



The neural mechanisms underlying passive and active processing of numerosity

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ABSTRACT

To investigate the difference in passive viewing and active processing of numerosity, we presented participants arrays of dots and concurrently measured their EEG. In the first condition, participants naïve to the subject under study passively viewed the dot-arrays. In the second condition, the participants were informed about the changes in numerosity and had to actively process numerosity. The visual properties of the dot-arrays were controlled and could therefore not explain possible numerosity related effects. The results revealed no numerosity related effects in the passive and active conditions. Instead, when the data was reorganised according to visual cue size (surface or diameter, etc.), strong effects of the visual cues were present at lateral occipital and parietal electrode sites. These electrode sites and time windows correspond to the ERP components often suggested to support numerosity processes. Furthermore, a larger central-parietal P3 amplitude effect was present for active versus passive numerosity processing. This result was not influenced by numerosity itself and could not be explained by response processing. It therefore appears to reflect general cognitive processes. Together, our results show that we do not (automatically) extract numerosity from a visual scene during passive or active processing of numerosity. Instead, these results are consistent with the notion that we rely on the continuous sensory properties of numerosity stimuli to make numerosity judgements.

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Introduction

The mainstream theory suggests that we rely on the approximate number system to judge which of two sets of items is more numerous or to estimate the number of items in a set (Dehaene, 1997). To date, many studies investigated the acuity of this approximate number system and tried to unravel its developmental pattern and neural mechanisms (Gebuis and Van der Smagt, 2011; Halberda and Feigenson, 2008; Piazza et al., 2004). Studies revealed significant relations between the acuity of the approximate number system and (future) mathematical abilities suggesting a prominent role for the approximate number system in mathematical development (Halberda et al., 2008; Mazzocco et al., 2011; Piazza et al., 2010). However, little is known about the initial stages of numerosity processing: the transition from a visual scene into number related activation. This is surprising as the translation from a visual image into the neural code for number might contain the key factor that determines our number sense acuity and thus (future) mathematical proficiency.

The role of the visual properties (e.g. surface and density) in number processing is a delicate issue in the field of numerical cognition because the visual cues of number stimuli are confounded with numerosity: when numerosity increases, its visual properties also

increase. Researchers who study the later stages of numerosity processing consider this confound problematic and put a great deal of effort in creating complex designs to account for it (e.g. Ansari and Dhital, 2006; Cantlon et al., 2006; Lyons et al., 2012; Piazza et al., 2004; Xu and Spelke, 2000). They manipulate the continuous sensory properties in such a manner that participants cannot base their judgement on a single visual property. Irrespective of these manipulations, participants can still judge numerosity above chance level if the difference in number is large enough. It is therefore often concluded that the approximate number system extracts number from the visual scene independent of its visual properties.

Importantly, the different methods to control the visual cues do not account for the possibility that we integrate information from multiple visual cues that are present in a single non-symbolic number stimulus. Researchers, investigating the influence of visual properties on number processing, show that number judgements are influenced by different visual variables (e.g. surface, diameter, and density) (Allik and Tuulmets, 1991; Dakin et al., 2012; Gebuis and Gevers, 2011; Gebuis and Reynvoet, 2011; Gebuis and Van der Smagt, 2011; Ginsburg, 1991; Ginsburg and Nicholls, 1988; Sophian and Chu, 2008; van Oeffelen and Vos, 1982). It could therefore be that we do not attend a single visual parameter but integrate the information from multiple visual parameters. In a recent study, we confirmed this idea by showing that the influence of the visual cues on numerosity judgement increases when more visual information is provided to the participant (i.e. manipulation of multiple versus a

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single sensory property) (Gebuis and Reynvoet, 2011; see for a similar reasoning: Allik and Tuulmets, 1991).

Different EEG studies suggest that the N1 and P2 components reflect numerosity related processes. Increases or decreases in peak amplitude at the lateral occipital electrode sites for these components were shown when participants had to actively compare (Libertus et al., 2007; Temple and Posner, 1998) or passively view non-symbolic number stimuli (Hyde and Spelke, 2009). However, when taking a closer look at the data, influences of sensory cues cannot be overruled. For instance, Temple and Posner (1998) found opposite effects of the P2 amplitude for non-symbolic and symbolic number comparison. Libertus et al. (2007) showed that this opposite P2 amplitude effect could be explained by the visual properties of the stimuli. Libertus et al. (2007) changed the visual properties of the stimuli and showed a reversed P2 amplitude effect for non-symbolic number (and their initial N1 amplitude effect disappeared). Similarly, Hyde and Spelke (2009) conducted two experiments. The only difference between both experiments was the method used to control the visual cues. In the first experiment they found an N1 effect for large numbers but not in the second experiment. Thus, influences of the visual properties of the stimuli are noticeable both at the N1 and the P2 component.

