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Research Report

Preattentive and attentive responses to changes in small numerosities of tones in adult humans

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ABSTRACT

The brain hosts a primitive number sense to non-symbolically represent numerosities of objects or events. Small exact numerosities (~4 or less) can be individuated in parallel. In contrast, large numerosities (more than ~4) can only be approximated. However, whether small numerosities can be approximated without their parallel individuation remains unclear. Parallel individuation is suggested to be an attentive process and numerical approximation an automatic process. We, therefore, tested whether small numerosities can be represented preattentively. We recorded adult humans' event-related potentials (ERPs) and behavioral responses to 300-ms sequences of six tones (each of either 440 Hz or 660 Hz in frequency). Mostly, a sequence was of 3 tones of each frequency. Occasionally ($P=0.1$), the numerosities were 4 and 2 (minor changes) or 5 and 1 (major changes). Mismatch negativity (MMN), but no later attention-related positive-polarity ERPs, was observed to the major but not to the minor changes during a visual non-numerical task. In a following attentive task, behavioral responses even to major changes resulted in a very low hit rates (0.11 for major and 0.023 for minor changes) and yet an above-zero false-alarm rate (0.052). The findings support a view that small numerosities of objects can be automatically approximated independently of their attentive individuation.

1. Introduction

Humans can creatively use abstract numerical symbols (such as number words) to mentally operate with numbers of objects or events (Dehaene, 2004). These advanced mathematical skills partly rely on a non-symbolic number sense already present in infants and animals (for a review, see, Feigenson et al. (2004). There are two core mechanisms identified to underlie the number sense, parallel individuation and numerical approximation (for a review, see, Feigenson et al. (2004)).

Parallel individuation accurately represents small numerosities (up to about 4) of objects by tracking them on a one-by-one basis (Jevons, 1871; Kaufman et al., 1949; Pylyshyn and Storm, 1988; Ansari et al., 2007; Ester et al., 2012). It has been

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found to depend on attentional resources (Burr et al., 2010; Railo et al., 2008), and, with sequential tones, to operate with a relative small capacity, a possible maximum of 2 (Camos and Tillmann, 2008; Repp, 2007). In contrast, large numerosities (above about 4) of visual objects or sequential sounds recruit an automatic mechanism for numerical approximation (Meck and Church, 1983; Dehaene and Changeux, 1993; Dehaene and Akhavein, 1995; Barth et al., 2003).

Numerical approximation is thought to come into play with small numerosities of objects if attentional resources are insufficient for the parallel individuation of the objects (Burr et al., 2010; Hyde, 2011). However, a possibility has also been raised that the approximation of small numerosities of objects may follow the attentive individuation of the objects (Cordes and Brannon, 2009), again, implying cognitive distinctiveness between small- and large-numerosity ranges.

To test whether automatic numerical approximation of objects is possible without their attentive individuation, the subject's attention to the objects must be carefully controlled for.

The subjects' mere passive exposure to the objects may not be enough for this purpose given that the adult brain's event-related-potential (ERP) markers for small absolute (N1 component) and large approximate (P2p component) numerosities of visual objects have both been observed to be present even if the objects are being merely passively viewed (Hyde and Spelke, 2009, 2012).

Therefore, instructing the subject to voluntarily engage him- or herself in a task of another modality than the objects is not enough to control for attention effects on numerical quantification of objects. Control should also be exerted for involuntary attention that the objects, even in specific numerosities (Hannula and Lehtinen, 2005), may attract.

The mismatch negativity (MMN, (Näätänen et al., 1978)) of ERPs is an index of preattentive processing of changes in repetitive aspects of the auditory environment (however, for attentional MMN modulation, see, Woldorff et al. (1991), Alain and Woods (1997) and Sussman (2007)). MMN in adult humans engaged in a visual task (van Zuijen et al., 2005; Ruusuvirta et al., 2007, 2008) and its positive-polarity correlate in sleeping infants (Ruusuvirta et al., 2009) have been observed in response to changes in a constant ratio between two small numerosities of tones of different frequencies across their serially presented sequences. These findings tentatively suggest that small numerosities are also represented preattentively. However, the attentive detectability of these changes (van Zuijen et al., 2005; Ruusuvirta et al., 2007, 2008) and, thus, possible involvement of involuntary attention in their processing, has remained unclear (Fig. 1).

