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Running head: PREATTENTIVE SMALL-NUMEROSITY REPRESENTATIONS

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.

Keywords: Auditory; event-related potential; human; mismatch negativity; numerosity; oddball condition.

1. Introduction

Humans can creatively use abstract numerical symbols (such as number words) to mentally operate with numbers of objects or events [1]. These advanced mathematical skills partly rely on a non-symbolic number sense already present in infants and animals (for a review, see, [2]). There are two core mechanisms identified to underlie the number sense, parallel individuation and numerical approximation (for a review, see, [2]).

Parallel individuation accurately represents small numerosities (up to about 4) of objects by tracking them on a one-by-one basis [3-7]. It has been found to depend on attentional resources [8,9], and, with sequential tones, to operate with a relative small capacity, a possible maximum of 2 [10,11]. In contrast, large numerosities (above about 4) of visual objects or sequential sounds recruit an automatic mechanism for numerical approximation [12-15].

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 [8,16]. However, a possibility has also been raised that the approximation of small numerosities of objects may follow the attentive individuation of the objects [17], 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 [18,19].

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 [20], may attract.

The mismatch negativity (MMN, [21]) of ERPs is an index of preattentive processing of changes in repetitive aspects of the auditory environment (however, for attentional MMN modulation, see, [22-24]). MMN in adult humans engaged in a visual task [25-27] and its positive-polarity correlate in sleeping infants [28] 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 [25-27] and, thus, possible involvement of involuntary attention in their processing, has remained unclear.

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, [29]).

2. Results

2.1.1. Electrophysiological results from the ignore condition

Figure 2 shows ERPs to 5:1 deviants and to immediately preceding 3:3 standards (Figure 2a), and to 4:2 deviants and to immediately preceding 3:3 standards (Figure 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), $F_{1,14} = 4.71$, $P = 0.047$, $\eta^2 = .252$ (Fig. 2c). This effect did not significantly interact with other main effects, including a stimulus type \times anterior-posterior (frontal, central, parietal) interaction, $F_{2,28} = 1.92$, $P = 0.184$, $\eta^2 = .120$, stimulus type \times laterality (left, midline, right) interaction, $F_{2,28} = 2.91$, $P = 0.078$, $\eta^2 = .172$, and the three way interaction, $F_{4,56} = 1.02$, $P = 0.396$, $\eta^2 = .068$.

ERPs could not be found to differ in amplitude between 4:2 deviants and immediately preceding 3:3 standards (Figure 2b). There was no significant main effect of stimulus type, $F_{1,14} = 0.042$, $P = 0.840$, $\eta^2 = .003$, a stimulus type \times anterior-posterior (frontal, central, parietal) interaction, $F_{2,28} = 1.89$, $P = 0.188$, $\eta^2 = .119$, stimulus type \times laterality (left, midline, right) interaction, $F_{2,28} = 0.39$, $P = 0.595$, $\eta^2 = .027$. For the three-way interaction, only a trend, $F_{4,56} = 2.85$, $P = 0.057$, $\eta^2 = .169$, was observed (Figure 2d).

-----Insert Figure 2 about here -----

2.1.2. 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 0.052 (Figure 3a). D' -values calculated for each participant were higher for 5:1 than for 4:2 deviants, $t_9 = 2.84$, $P = 0.020$, Cohen's $d = 1.35$ (Figure 3b). One-sample t-test further indicated that these values differed from zero for 5:1 deviants, $t_9 = 3.22$, $P = 0.010$, but not for 4:2 deviants, $t_9 = 0.93$, $P = 0.376$.

-----Insert Figure 3 about here -----

3. Discussion

Differential ERPs of negative polarity, with no following involuntary-attention-related ERPs of positive polarity, were found to 5:1 deviants but not to 4:2 deviants relative to 3:3 standards in adult humans engaged in a visual task. Furthermore, only 10.8 % of 5:1 deviants were detectable at an attentive level while as much as 5.1 % of 3:3 standards were erroneously detected as deviant sequences.

3.1. *ERPs in the ignore condition*

Differential ERPs to 5:1 deviants bore a close resemblance to MMN [21], an index of preattentive auditory change detection [32]. They were of negative polarity within 250 ms post-change and obtained to task-irrelevant auditory events during a visual task. Consistent with this, as Figure 2 illustrates, differential ERPs to 5:1 deviants were not followed by P3a- or P3b-like deflections as indices of involuntary or voluntary attention switches, respectively, triggered by these deviants [33].