The possibility that continuous variables explain the numerosity effects is not that surprising if you look at previous neuroimaging studies investigating abstract number processing. These studies show that areas affected by numerosity are also active for the continuous visual properties that comprise the non-symbolic number stimuli (Cohen Kadosh et al., 2005; Pinel et al., 2004). Similarly, monkey neurophysiology data shows that neurons responsive to numerosity are also responsive to line length (Tudusciuc and Nieder, 2007, 2009). From these results it is even concluded that these different continuous visual and numerosity processes are supported by a single neural mechanism (for a review see: Cohen Kadosh et al., 2008). In a recent EEG study, we therefore questioned whether these neural responses to numerosities reflect responses to the parts (continuous visual properties) and not the whole (numerosity) (Gebuis and Reynvoet, 2012a). In the first experiment, we manipulated the continuous visual variables that comprise the dot arrays (diameter, surface and convex hull). The results showed that the neural responses underlying the different visual properties are similar to the ERP responses suggested to reflect numerosity processes. The N1 and P2 amplitudes increased or decreased with increasing visual cue size. In the second experiment, we carefully controlled the continuous visual variables: the visual cues were not linearly correlated with numerosity. Consequently, an increase in peak amplitude for numerosity could not result from an increase in continuous visual variables. In this case, the data did not reveal numerosity related effects at any electrode site. Together, the results suggest that previous numerosity related ERP effects were caused by improperly controlled visual cues (for a similar reasoning see Libertus et al., 2007) and we most likely rely on these continuous visual variables to judge numerosity.

Although, the theory of the approximate number system postulates that numerosity is automatically extracted from a visual scene, some researchers suggest that we might prefer to attend to the more prominent sensory properties than numerosity (e.g. Clearfield and Mix, 2001; Hurewitz et al., 2006). This notion could explain the absence of numerosity related results in our previous passive viewing experiment. In the current study, we therefore wanted to directly compare active and passive processing of numerosity. If explicit processing of numerosity is necessary to evoke number related ERP responses, the N1 and P2 components at lateral occipital electrode sites should increase or decrease in amplitude with numerosity in the active and not in the passive viewing task. However, if we do not process numerosity independent of the visual cues but instead rely on these visual variables to judge numerosity, active processing

of numerosity will not evoke numerosity related effects either. Instead, when the data is analysed according to visual cue size, increasing or decreasing amplitudes of the N1 and P2 components should be visible with increasing visual cue size.

Methods

Participants

Eighteen participants participated in the study. Of these, seventeen (10 females) were included in the analyses ($M = 19$ years, $SD = 2.1$). One participant was excluded because more than 25% of the EEG data contained artefacts. All participants were native Dutch speakers and had normal or corrected-to-normal vision. Written informed consent was obtained according to the Declaration of Helsinki.

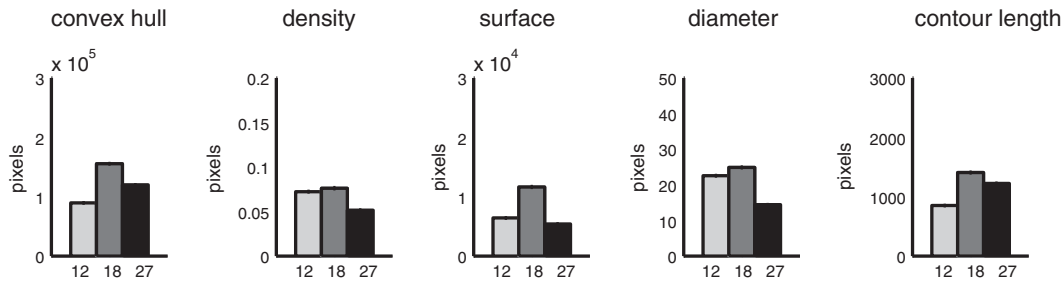
Apparatus, stimuli and procedure

The stimuli were displayed on a 23-inch CRT monitor using Matlab 7.5. The viewing distance was approximately 57 cm. Participants were presented with arrays of grey and occasionally red dots on a black background. These non-symbolic number stimuli were generated using an adapted version of the programme created by Gebuis and Reynvoet (2011). Using this programme we controlled for the different visual cues that are confounded with number (convex hull, diameter, aggregate surface, density and contour length). Each visual cue did not linearly increase or decrease with number (for a similar approach see: Gebuis and Reynvoet, 2012a). The arrays consisted of three target numbers that differed with a 2:3 ratio (12, 18, and 27 dots) and filler trials (10, 14, 16, 21, 25 and 29 dots). The filler trials were included to prevent participants from noticing that we were only investigating responses to three different numbers. The visual cues were controlled in two different ways: (1) number and the different visual cues did not correlate across all trials (all R^2 values < 0.1) and (2) the average of each visual cue did not significantly increase or decrease with increasing number (see Fig. 1).

