Neuropsychologia 111 (2018) 180–189

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

A rapid, objective and implicit measure of visual quantity discrimination

Mathieu Guillaume[a,*], Sandrine Mejias[b], Bruno Rossion[c,d], Milena Dzhelyova[a,c], Christine Schiltz[a]

[a] Cognitive Science and Assessment Institute (COSA), University of Luxembourg, Luxembourg
[b] Sciences Cognitives et Sciences Affectives (SCALab), Université Lille 2, France
[c] Institute of Research in Psychological Science, Institute of Neurosciences, Université Catholique de Louvain, Belgium
[d] Neurology Unit, Centre Hospitalier Universitaire (CHRU) de Nancy, France

ARTICLE INFO

Keywords:
Electroencephalography (EEG)
Steady State Evoked Potential
Numerical cognition
Number sense
Approximate Number System

ABSTRACT

There is evidence that accurate and rapid judgments of visual quantities form an essential component of human mathematical ability. However, explicit behavioural discrimination measures of visual quantities are readily contaminated both by variations in low-level physical parameters and higher order cognitive factors, while implicit measures often lack objectivity and sensitivity at the individual participant level. Here, with electrophysiological frequency tagging, we show discrimination differences between briefly presented visual quantities as low as a ratio of 1.4 (i.e., 14 vs. 10 elements). From this threshold, the neural discrimination response increases with parametrically increasing differences in ratio between visual quantities. Inter-individual variability in magnitude of the EEG response at this population threshold ratio predicts behavioural performance at an independent number comparison task. Overall, these findings indicate that visual quantities are perceptually discriminated automatically and rapidly (i.e., at a glance) within the occipital cortex. Given its high sensitivity, this paradigm could provide an implicit diagnostic neural marker of this process suitable for a wide range of fundamental and clinical applications.

1. Introduction

Typical human adults are thought to possess a *Number Sense*, an ability that allows them to represent and manipulate large numerical magnitudes (Dehaene, 1997). This numerical sense has been characterized as a cognitive system sensitive to scalar variability (Gallistel and Gelman, 2000; Platt and Johnson, 1971), the *Approximate Number System* (ANS). The ANS follows the Weber-Fechner law (Dehaene, 2003; but see Cantlon et al., 2009, for an alternative view), such that the value of the Weber fraction – the ratio between the amount just noticeably different from a magnitude and the magnitude itself (see Stevens, 1957; and Van Oeffelen and Vos, 1982) – is generally used to assess ANS acuity (Nieder and Miller, 2003; Piazza et al., 2004). Since the value of the Weber fraction predicts young adolescents' arithmetic performance throughout their scholarship (Halberda et al., 2008), there is considerable scientific interest on the relation between ANS acuity and more elaborated numerical and mathematical skills (see Hyde et al., 2016; but also Reynvoet and Sasanguie, 2016, for recent reviews).

Although a tight coupling between ANS acuity and mathematical ability has been reported in some studies (e.g., in children, Inglis et al., 2011; Mejias et al., 2012; in adults, DeWind and Brannon, 2012; Nys et al., 2013; see Chen and Li, 2014, for a meta-analysis), other studies failed to report such a relationship (e.g., Sasanguie et al., 2013; Price et al., 2012). This discrepancy has been attributed to ambiguities and difficulties in measuring ANS acuity (DeWind and Brannon, 2016; Gebuis et al., 2016; Norris and Castronovo, 2016; Szücs et al., 2013). Indeed, the evaluation of the ANS is affected by non-numerical factors (Guillaume et al., 2016; Leibovich et al., 2017; Smets et al., 2014, 2015, 2016), since there are inherent confounds between numerical magnitude and visual cues (such as the size of the elements or their total occupied area, see Gebuis and Reynvoet, 2012a, 2012b). This issue is particularly acute for non-symbolic comparison tasks when participants are explicitly instructed to judge two collections of elements. In these conditions, they are likely to make use of the available perceptual visual information to take their decision (Gebuis et al., 2016). Hence it is not surprising that inhibition and executive processes appear to have a large impact on numerical judgements (Cragg and Gilmore, 2014; Gilmore et al., 2013).