To this end, the present study aimed at exploring adult humans' not only preattentive (as reflected by MMN), but also attentive (behavioral) ability to detect changes in a constant ratio (from 3:3 to 4:2 and from 3:3 to 5:1) between small numerosities of tones of different frequencies across their serially presented brief sequences. It was reasoned that if an automatic approximation in the small numerosity range was indeed independent of an attentive individuation of the tones, adult humans engaged in a visual task should show preattention-related ERPs (MMN). Furthermore, MMN was expected to be observed even if the changes were not attentively detectable in a subsequent behavioral task (see also, Paavilainen et al. (2007)).

2. Results

2.1. *Electrophysiological results from the ignore condition*

Fig. 2 shows ERPs to 5:1 deviants and to immediately preceding 3:3 standards (Fig. 2a), and to 4:2 deviants and to immediately preceding 3:3 standards (Fig. 2b).

5:1 deviants displaced ERPs towards negative polarity relative to 3:3 standards, as indicated by a main effect of stimulus type (deviant, standard), $F_{1,14}=4.71$, $P=0.047$, $\eta p2=0.252$ (Fig. 2c). This effect did not significantly interact with other main effects, including a stimulus type × anterior–posterior (frontal, central, parietal) interaction, $F_{2,28}=1.92$, $P=0.184$, $\eta p2=0.120$, stimulus type × laterality (left, midline, right) interaction, $F_{2,28}=2.91$, $P=0.078$, $\eta p2=0.172$, and the three way interaction, $F_{4,56}=1.02$, $P=0.396$, $\eta p2=0.068$.

ERPs could not be found to differ in amplitude between 4:2 deviants and immediately preceding 3:3 standards (Fig. 2b). There was no significant main effect of stimulus type, $F_{1,14}=0.042$, $P=0.840$, $\eta p2=0.003$, a stimulus type × anterior–posterior (frontal, central, parietal) interaction, $F_{2,28}=1.89$, $P=0.188$, $\eta p2=0.119$, stimulus type × laterality (left, midline, right) interaction, $F_{2,28}=0.39$, $P=0.595$, $\eta p2=0.027$. For the three-way interaction, only a trend, $F_{4,56}=2.85$, $P=0.057$, $\eta p2=0.169$, was observed (Fig. 2d).

2.2. *Behavioral results from the attentive condition*

The hit rates for both the 5:1 and the 4:2 deviants were very low (0.11 and 0.023, respectively), the false alarm rate being

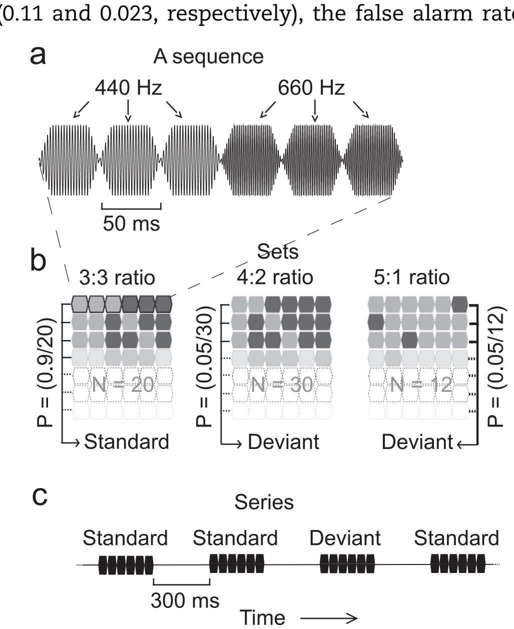

Fig. 1 – Auditory stimuli used. (a) The waveform of a sequence comprising three tones of each frequency (440 Hz and 660 Hz) forming the ratio of 3:3 between the tones. (b) Three sets of sequences for their corresponding ratios (3:3, 4:2, 5:1). Dark gray marks 660 Hz and light gray 440 Hz frequency. The number of sequences in a set is marked in gray on the set. Each of the sequences in a set had the same probability to be assigned to the series. (c) A schematic illustration of the resulting series of sequences.