The experiment consisted of two conditions, an active condition and a passive viewing condition. The stimuli for both conditions were created in exactly the same manner. The two viewing conditions were presented in separate blocks. All participants were naive to the subject under study and started with the passive viewing condition. To keep the participants' attention directed towards the screen we included trials with red instead of grey dots (hereafter referred to as "attention trials"). Participants had to press the space bar when they noticed the change in colour. After the passive viewing condition was completed we asked the participants whether they had an idea what the experiment was about. All participants included in the experiment reported to be unaware of the numerosity manipulation. For the second experiment, the participants were told that numerosity would constantly change and instructed to actively attend numerosity. During the active viewing condition, a question mark appeared occasionally (hereafter referred to as "attention trials"). Now the participants had to enter the number of dots that they estimated in the last trial using the numbers on the keyboard. This task ensured that the participants were constantly monitoring numerosity.

Both conditions consisted of 288 trials of which 192 were target trials (64 per number) and 96 were filler trials (16 per number). There was a 20% chance that a filler trial was presented in red (passive condition) or followed by a question mark (active condition). The filler and thus also the attention trials were not included in the analyses. All trials were presented in fully randomised order. The dot arrays were presented for 300 ms and the inter-stimulus interval varied between 1250 and 1500 ms. For the filler trials of the active condition, the question mark appeared 1000 ms after stimulus presentation and remained on the screen until the participant responded, next the inter-stimulus-interval of 1250–1500 ms started.

PASSIVE VIEWING: size of each visual cue present in the number stimuli



ACTIVE VIEWING: size of each visual cue present in the number stimuli

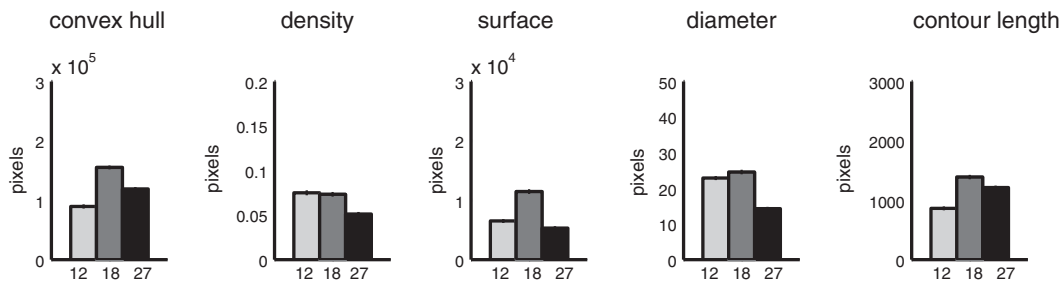


Fig. 1. The size of each visual cue (in pixels) that comprised the images included in the analyses. We averaged the continuous visual properties of the images for the three number conditions. For instance, we calculated the average convex hull that was present in the images representing 12, 18 and 27 dots. Trials that were removed because of artefacts and the filler and/or attention trials are not included in these averages. None of the visual cues consistently increased or decreased with increasing number in the passive and active viewing condition. Possible significant increases in peak amplitude with increasing number can therefore not be attributed to visual cues.

Electrophysiological recordings and pre-processing

The EEG was recorded from 64 scalp electrodes according to the International 10/20 EEG system (sampling rate of 2048 Hz) using the Active Two system (BioSemi, Amsterdam, The Netherlands; for an explanation see www.biosemi.com). The vertical electro-oculogram (VEOG) was recorded from electrodes attached above and below the left eye and the horizontal electro-oculogram (HEOG) from the outer canthi of both eyes.

EEG and EOG data were analysed using EEGlab (Delorme and Makeig, 2004). The data was down-sampled to 250 Hz. EEG signals were filtered using a low-pass filter of 40 Hz and corrected for eye movements using independent component analyses. The EEG was segmented into epochs from 200 ms prior to 800 ms after the number stimulus. The 200 ms pre-stimulus interval was used for the baseline correction. Trials with artefacts (peak amplitudes larger than $\pm 100 \mu\text{V}$), trials during which a response was given and the filler trials were rejected from further analyses. After artefact rejection, out of the 192 trials, 180 trials (STD = 8.7) were left in the passive and 176 trials (STD = 15.6) in the active condition. Furthermore, noisy electrodes were excluded from the analyses. A noisy electrode was defined as a single electrode that causes rejection of more than 25% of all epochs recorded. These electrodes were interpolated using spherical splines. In both conditions we removed the trials that were included to keep the attention directed towards the screen (in the passive task the colour trials and in the active task the number estimation trials).

We conducted separate analyses for the numerosity and visual cue effects. For the numerosity effects, to identify the electrodes and time windows of interest, a numerosity (12, 18, and 27) \times condition (active and passive) ANOVA was conducted for each data point between 0 and 600 ms after stimulus presentation. Conservative measures were used to identify electrodes and time windows showing significant main effects or a significant interaction: at least 7 consecutive data points (28 ms) should be significant in four neighbouring electrodes when $\alpha = 0.025$ (see for a similar approach: Szucs and Soltesz, 2008; Szucs et al., 2007). After identifying the clusters of electrodes and time windows of interest we created an average for each electrode cluster. For each cluster and time window we conducted a repeated measures

analyses including numerosity (12, 18, and 27) \times condition (active and passive) as independent within subject variables to investigate whether the EEG is modulated by numerosity and/or condition. In the presence of a main effect for numerosity, linear contrast analyses were conducted to investigate whether the ERP amplitude increased or decreased with increasing number. The three numerosities differed with a ratio of 2:3, which is well above the criterion that adults can differentiate; hence an equally strong increase or decrease of peak amplitude with increasing numerosity can be expected.