Deviant sequences differed from standard sequences only the ratio between two numerosities of tones of different frequencies, the total number of the tones being

constant. The numerosities underlying differential ERPs to 5:1 deviants could, thus, not be of general auditory activations (with no reference to sound frequencies) but of frequency-specific tones. The use of ratio instead of absolute numerosity as the deviant attribute also allowed us to control for various non-numerical temporal factors (tone, inter-tone or sequence durations), each capable of MMN generation (for a review, see, [32]). The random ordering of the tones across their sequences, in turn, prevented melodic tone patterns [30] and intervals between the first and the last tone of each frequency in a sequence (for auditory stream integration, see, [34]) from producing similar confounding. Even the numerosity of the melodic steps from one tone of one frequency to the next tone of the other frequency in a sequence was not likely to account for our finding. This is because these steps not only varied within, but also partially overlapped in numerosity across the sequence types as opposed to the numerosities of the tones that were perfectly constant within and fully distinguished between the sequence types.

Differential ERPs to 5:1 deviants could, thus, be connected to the ratio between the two numerosities of the tones (for a cortical ratio correlate for visual objects, see, [35]) or the numerosities themselves. Obviously, they could also be linked to one of the two numerosities in a sequence at a time as the change in one numerosity might have been detectable differently from the other numerosity. For example, the change from 3 to 1 tone (of one frequency) was relatively greater than the change from 3 to 5 tones (of the other frequency) [1,36] and, thereby, potentially easier to detect. Other processes specific to the serial order between the two numerosities [37] might also have asymmetrically modulated the responses to the distance between the numerosities. Note also that 5:1 deviants numerically violated 3:3 standards before the last tone of a sequence. Namely, the number of three identical tones was exceeded by

one already at the 4th tone of a sequence in two out of six 5:1-deviant variants and at the 5th tone of a sequence in the remaining four of these variants. In fact, if also the accumulation trajectories of the numerosities had been included in the neural representation of the numerosities, MMN could have been elicited by a part of 5:1 deviant variants even prior to the 4th tone of a sequence. Namely, whereas only 4 out of the 40 variants of 3:3 standards (and only 6 out of the 30 variants of 4:2 deviants) begun with three identical tones, as many as 6 out of the 12 variants of 5:1 deviants had these early triplets. The early triplets were, thus, not only serially rare but also characteristic to 5:1 deviants in particular. Indeed, as if there were very early signs of differential ERPs to 5:1 deviants in some (especially F4) channels when visually inspecting the grand averaged waveforms (Figure 2).

Differential ERPs to 5:1 but not 4:2 deviants suggest that the smallest neurophysiologically detectable numerosity change might have fallen somewhere between 3 vs. 1 and 3 vs. 2 tones (given that the changes in the tones of the other frequency from 3 to 5 or 3 to 4 were of a smaller relative magnitude). This was unexpected in the light of considerably higher numerical discrimination accuracies (e.g., between 7 and 6) previously observed with parallel sets of visual objects [38, 39].

The low attentive detectability of 5:1 deviants could have been due to the interference that the deviance irrelevant melodic variation of the sequences produced to numerosity registration or change detection (for interference of change detection by deviant-irrelevant physical sound features, see, [40]). The fast pace of the tones in a sequence could also have degraded the registration of the sequential positions of individual tones in a sequence [41].

The order of the tones in a sequence randomly varied across the sequences, which resulted in a smaller latency jitter of ERPs [42,43] to 5:1 than 4:2 due to the different proportions of the tones of different frequencies in a sequence. However, this difference could hardly explain differential ERPs to 5:1 but not 4:2 deviants. In 5:1 deviants, the first tone to exceed the standard numerosity (3) was always the 4th or 5th tone of a sequence. In 4:2 deviants, this tone was mostly (in 93.3% of their variants) the 5th or 6th sixth tone of a sequence (again, resulting in a one-tone jitter). Only in 6.7% of the variants of 4:2 deviants, the 4th tone of a sequence exceeded the standard numerosity. Such rare “two-tone-jittered” variants of 4:2 deviants could hardly abolish grand-averaged differential ERPs averaged across all variants of these deviants (Figure 2). Neither is the distance between the first and the last tone of each frequency of a sequence [34] likely to explain our findings. This is because they varied within, and partially overlapped between, the sequence types while the numerosities of the tones were fully invariant within, and fully distinguished between, the three sequence types applied.

Nevertheless, our findings could eventually be accounted for by some, yet unknown auditory attribute across the tones merely as a correlate of their numerosities (e.g., the temporal density of tones). Numerosity representations should not be tied to a specific stimulus modality. Future ERP studies should, therefore, be conducted with non-auditory, or multimodal, stimuli to explore the extent to which findings like ours could, indeed, be connected to numerosities as modality-independent perceptual abstractions.

