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The visual mismatch negativity is sensitive to symmetry as perceptual category

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Abstract

We investigated the sensitivity of visual mismatch negativity (vMMN) to an abstract and non-semantic category, the vertical mirror symmetry. Event-related potentials were recorded to random and symmetric square patterns, delivered in passive oddball paradigm (participants played a video game). In one of the conditions, symmetric patterns were frequent (standard) stimuli and the random patterns were infrequent (deviant) stimuli, in the other condition the probabilities were reversed. We compared the ERPs to symmetric stimuli as deviants and as standards, and similarly, the ERPs to the random deviants and random standards. As the difference between the ERPs to random deviant and random standard stimuli a posterior negativity emerged in two latency ranges (112–120-ms and 284–292-ms). These negativities were considered as visual mismatch negativity (vMMN) components. We suggest the two vMMN components are organized in cascade error signals. However, there was no significant difference between the ERPs to the symmetric deviants and symmetric standards. Emergence of vMMN to the deviant random stimuli is considered as a deviation of a perceptual category (in the symmetric standard's sequence presented). Accordingly, random stimuli acquired no perceptual category, for this reason the symmetric deviant (in the random standard's sequence presented) elicited no vMMN.

The results show that the memory system underlying visual mismatch negativity is capable of coding perceptual categories such as bilateral symmetry, even if the stimulus patterns are unrelated to the ongoing behavior.

Introduction

At the level of conscious experience, the visual system is surprisingly insensitive to environmental changes if such changes are outside the focus of attention (Simons & Levin, 1997). However, research on the visual mismatch negativity (vMMN) component of event-related potentials (ERPs) shows that non-attended visual changes violating the regularity of stimulation are registered in posterior brain structures. In fact, vMMN occurs even if participants cannot report the stimulus change (Czigler & Pató, 2009) or the change appears during a period of attentional blink (Berti, 2011).

Visual mismatch negativity (an ERP component in the 100-300 ms latency range) is a counterpart of the auditory MMN (for reviews see Kujala *et al.*, 2007, Näätänen *et al.*, 2007). VMMN is elicited by various deviant visual features such as color (Czigler, *et al.*, 2002), orientation (Astikainen, *et al.*, 2008), movement direction (Pazo-Alvarez *et al.*, 2004) spatial frequency (Heslenfeld, 2003) and contrast (Stagg *et al.*, 2004). Besides sensitivity to single visual features, the system underlying vMMN is sensitive to more complex visual changes such as deviant conjunction of visual features (Winkler *et al.*, 2005) and deviant sequential relationships (Stefanics *et al.*, 2011); for reviews see Czigler, (2007); Kimura *et al.* (2011a). Some ERP studies have shown that vMMN is sensitive to stimulus categorization in case of facial expressions (Astikainen *et al.*, 2009; Stefanics *et al.*, 2012). Categorical sensitivity in the color domain has also been demonstrated.

Clifford *et al.* (2010) and Mo *et al.* (2011) reported larger vMMNs were elicited if deviants and standards belonged to different color categories compared with if deviants and standards belonged to same color category irrespective of that the distances in color space were identically.

The present study aimed to investigate whether the implicit system underlying vMMN was capable of registering vertical mirror symmetry as a perceptual category. Several behavioral studies reported that the visual system is particularly sensitive to various forms of symmetry (for review see Treder, 2010). Corresponding to Carmody *et al.* (1977) and Tyler *et al.* (1995), stimulus duration in

the 40 to 80-ms range is long enough to recognize symmetric patterns. Other behavioral studies show that symmetry can be detected automatically (Baylis & Driver, 1994; Huang *et al.*, 2004; Machilsen *et al.*, 2009; Wagemans, 1995).

Vertical mirror symmetry is a salient feature of living objects and has obvious biological significance (Tyler & Hardage, 1996). However, so far no ERP study analyzed the level of processing sensitive to symmetry and the automaticity of sensitivity to symmetry.

Few studies have investigated the processing of symmetric stimuli on the basis of event-related brain activity. Jacobsen & Höfel (2003) and Höfel & Jacobsen (2007) reported a posterior negative wave to symmetric patterns. In these studies symmetry *per se* was task-irrelevant, participants made aesthetic judgments, performed a detection task or contemplated the beauty of the stimuli. The negativity emerged in the 380 to 890-ms poststimulus latency range, therefore, this effect may not be a correlate of elementary perceptual processes. However, in a sequence of alternatively presented random and symmetric dot-patterns, the symmetric patterns elicited a sustained posterior negativity with ~220-ms onset whereas random patterns elicited positivity with earlier onset (~130-ms) (Norcia *et al.*, 2002). Such activities were considered as correlates of the appearance of global forms, i.e., an activity more general than a specific symmetry effect.