For the visual cue effects we organised all trials according to visual cue size, for example we ordered all trials from the smallest to the largest aggregate surface. Next, the trials were divided in five bins. To create maximally dissociable conditions, we only used the first (contains the stimuli with the smallest aggregate surface), the third (contains the images with medium sized aggregate surface) and the fifth bin (containing images with the largest aggregate surface). If we had divided the trials in 3 bins we would have had an overlap between the different visual cue conditions. Recall that we created the design on the basis of numerosity (not visual cue size) and controlled for the confound with visual cue size. Similar as for the numerosity analyses we first conducted point-by-point analyses to identify the electrode sites and time windows of interest. Next, we conducted a repeated measures analysis including visual cue size (small, medium, and large) \times condition (active and passive) as independent within subject variables to investigate whether the EEG is modulated by visual cue size and/or condition. In the presence of a main effect for visual cue size, linear contrast analyses were conducted to investigate whether ERP amplitude increases or decreases with increasing visual cue size. We performed this sequence of analyses for each visual cue size separately (convex hull, aggregate surface, average diameter, density and contour length).

Results

Numerical effects

On the basis of the point-by-point analyses we identified parietal-occipital electrode sites (PO7, PO3, O1, Oz, O2, PO8, and PO4) responsive

to numerosity from 100 to 120 ms. A large central–parietal area (C1, CZ, C2, CP3, CP1, CPz, CP2, CP4, P3, P1, Pz, P2, and P4; 440–520 ms) and a smaller central parietal area (CP1, CPz, P1, Pz, and P2; 240–520 ms) were modulated by condition (see Fig. 2). These electrode sites and time windows were included in our main analyses. For the three areas separately, the average signal present in the time windows obtained in the point-by-point analyses were subjected to a numerosity (12, 18, and 27) \times condition (passive and active) repeated measures ANOVA.

The *parietal–occipital area* revealed a significant main effect for numerosity [$F(2,32)=21.9, p<0.001$]. However, post hoc linear contrast analyses showed no significant change in peak amplitude with increasing numerosity [$F(1,48)=2.09, p=0.15$]. The main effect was most likely the result of numerosity 12 differing from 18 and 24 (see Fig. 3) while the lack of a linear increase was caused by a strong overlap in variance between the different numerosity conditions. The non-significant linear contrast and the much earlier time window (100–120 ms) than what can be expected for numerosity processes suggest that the significant main effect was not induced by numerosity. Furthermore, the main effect for condition [$F(1,16)=0.004, p=0.95$] and the interaction between numerosity and condition did not reach significance [$F(2,32)=1.67, p=0.20$].

For the *large central–parietal area* consistent with the point-to-point analyses, no significant main effect for numerosity was present [$F(2,32)=0.54, p=0.59$]. Instead a significant main effect for condition was obtained [$F(1,16)=22.5, p<0.001$]: larger peak amplitudes were present in the active compared to the passive condition (see Figs. 2 and 4). Also, numerosity and condition interacted [$F(2,32)=4.04, p<0.027$]. The peak amplitudes were larger for numerosity 18 compared to 12 and 27 in the passive condition (0.48 μ V, 0.76 μ V, and 0.4 μ V) but the reverse occurred in the active condition (1.9 μ V, 1.4 μ V, and 1.9 μ V). We conducted Bonferroni corrected paired samples T-Tests to further investigate this effect and compared numerosity 12 and 18, and 18 and 27. The results did not show a clear pattern. Most of the comparisons were non-significant: for the passive task (12 versus 18: $p=0.37$, 18 versus 27: $p=0.05$) and active task (12 versus 18: $p=0.17$, 18 versus 27: $p=0.35$). The interaction therefore does not seem to reflect a meaningful result.

The *small central–parietal area* revealed similar results as the large central–parietal area: no significant main effect for numerosity [$F(2,32)=0.37, p=0.69$] but a significant main effect for condition [$F(1,16)=42.7, p<0.001$] (see Figs. 2 and 3) and a trend towards significance for the interaction between numerosity and condition [$F(2,32)=2.85, p=0.072$]. Again the interaction was the result of a