3.2. *Behavioral responses in the attend condition*

In the attend condition, the participants' behavioral responses showed very low hit rates for both the 5:1 deviants (0.108) and the 4:2 deviants (0.027). Their low, yet

existing, false alarm rate (0.051) resulted in a low albeit above-zero d' -prime value (0.362) for 5:1 deviants. These findings conform to previous MMN studies using other types of higher-order auditory changes with behavioral hit and false alarm rates comparable to those in the present study [29,44].

MMN has been suggested to be an all-or-none phenomenon on a single-epoch level [45]. That is, it is either generated, or not, by individual deviant stimuli. Let us then presume that the percentage of correct behavioral responses to deviant sequences (hits) in the attend condition could, on this basis, be used to approximate the percentage of discrete MMNs to the same sequences in the ignore condition. Let us also presume that the percentage of erroneous behavioral responses to standard sequences (false alarms) in the attend condition can be used to approximate the percentage of discrete MMNs to these sequences in the ignore condition. If MMN had been triggered correctly by only 10.8% of 5:1 deviants and erroneously by 5.1% of 3:3 standards, MMN could hardly have been observable in the averaged waveforms [45]. And yet differential ERPs to 5:1 deviants were observed in the ignore condition during which the participants' voluntary attention was directed away from these stimuli to a visual task. It thus appears that there is a reasonable basis to dissociate these ERPs from their dependence on attentive processing stages.

In all, the behavioral findings suggest that differential ERPs to 5:1 deviants were unlikely to reflect voluntary or involuntary attention switches towards these deviants but rather their genuine preattentive detection as reflected by MMN [32].

3.3. *Conclusion*

Differential negative-polarity ERPs at 150-200 ms post-stimulus (MMN) were found in adult humans in response to task-irrelevant changes of sufficient numerical magnitudes in sequential tones of specific frequencies. These ERPs were not followed

by attention-related positive-polarity ERPs. Furthermore, subsequently measured attentive behavioral responses to the changes showed a very low hit rate (0.108) and yet an existing false alarm rate (0.051). The negative-polarity ERPs to the changes, therefore, most likely reflected the preattentive detection of the changes. The findings conform to the view that automatic numerosity approximation mechanism is not dependent on attentive individuation mechanism when being recruited by small numerosities of perceptually specific objects.

4. Experimental Procedure

4.1. Participants

Participants were 15 (10 female) adults (age range from 19 to 26 years, five left-handed) with no diagnosed neurological or hearing problems. Informed consent was obtained from the participants after the nature of the experiment was explained to them.

4.2. Materials

Figure 1 illustrates the auditory stimuli used. They were delivered via closed-type earphones. The stimuli comprised of six consecutive 50-ms tones (including 10-ms onset-offset ramps in each) of about 80 dB (SPL) (Brül & Kjær Type 2235). The sequences of a total of 6 tones were construed and serialized online (Presentation, 14.7., Neurobehavioral Systems, Albany, CA, USA). The sequences of 300 ms in duration were presented at 600-ms onset-to-onset intervals. Each tone in a sequence was either 440- or 660-Hz in frequency.

Most of the sequences were of three tones of each frequency ('3:3 standards', $P = 0.9$). In the remaining minority of the sequences, this ratio was either 4:2 ('4:2 deviants', $P = 0.05$) or 5:1 ('5:1 deviants', $P = 0.05$).

The order of the tones in a sequence was pseudorandom to control for confounding by melodic patterns [30], resulting in a total of 20 variants of 3:3 standards, 30 variants of 4:2 deviants, and 12 variants for 5:1 deviants (Figure 1b).

Each of the variants within a sequence type had the same probability of occurrence that equaled to the number of the variants divided by the probability of the sequence type to which they belonged. The order of the sequences in their series was pseudorandom with an exception of there being at least two standards separating consecutive deviants (Figure 1c).

----- Insert Figure 1 about here -----

4.3. Procedure

The participants sat in a comfortable chair in a sound-attenuated chamber. In the first block of 2000 sequences (ignore condition), they were instructed to concentrate on a silent subtitled movie on a computer screen in front (at a ~1.5 m distance) and to ignore any auditory stimuli they may hear. In the second, shorter (1000 sequences) block of the same sequences (attend condition), the participants were instructed to promptly press the left mouse button with their dominant hand in response to any type of changes they may perceive in the series (attend condition). In the beginning of the attend condition, the participants were informed about the 10% probability of occurrence of such changes albeit nothing about the nature of the changes.

4.3.1. Data Acquisition

The electroencephalogram (EEG) was recorded (NeuroScan software, NeuroScan Co., USA) with Ag-AgCl electrodes positioned at F3, Fz, F4, C3, Cz, C4, P3, Pz, P4 scalp sites according to the 10-20 system. The signal was amplified (SynAmp

amplifiers, NeuroScan Inc., Herndon, Va., USA), filtered online with a band pass of 0.05-70 Hz and sampled at a 1000-Hz sampling rate. Eye-related activity was monitored with electrodes positioned at the outer canthi of the left and the right eye, and above and below the right eye. The electrode at the tip of the nose served as the reference electrode. The signal was filtered offline (Infinite impulse response, IIR filter) with a band-pass of 0.1-45 Hz (24 dB per octave roll offs).