In the present experiment we tested whether the system underlying vMMN is sensitive to symmetry as perceptual category. If so, the regular presentation of stimuli belonging to the same perceptual category (symmetry) would establish a mental representation containing the sequential rule of the stimulation. Irregular stimuli (which do not belong to this category) will violate the prediction that derives from mental representation and therefore elicit the vMMN component. For that reason we infrequently embedded symmetric patterned stimuli (deviants) in a series of random patterned stimuli (standards) whereas in another condition random deviants appeared in the context of symmetric standards. Thus, we could compare the ERPs elicited by categorically identical standard and deviant stimuli. We expect ERP difference between the deviant and standard random

pattern; we hypothesize that ERP difference is a vMMN, i.e., a posterior negativity within the 100-300 ms latency range. However, “randomness” cannot be considered as a categorical rule, therefore a deviant symmetric pattern does not violate a perceptual regularity. We suggest no similar difference is expected in the case of symmetric deviants.

The vMMN-related stimuli – high contrast black-and-grey squares – were presented on the lower half of the visual field since the lower half-field stimulation usually elicits more pronounced ERP components (Jeffreys & Axford, 1972), and vMMN (Sulykos & Czigler, 2011). The task-related stimuli were delivered on the opposite half of the visual field. The visual task required continuous fixation on the center of the task-field.

Materials and Methods

Participants

Participants were 12 paid students (4 women; mean age: 21.8 years; standard deviation: 1.7 years) with normal or corrected-to-normal vision. Written consent was obtained from all participants prior to the experimental procedure. The study was conducted in accordance with the Declaration of Helsinki, and approved by the United Committee of Ethics of the Psychology Institute in Hungary.

Stimuli

The stimuli were either bilaterally symmetric or random black-and-grey square patterns. Patterns with vertical symmetry were used since this type of symmetry is more prominent than horizontal symmetry (Barlow & Reeves, 1979; Wagemans *et al.*, 1991). The size of a square item was 1 deg. from the 1.2 m viewing distance. The pattern consisted of 2 matrices of 16 items (4 columns \times 4 rows), therefore, the size of the pattern was 4 \times 4 deg. in each half-field. The 2 halves of the pattern were separated by a vertical line of 0.3 deg., and the task-field and the patterns were

separated by a horizontal line of 0.4 deg. Each matrix consisted of 9 grey and 7 black squares. Figure 1 shows a sample stimulus (A) and the experimental stimulus sequences (B).

Insert Figure 1 about here

The luminance of the grey squares was 20.1 cd/m², and the (Weber) contrast was 3.54. The stimuli appeared on a 17" monitor (Samsung SyncMaster 740B, 60-Hz refresh rate) in a dimly lit and soundproof room. The stimulus duration was 167-ms, and the interstimulus interval was 417-ms. Before the repetition of a particular pattern, at least 4 physically different patterns were presented. Symmetric and random stimuli were delivered in oddball sequences. In one of the conditions, symmetric patterns were the frequent (standard) stimuli ($p = 0.84$) and random patterns were the deviant stimuli ($p = 0.16$). In the other condition, these probabilities were reversed, that is the random patterns were standards and the rare symmetric patterns were deviants. A sequence consisted of 400 stimuli. There were 2 sequences for both conditions. The sequences were delivered in alternate order ("ABAB" or "BABA"). The sequence orders were counterbalanced across participants.

Task

The stimuli for the task appeared on the upper half of the visual field (Figure 1). To facilitate the participants' interest, the primary task was designed as a simple video game. The participants used a gamepad controller to maneuver a spaceship in a canyon. The canyon – rectangular cross-section tube – lay in the surface of a schematic planet. In the canyon, there were 3 types of spaceships marked by different color (blue, red and green). The color of the controlled spaceships was blue which fixed on a stationary vertical position in the canyon. The manipulated spaceship was directed with the gamepad along the horizontal dimension of the canyon. In every second one

spaceship appeared at start of the canyon and moved toward the blue spaceship. The color of the spaceship was red with 0.6 probability and green with 0.4 probability. The aim of the task was to avoid the red spaceships and to catch the green ones with the controlled spaceship. To perform the task properly, participants had to fixate in the location where the spaceships appeared. For more details, see Sulykos & Czigler (2011).

Measuring brain electrical activity

Electroencephalography was recorded (DC-70 Hz; sampling rate, 500 Hz; Synamps2 amplifier, NeuroScan recording system) with Ag/AgCl electrodes placed at 61 locations according to the extended 10-20 system by using an elastic electrode cap (EasyCap). The reference electrode was on the nose tip, and offline re-referenced to the average activity. Horizontal electrooculography was recorded using a bipolar configuration between electrodes positioned lateral to the outer canthi of the eyes. Vertical eye movement was monitored with a bipolar montage between electrodes placed above and below the right eye.