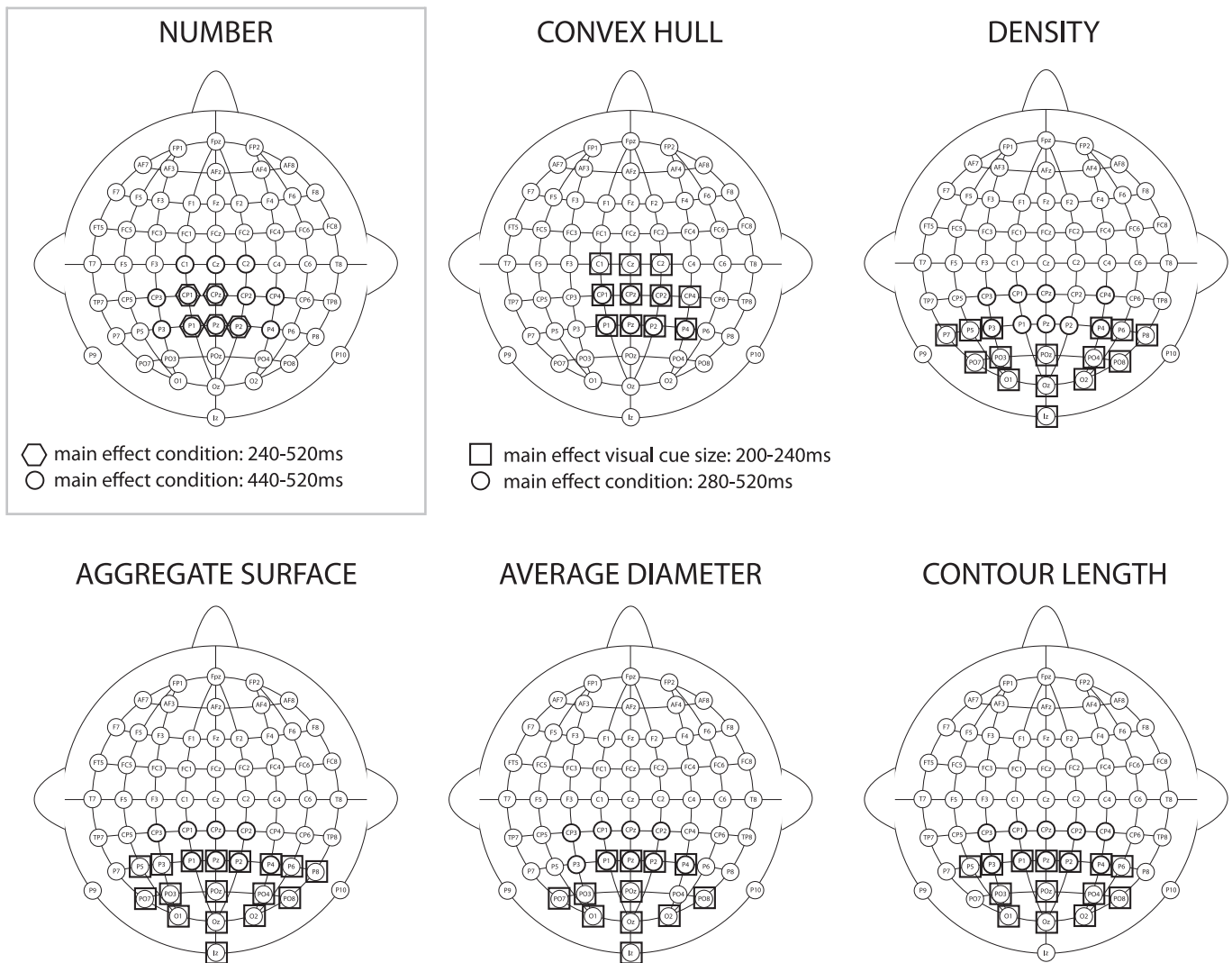


Fig. 2. The electrode sites and time windows revealing significant effects of condition or visual cue size. Central–parietal electrode sites were involved in active versus passive processing of the dot arrays at a time window that corresponds with the P3 component. Except for convex hull, visual cue size affected parietal–occipital electrode sites. The main effect for visual cue size appeared at a time window that corresponds with the P2 component. This component is related to the sensory processing of large numerosities. For convex hull, a main effect of visual cue size was present at the central–parietal electrode sites.