4.3.2. *Data Analysis*

4.3.2.1. *Electrophysiological data*

ERPs were only analyzed for the ignore condition. Brain Vision Analyzer 2.0 software (Brain Products, GmbH, Munich, Germany) was used in the analysis. Epochs (650 ms duration, including 50-ms pre-sequence time) for deviants and standards which immediately preceded the deviants were extracted from EEG and corrected against the baseline that referred to the average amplitude of EEG activity between 0 and 100 ms from sequence onset.

Epochs exceeding $\pm 150 \mu\text{V}$ in amplitude were discarded from further analyses. No less than 42 epochs were available for averaging in each participant. The accepted epochs were averaged for each subject, stimulus type (deviants and immediately preceding standards), and electrode.

Subsequently, mean amplitudes were extracted from the time window of 150-200 ms from the onset of the fourth tone of a sequence for 4:2 deviants, 5:1 deviants, and 3:3 standards immediately preceding each of these deviant types. This onset was chosen because there could be three identical tones in 3:3 standards. The extractions were performed for each stimulus type and each electrode.

The resultant values were analyzed with a repeated measures analysis of variance (ANOVA) with stimulus type (standard vs. deviant), laterality (left, midline,

vs. right), and anterior-posterior (frontal, central, vs. parietal) as factors. An alpha level of .05 was used in all analyses. Greenhouse–Geisser-adjusted degrees of freedom were used whenever the sphericity assumption (Mauchly’s test of sphericity) was violated. P-values were reported accordingly. All the tests were two tailed and performed using SPSS for Windows v16.0.1 software (SPSS Inc., Chicago, IL, USA). Partial eta squared (η^2) was used as a measure of effect size in ANOVAs and Cohen’s *d* and effect size correlation in paired t tests.

4.3.2.2. *Behavioral data*

Button presses the participants made in response to deviants were recorded in the attend condition. A button press was classified as a hit if occurring no later than 1.2 s from deviant onset. The time window included one standard immediately following each deviant in the series.

The hit rate was obtained by dividing the number of hits by the number of deviants. Outside the time window of 200-1200 s from deviant onset, a button press was classified as a false alarm. The false alarm rate was obtained by dividing the number of false alarms by the adjusted number of standards. The latter number was obtained by subtracting the total number of standards by the number of standards immediately following deviants (responses to these standards were defined as hits) and dividing the resulting number by two (to mimic the 1.2-s time window, which covers two sequences, used to define responses to deviants as hits).

The stimulus series in the attend condition comprised 1000 stimuli at maximum. Note that the behavioral data of only the first 10 participants were available for analysis due to the loss of these data of the last five participants as a result of a technical error in data acquisition. Also, due to technical problems in data acquisition, in two of the participants, the number of stimuli was lower (319 and 218 stimuli). The

data from these participants were, nevertheless, included in the analyses as the problem was not specific to sequence type. D-values [31] were calculated from hit and false alarm rates.

For the participants showing hit or false-alarm rates of 0 (one with a 0 false-alarm rate, five with a 0 hit rate for 4:2 deviants, and two with a 0 hit rate for 5:1 deviants), d' -values of zero, were applied. This was because corrections by using the formula $1 / (N \times 2)$ would, due to much lower Ns for deviants than for standards, have unjustifiably exaggerated the d' -values. Paired t-tests applied to analyze the behavioral data were two-tailed.

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Figure Captions

Figure 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 grey marks 660 Hz and light grey 440 Hz frequency. The number of sequences in a set is marked in grey 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.

Figure 2. Electrophysiological results. Grand-averaged ERPs at each scalp location (a) for 5:1 deviants and immediately preceding 3:3 standards, and (b) for 4:2 deviants and immediately preceding 3:3 standards. The time window used to calculate mean ERP amplitudes are illustrated by a dashed-line rectangle placed above the waveforms. A sequence of tones is illustrated below each x axis. Parts (c) and (d) illustrate mean amplitudes and their standard errors for 5:1 deviants and 3:3 standards immediately preceding them, and for 4:2 deviants and 3:3 standards immediately preceding them, respectively.

Figure 3. Behavioral results. (a) The means and their standard errors for the hit rates for 5:1 and 4:2 deviants and for the false alarm rate. (b) The means and their standard errors for d' -values calculated for 5:1 and 4:2 deviants.

Figure 1

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