visual experience. These fine-grained differences of numerical developmental processing, time duration, age differentiation, format presentation (numerals, words), provide new information and new hypotheses, and models which are impossible to test without neuroimaging (Table 1).

Table 1: Comparative context of research methods relevant to number processing.

<table>
<thead>
<tr>
<th>Neuro-Psychological Research methods used for numerical processing</th>
<th>Validity of data for numerical ability testing</th>
<th>Reliability of data findings of numerical abilities.</th>
<th>Topographic accuracy (loci of brain/gene)</th>
<th>Temporal accuracy (of brain/gene function)</th>
<th>Overall assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qualitative research methods</td>
<td>1.2. Very Weak non replicable</td>
<td>1.2. Unreliable, non-replicable</td>
<td>1.2. Impossible to identify brain regions or genes responsible for outcomes</td>
<td>1.2. Impossible to measure brain activity related to outcomes</td>
<td>Useful to identify general phenotypic and behavioural traits. Tentative hypothesis development</td>
</tr>
<tr>
<td>1. Observations</td>
<td></td>
<td></td>
<td></td>
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<td>2. Focus groups and dept interviews</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Quantitative Research tools</td>
<td>1,2,3. Week Inferential correlational</td>
<td>1,2,3. Reasonable but correlational</td>
<td>1,2,3. Impossible NA</td>
<td>1,2,3. Impossible NA</td>
<td>Useful to test individual and group trait correlational differences</td>
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<td>1. Surveys</td>
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<td>2. Experiments</td>
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<tr>
<td>3. Behavioural tests</td>
<td></td>
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<tr>
<td>Neuroscience research tools</td>
<td>1. Medium</td>
<td>1. High</td>
<td>1. Low</td>
<td>1. High</td>
<td>1.2. Good for temporal activity, RT.</td>
</tr>
<tr>
<td>5. Highest</td>
<td>5. Highest</td>
<td></td>
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<tr>
<td>Genetic research tools</td>
<td>1. excellent</td>
<td>1. excellent</td>
<td>1.1. NA, but can predict long term effects</td>
<td>1.1. NA, but can predict long term effects</td>
<td>Excellent but pluripotency of single genes</td>
</tr>
<tr>
<td>1. GWS Molecular</td>
<td></td>
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</table>
Future Directions

The meta-analysis by Arsalidou [40], found that the core brain regions for numerical processing are indeed the parietal regions (IPS and precentral), the insula, claustrum, the frontal cortex (e.g., superior and medial frontal gyri), and cingulate. However, the developmentally changing networks and the function of typical and atypical brains regarding all interconnected areas (bilateral frontal (DLPFC, VLPFC), parietal (IPS, AG, SMG), occipito-temporal and medial temporal, including HC areas) are not well understood yet, according to Peters and De Smedt [41]. New ways of investigating brain network hubs using resting-state fMRI can fine-tune our understanding of numerical connectivity Van Den Heuvel [42].

Educational Implications

The impressive neuroscience discoveries so far have identified more brain areas and networks involved using multiparameter neuroimaging approaches to discover causal relationships (Amalrick et al., 2018). Glen [43] found that neuroplasticity and active epigenetic input of numerical exposure/talk, can improve and reverse some numerical deficiencies (Michels, et al., 2019). De Muoi, et al., (in press), eye tracking can help educationalists to identify appropriate individualised teaching methods to cope with time pressure. Dillon [44] suggest that developing relevant games to teach children numerical skills, and approximate number systems have positive and long-lasting improvements (Amalrick et al., 2018). Glen [43] found that neuroplasticity and active epigenetic input of numerical exposure/talk, can improve and reverse some numerical deficiencies (Michels, et al., 2019). De Muoi, et al., (in press), eye tracking can help educationalists to identify appropriate individualised teaching methods to cope with time pressure. Dillon [44] suggest that developing relevant games to teach children numerical skills, and approximate number systems have positive and long-lasting improvements (Amalrick et al., 2018). Glen [43] found that neuroplasticity and active epigenetic input of numerical exposure/talk, can improve and reverse some numerical deficiencies (Michels, et al., 2019). De Muoi, et al., (in press), eye tracking can help educationalists to identify appropriate individualised teaching methods to cope with time pressure. Dillon [44] suggest that developing relevant games to teach children numerical skills, and approximate number systems have positive and long-lasting improvements (Amalrick et al., 2018). Glen [43] found that neuroplasticity and active epigenetic input of numerical exposure/talk, can improve and reverse some numerical deficiencies (Michels, et al., 2019). De Muoi, et al., (in press), eye tracking can help educationalists to identify appropriate individualised teaching methods to cope with time pressure. Dillon [44] suggest that developing relevant games to teach children numerical skills, and approximate number systems have positive and long-lasting improvements (Amalrick et al., 2018). Glen [43] found that neuroplasticity and active epigenetic input of numerical exposure/talk, can improve and reverse some numerical deficiencies (Michels, et al., 2019). De Muoi, et al., (in press), eye tracking can help educationalists to identify appropriate individualised teaching methods to cope with time pressure. Dillon [44] suggest that developing relevant games to teach children numerical skills, and approximate number systems have positive and long-lasting improvements (Amalrick et al., 2018). Glen [43] found that neuroplasticity and active epigenetic input of numerical exposure/talk, can improve and reverse some neuronal connectivity Van Den Heuvel [42].

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