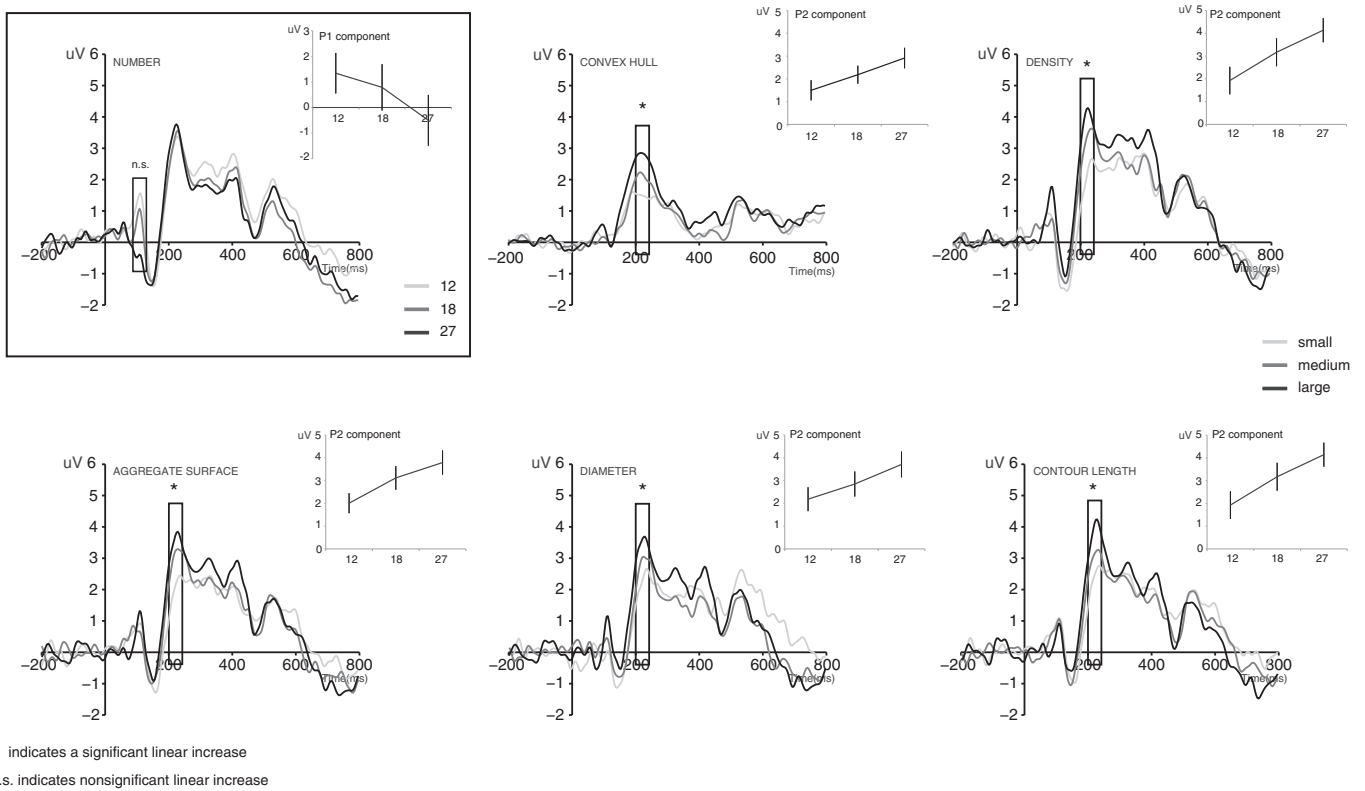


Fig. 3. ERPs averaged over parietal–occipital electrode sites (or central–parietal for convex hull) showing a main effect for visual cue size. Linear contrast analyses showed no significant main effect for number (upper left image) at the P1 component. In contrast, a significant main effect for visual cue size was present for the five different visual cue conditions at the parietal–occipital electrode sites (and central–parietal for convex hull). The P2 amplitude increased with increasing visual cue size.

larger peak amplitude for numerosity 18 compared to 12 and 27 in the passive condition (0.8 μ V, 1.1 μ V, and 0.5 μ V) but the reverse was true in the active condition (2.3 μ V, 1.9 μ V, and 2.3 μ V). We

conducted Bonferroni corrected paired samples T-Tests to further investigate this effect and compared numerosity 12 and 18, and 18 and 27. The results did not show a clear pattern. Most of the comparisons