In light of these issues, implicit measures to assess ANS acuity have been developed, using functional magnetic resonance imaging (e.g., Ansari et al., 2006; Cantlon et al., 2006; Piazza et al., 2004) or event-related potentials with electroencephalography (EEG, e.g., Fornaciai et al., 2017; Gebuis and Reynvoet, 2013; Park et al., 2016). Here we used EEG recording coupled with a Fast Periodic Visual Stimulation

---

* Correspondence to: Université du Luxembourg, Maison des Sciences Humaines, 11, Porte des Sciences, L-4366 Esch-sur-Alzette, Luxembourg.
E-mail address: mathieu.guillaume@uni.lu (M. Guillaume).

https://doi.org/10.1016/j.neuropsychologia.2018.01.044
Received 6 July 2017; Received in revised form 30 January 2018; Accepted 31 January 2018

(FPVS) approach to provide a rapid (i.e., time-constrained), sensitive, objective and yet specific (i.e., minimizing biases) measure of the ANS. This approach is based on the relatively old observation that the human brain synchronizes its activity to the periodic state of a flickering stimulus (Adrian and Matthews, 1934), leading to so-called Steady-State Visual Evoked Potentials (SSVEPs, Regan, 1977). Given its advantages in terms of sensitivity (i.e., high Signal-to-Noise ratio, SNR) and objectivity (i.e., measure at an experimentally-defined frequency, see Regan, 1989; and see Norcia et al., 2015, for a review), it has recently been extended to complex visual stimuli, such as faces for instance, measuring sensitivity to changes of identity at specific periodic frequency rates (Rossion and Boremanse, 2011; Rossion, 2014).

To our knowledge, only two studies have applied a fast periodic visual stimulation approach in EEG in the domain of visual quantities. Libertus et al. (2011) reported brain responses driven by rapid (i.e., 12.5 Hz) periodic numerical changes, these changes increasing between two ratios of numerical magnitudes. Interestingly, brain responses showed qualitatively similar increases for infants and adults. However, since the authors did not systematically manipulate non-numerical visual cues, the extent to which their recorded responses were affected by fluctuations within the irrelevant dimensions remains unknown. Most recently, Park (2017) reported specific brain responses to numerosity changes in visual dot displays changing in size, position and spacing at a faster rate of 8 Hz. The author was able to record neuronal synchronisation, over the medial occipital cortex, to periodic numerical variations (1 Hz), distinct from fluctuations within other dimensions. This paradigm achieved disentangling number from low-level visual cues, but it did not allow the measurement of numerical discrimination thresholds. In the current study, we aimed at combining the contributions of both paradigms in controlling for visual cues and evaluating numerical discrimination threshold. Moreover, we optimized a number of methodological advantages of the FPVS-EEG approach (e.g., long time windows with high frequency resolution to increase SNR, baseline correction of EEG response, and quantification of the response through sums of harmonics; see e.g., Retter and Rossion, 2016) in order to obtain significant responses at the individual participant level, to relate to behavioural measures.

To achieve these goals, we used a specific version of the FPVS-EEG approach in which physically variable standard stimuli are presented at a fast periodic rate (e.g., at 10 Hz). Then, stimuli that deviate at the level of a high-level visual property are introduced in the sequence at a slower periodic rate (e.g., 1 out of 8 stimuli, at 1.25 Hz). Neural responses at the deviation rate in the EEG frequency domain emerge if and only if there is high-level visual discrimination of the deviant from the standard (e.g., face identities, Liu-Shuang et al., 2014; facial expressions, Dzhelyova et al., 2016; letters or words vs. pseudo-fonts, Lochy et al., 2015). This approach is highly sensitive to neural discrimination, and provides objective responses (i.e., at frequencies determined by the experimenter) without requiring explicit processing of the discrimination.