The electroencephalographic signal was band pass filtered offline, with cutoff frequencies of 0.1 and 30 Hz (24-dB slope). Epochs of 600-ms duration, including a 100-ms prestimulus interval, were extracted for each event and averaged separately for the standard and deviant stimuli. The mean voltage during the 100-ms prestimulus interval was used as the baseline for amplitude measurements, and epochs with an amplitude change exceeding $\pm 50 \mu\text{V}$ on any channel were rejected from further analysis.

ERPs were averaged separately for the standard and deviant stimuli (symmetric and random) in the 2 conditions. Responses to the third to the seventh standards after a deviant were included in the standard-related ERPs. To identify change-related activities, ERPs to standard stimuli were subtracted from ERPs to deviant stimuli in the reverse condition.

{Footnote 1: In many studies vMMN was calculated as the difference between the ERPs to the deviant and standard of the same stimulus sequence. In this method the effect of physical difference between the deviant and standard and the effect of memory-related mismatch effects are confounded. Therefore the method of comparing ERPs to identical stimuli is highly recommended (c.f. Kujala *et al.*, 2007). Furthermore the comparing physically identical stimuli (presented frequently / infrequently) in different conditions will not be sufficiently to get ride off refractoriness effects adding to plain memory-related effects (Kimura *et al.*, 2009). However, this problem does not apply to our study as we used different types of standard stimuli which make the contribution of refractoriness effects to our vMMN response rather unlikely.}

VMMN was identified if within the 100-300 ms latency range deviant- *minus*- standard amplitude difference was different from zero at least at 5 subsequent points at any occipital locations (for reviews of the characteristic of the range and surface distribution of the vMMN see Czigler, 2007; Kimura, 2011b). This way we identified an earlier (112–120-ms) and a later (284–292-ms) range of the difference potentials. At six electrodes locations (PO3, POz, PO4, O1, Oz, and O2), as region of interest, the average amplitude values of these epoch were calculated, entered into ANOVAs with factors of probability (deviant or standard), anteriority (parieto-occipital or occipital), and laterality (left, midline or right). We compared, at the same electrode locations, the peak latencies and scalp distributions of the exogenous components and the difference potentials.

{Footnote 2: At lower half-field stimulation C1 and C3 components are positive and C2 is negative. Investigation of the relationship between a negative component and the vMMN is relevant, because it is important to separate the refractoriness/habituation of an exogenous activity from vMMN. In this context, the similar analysis of the positive components (C1 and C3) is less important, because reduced exogenous positivities cannot be expected to the deviant stimuli (in case of stimulus-specific refractoriness/habituation amplitude reduction is expected, i.e., positive deviant minus standard difference).}

Peak latencies were measured at the maxima of the components. The distributions of the difference potential and the C2 were compared on vector-scaled amplitude values (McCarthy & Wood, 1985). Where appropriate Greenhouse–Geisser correction was applied. Effect size was characterized as partial eta-squared (η^2). Post hoc analyses were calculated by the Tukey’s HSD test. In the reported effects, the alpha level was at least 0.05.

Results

Behavioral results

Participants avoided the “red ship” with 82% (standard error of mean: 1.53%), and caught the “green ship” with 83% (standard error of mean: 1.05%). This difference was not significant. There was no difference in performance between the random and symmetric standard conditions either.

Event-related potentials

Figure 2 shows the ERPs to the symmetric (A) and random (B) stimuli, as both standards and deviants, furthermore the deviant– minus– standard difference potentials. The stimuli elicited a positive-negative-positive (C1-C2-C3) set of pattern-specific exogenous components (Jeffreys & Axford, 1972). Table 1 shows the latency values of the exogenous components and the Figure 3 shows the scalp distribution of C1, C2, C3 and the difference surface distributions. Figure 2 shows that the deviant and standard symmetric stimuli elicited similar ERPs. In fact, in the t-tests the difference did not reach the criteria level (deviant *minus* standard amplitude difference is different from zero at least 5 subsequent points). However, over the posterior-occipital locations random deviant and random standards were different in an earlier (112–120-ms) and in a later (284–292-ms) range. In both ranges the difference was negative. Table 2 shows the amplitudes of the random deviants and standards in the two ranges.