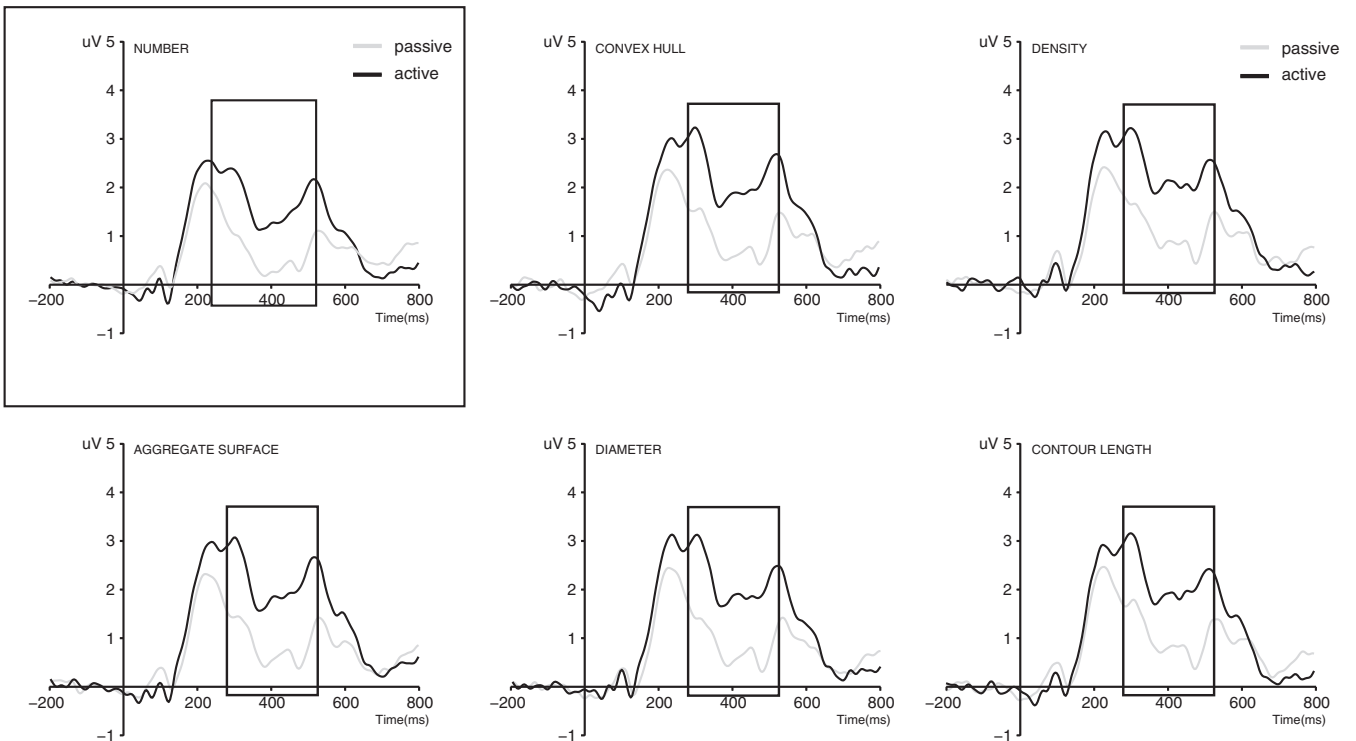


Fig. 4. ERPs averaged over central parietal electrode sites showing a main effect for condition (passive versus active viewing of number stimuli). Active processing of the number stimuli resulted in larger P3 amplitude effects than passive viewing.

were non-significant: for the passive task (12 versus 18: $p=0.36$, 18 versus 27: $p=0.10$) and the active task (12 versus 18: $p=0.02$, 18 versus 27: $p=0.16$). The interaction therefore does not seem to reflect a meaningful result.

Visual cue effects

Except for convex hull, the point-by-point analyses revealed main effects for visual cue size at the parietal–occipital electrode sites while main effects for condition were present at the central–parietal electrode sites. Only for convex hull, both main effects were present at central–parietal electrode sites (for the exact electrode sites and time windows see Fig. 2). For each visual cue condition and electrode site separately, the average peak amplitude of the above-specified time windows was subjected to a repeated measures analyses with visual cue size (small, medium, and large) and condition (passive and active) as within subject variables.

The repeated measures analyses for convex hull at the *central–parietal electrode sites* and the other visual cue conditions at the *parietal–occipital electrode sites* showed a significant main effect for visual cue size (all $F_s > 15.4$ and all $p_s < 0.001$). Similar as for numerosity, we next conducted linear contrast analyses. These showed that the peak amplitude of the P2 component significantly increased with increasing visual cue size for all visual cues (all $F_s > 5.4$; all $p_s < 0.024$) except for average diameter, which showed a marginally significant effect of visual cue size [$F(1,48) = 3.9$, $p = 0.054$] (see Fig. 3). In contrast, no significant main effect for condition (all $F_s < 2.25$ and all $p_s > 0.15$) or an interaction between visual cue size and condition (all $F_s < 1.01$ and all $p_s > 0.38$) was present for any of the 5 visual cue conditions.

At the *central–parietal electrode sites*, from 280 to 520 ms a significant main effect for condition was obtained for all five visual cues (all $F_s > 26.2$ and all $p_s < 0.001$) (see Fig. 4). This peak amplitude corresponds with the P3 component and is larger for the active compared to the passive condition. Furthermore, a (marginally) significant main effect for visual cue size was present for convex hull [$F(2,32) = 3.22$, $p = 0.053$] and a significant main effect for diameter [$F(2,32) = 3.87$, $p = 0.03$]. Nevertheless, linear contrast analyses showed no significant increase in amplitude with increasing convex hull ($p = 0.384$; small = 1.4 μV , medium = 1.6 μV , and large = 1.9 μV) or diameter ($p = 0.869$; small = 1.6 μV , medium = 1.2 μV , and large = 1.7 μV). For the remaining visual cue conditions no significant main effect for visual cue size was obtained (all $F_s < 1.29$ and all $p_s > 0.29$) and no significant interaction between visual cue size and condition was present for all five visual cues (all $F_s < 2.49$ and all $p_s > 0.1$).

Discussion

To investigate the difference in passive viewing and active processing of numerosity, we presented participants' arrays of dots and concurrently measured their EEG. In The first condition, participants naïve to the subject under study passively viewed the dot arrays. In the second condition the participants were informed about the changes in numerosity and had to actively process numerosity. The visual properties of the dot-arrays did not increase or decrease with numerosity and could therefore not explain possible numerosity related effects. An increase in peak amplitude with increasing numerosity in the active but not the passive condition would indicate that active processing of numerosity is required to extract numerosity from the visual scene. In contrast, an absence of numerosity related effects in both conditions would indicate that we do not extract numerosity independent of its visual variables but instead rely on these variables to judge numerosity.