Here, in a FPVS-EEG design, we presented 45 s stimulation sequences to adult participants, during which the numerical ratio between a standard number and the deviant was parametrically manipulated. Crucially, participants were not involved in any numerical explicit decision, leading to a bias-free measure of ANS. Additionally, low-level visual cues such as luminance or density were varied at random at each stimulation cycle, such that quantity was the only parameter periodically manipulated (see Fig. 1). If this approach is sensitive to numerical processing, we expect EEG signal at the frequency of change of magnitude to increase when the ratio between the frequent and deviant stimuli increases. Besides, in a parametric design, EEG spectra should reveal the numerical threshold from which discrimination is successful (i.e., the smallest ratio in which a response to the deviant quantity was observed), and this EEG threshold can be directly compared to behavioural results obtained in explicit tasks (i.e., the Weber fraction).

2. Methods

2.1. Ethical considerations

We followed APA ethical standards to conduct the present study. The Ethic Review Panel from the University of Luxembourg approved the methodology and the implementation of the experiment before the start of data collection. The data reported in the present article were part of a larger EEG recording session that also evaluated language and symbol processing (which will be the focus of another manuscript) and that lasted 3 h in total. Participants received 30 euros for their participation.

2.2. Participants

Twenty-five participants were recruited among undergraduate students at the University of Luxembourg. We excluded participants with any neurological or neuropsychological disorder, or any uncorrected visual impairment. To ascertain that no participant suffered from dyscalculia, we evaluated their arithmetic ability with the use of the Tempo Test Rekenen (De Vos, 1992), which is a timed pen-and-paper test (five minutes) consisting in arithmetic problems of increasing difficulty. All participants reached the inclusion criterion, which was 100 correct items out of 200, and were included into in the present study. However, one participant was excluded due to poor instruction compliance during EEG acquisition (too many movement artefacts). In the end, the data of twenty-four adult participants was considered (sixteen females). Mean age was 26 years (ranging from 21 to 35).

2.3. Material and procedure

2.3.1. Experimental setup

Stimulus presentation and data collection were carried out with MATLAB (The MathWorks), using the Psychophysics Toolbox extensions (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997). The behavioural number comparison task and the EEG recording took place within a shielded room (in a Faraday cage, 2.88 m length, 2.29 m width, and 2.22 m height). The order of the tasks was counterbalanced across participants (13 participants started with the EEG measure, 11 with the behavioural paradigm). The latter were comfortably seated at a distance of 1 m from the display screen (a 24″ LED monitor, 100 Hz refresh rate, 1 ms response time).

2.3.2. Number comparison task

Participants were instructed to determine as accurately and as fast as possible the more numerous of two dot arrays simultaneously displayed on two sides of a screen. Stimuli consisted of a multitude of plain dark blue dots on a light blue background.[1] We created dot arrays following the methodology used by Piazza et al. (2004). For half of the stimuli, the surface (i.e., the total area occupied by the dots) was manipulated as a function of the numerical magnitude and other visual parameters were left to vary at random; for the other half, the mean dot size was controlled whereas other visual cues randomly varied. We generated collections in pairs, and constantly maintained one collection to ten dots, varying the number within the other one, from ten to twenty-four dots with an increment of two. This manipulation led to eight different numerical ratios. We created twenty-four pairs per ratio, and every participant had thus to judge 192 trials.

---

[1] The RGB colour codes for the dots and the background were 003-037-082 and 188-185-255, respectively. As their colour was plain, the stimuli luminance and the brightness contrast were confounded with accumulated dot surfaces. We chose this colour combination to reduce as much as possible the brightness contrast as the latter induces retinal after-effects (Hochberg and Triebel, 1955). The reduction of such after-effects was not specifically relevant for the numerical comparison task, but it was crucial for the Fast Periodic Visual Stimulation, during which dot arrays needed to be displayed for a very short period of time and without any following mask.