For the passive and active condition, we did not find an increase in amplitude with increasing or decreasing numerosity at any of the electrode sites. The absence of a numerosity related effect in the

passive condition is consistent with our previous study. In this study small (3, 4, and 5) and large numerosities (12, 18, and 24) did not induce numerosity related effects when the participants passively viewed the stimuli (Gebuis and Reynvoet, 2012a). However, it can be argued that the more prominent visual features prevented automatic processing of numerosity when participants are not aware of the numerosity changes. If this was indeed the case, a numerosity effect should be present in the active condition but the active condition did not show any numerosity related effect either. The absence of a numerosity effect in both conditions is in line with the hypothesis that we do not extract numerosity from a visual image but only process its parts: the continuous visual properties. These sensory properties could then serve as a basis for our numerosity estimates. More specifically, we might weigh the different visual variables present in the stimulus to come to a number estimate (Gebuis and Reynvoet, 2011). This would also explain the large number of studies showing influences of different visual variables on numerosity estimates (e.g. Dakin et al., 2012; Gebuis and Gevers, 2011; Gebuis and Reynvoet, 2012b; Ginsburg and Nicholls, 1988; Soltesz et al., 2010; Sophian and Chu, 2008).

Furthermore, the results showed a significant main effect of passive versus active viewing. Large central–parietal amplitude effects corresponding with the P3 component were present. The P3 amplitude was larger for the active compared to the passive viewing. Previous studies showed that this component increases with increasing symbolic but also non-symbolic number distance (Libertus et al., 2007; Turconi et al., 2004). However, it is highly debated whether the P3 reflects pure number processes or stimulus evaluation, categorization, or response processes (Cohen Kadosh et al., 2007; Gebuis et al., 2010; Szucs and Soltesz, 2007, 2008). Contrary to previous studies, the participants were not required to generate an actual response in each trial. Instead, participants occasionally had to respond to colour changes or numerosity. These response trials were not included in the analyses. The difference in P3 amplitude between the passive and active conditions can therefore not result from differences in response processing. Also numerical magnitude did not modulate the P3 amplitude suggesting that the P3 amplitude effect does not reflect numerosity processes either. Instead, it appears most likely that the P3 amplitude effect reflects general cognitive processes such as attention or visual working memory. This appears plausible in light of the tasks at hand: detecting changes in colour versus the cognitively more demanding task of estimating numerosity.

The most important difference between our study and the previous studies about numerosity processing is the method to control the visual cues of the stimuli. In our study, the different visual variables did (on average) not linearly increase or decrease with numerosity. Our post hoc analyses underlined the importance of properly controlling the visual cues. The sensory properties of the dot arrays mimicked numerosity related effects. When the stimuli were reorganised according to visual cue instead of number size an increase in P2 amplitude with increasing visual cue size was present. The P2 component was previously suggested to support the processing of numerosities (Hyde and Spelke, 2009; Libertus et al., 2007). However, our results show that improperly controlled visual cues can explain these P2 amplitude effects. Although our study only investigated the effect of the visual cues on the ERP signal it appears likely that these confounds are also present in related neuroimaging studies where researchers only prevented the participants from using a visual cue related strategy to solve the task but did not control for a correlation between the average size of one or more visual cues and numerosity (e.g. Piazza et al., 2003, 2004; Roggeman et al., 2010, 2011; Santens et al., 2010).

Interestingly, for convex hull we did not find an effect of its visual cue size at the parietal–occipital but at the parietal–central electrode sites. Consequently, the visual cue effect for convex hull overlapped with the main effect of condition: passive versus active processing

of numerosity. This difference in location of the neural responses for this particular visual cue is striking. De Hevia and Spelke (2009) showed that children bisect a line towards the larger non-symbolic number. However, it appeared that convex hull could better explain the child and adult numerosity bisection biases (Gebuis and Gevers, 2011). When the convex hull was manipulated participants bisected the line towards the larger convex hull even when numerosity was smaller. Furthermore, Tibber et al. (2012) showed a stronger influence of convex hull on numerosity judgement compared to the diameter of the different items. The fact that specifically this visual cue affected the electrode sides involved in passive and active processing of numerosity might indicate a more prominent role for convex hull than other continuous visual variables in numerosity processing.

Together, no significant effects of numerosity were present in the passive and active conditions. This implicates that even when participants are informed about the numerosity changes, no numerosity specific processes occur. It can be questioned what then subserves our numerosity estimates? The post hoc analyses on the sensory properties of the stimuli show strong parieto-occipital effects at components previously associated with numerosity. This suggests that previous numerosity related findings might be induced by improperly controlled visual cues. Recently, an increasing number of studies showed that sensory properties of the stimuli influence number judgments (e.g. Dakin et al., 2012; Gebuis and Reynvoet, 2011, 2012b; Ginsburg and Nicholls, 1988; Sophian and Chu, 2008; Tibber et al., 2012). These observations together with our results provide evidence in favour of the notion that we do not automatically extract numerosity from a visual scene but instead integrate the different visual variables.

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