Please Insert Figure 2 and Figure 3, Table 1 and Table 2 about here

ERP amplitudes to the deviant and standard random stimuli were compared in both latency ranges using ANOVAs with factors of probability (deviant, standard), anteriority (parieto-occipital, occipital) and laterality (left, midline and right). In the 112–120-ms range, only the probability main effect was significant [$F(1,11) = 6.31$, $p < 0.05$, $\eta^2 = 0.36$], showing the occipital/parieto-occipital distribution of the early negativity. In a similar analysis of the 284–292-ms range, the main effect of anteriority [$F(1,11) = 7.13$, $p < 0.05$, $\eta^2 = 0.39$] and the probability X anteriority interaction [$F(1,11) = 7.52$, $p < 0.05$, $\eta^2 = 0.41$] were significant. According to the Tukey HSD tests, the deviant-standard difference was significant only at the occipital locations ($p < 0.01$ in all cases). As the results show, vMMN appeared in two latency ranges. However, it is possible that instead of the emergence of vMMN, the earlier effect was an amplitude modulation of the C2 component. Still, as Figure 2 shows, the latency of the difference potential was shorter at the occipital locations. To investigate the latency difference (116 vs. 130 ms), we compared the C2 and difference potential latencies at the parieto-occipital and occipital locations (POz, Oz). In an ANOVA, the main effect of anteriority was significant [$F(1,11) = 6.33$, $p < 0.05$, $\eta^2 = 0.36$] and the component (difference vs. standard) X anteriority interaction was significant [$F(1,11) = 4.93$, $p < 0.05$, $\eta^2 = 0.30$]. However the main effect of component was only marginally significant [$F(1,11) = 3.46$, $p < 0.09$, $\eta^2 = 0.24$]. To investigate further the relationship between the C2 and the difference potential, we compared the surface distributions. As Figure 3 indicates, the distribution of the difference potential is wider than the C2 distribution. To investigate the possibility of distribution difference, we added further electrodes to both sides on both rows (P7, P8, PO7, PO8) to the previous electrode set (PO3, POz, PO4, O1, Oz, O2) and vector-scaled the data (McCarthy & Wood, 1985). The C2 amplitude was measured as the average of a +/- 4 ms point around the peak of the component (130-ms). In an ANOVA with factors

of component (C2 and difference potential), anteriority and laterality, only the three-way interaction was significant [$F(4,44) = 3.82$, $p < 0.05$, $\epsilon = 0.53$, $\eta^2 = 0.26$]. According to the Tukey HSD test, C2 was larger at the anterior row, moreover C2 amplitude was larger at the midline. We found significant differences in the distribution of early vMMN and C2. Additionally we compared the vector-scaled amplitude values of the two vMMNs. In the ANOVA with factors of difference potential (early, late) anteriority (parieto-occipital, occipital) and laterality (left, midline, right). Due to the lack of significant effects we could not consider that the surface distributions were different.

Discussion

Frequent (standard) and infrequent (deviant) symmetrical patterns elicited identical ERPs. However, in the context of symmetric patterns, random deviant stimuli elicited two posterior negative components. The negative difference potentials cannot be explained as the refractoriness of low-level visual processes for the following reasons: first, the scalp distribution of the exogenous activity (C2 component) differed from the characteristics of the difference potential in the earlier latency range. Second, there was a tendency for peak latency differences between the C2 and the difference potentials. Third, in the later latency range, there was no exogenous difference corresponding to the posterior negativity. We consider the two difference potentials as sub-components of vMMN. Emergence of multiple VMMN is not unprecedented (Maekawa *et al.*, 2005, Astikainen *et al.*, 2009, Sulykos & Czigler, 2011). Considering the difference potentials as vMMN, we interpreted the asymmetry of the random and symmetry conditions as a manifestation of a category effect. Unlike the random patterns, symmetric stimuli may acquire a category. Rare random (deviant) stimuli violated the representation of the category (symmetry) and elicited vMMN. Thus far, category influences on vMMN have been reported in the color domain (Athanasopoulos *et al.*, 2010; Clifford *et al.*, 2010; Mo *et al.*, 2011) and in the case of facial emotions (Astikainen *et al.*, 2009; Stefanics *et al.*, 2012; Zhao *et al.*, 2006). According to the present results, high-order visual

features acquired a category without the involvement of attentional processes, and stimuli deviating from the sequential appearance of patterns belonging to such a category were automatically registered.

The present findings are in line with behavioral results showing the fast and automatic sensitivity of the visual system to symmetry (Baylis & Driver, 1994; Carmody *et al.*, 1977; Huang *et al.*, 2004; Tyler *et al.*, 1995; Wagemans, 1995). According to some studies, short latency vMMN is generated in retinotopic areas (Czigler *et al.*, 2004; Pazo-Alvarez *et al.*, 2004; Sulykos & Czigler, 2011). Nevertheless, according to neuroimaging and transcortical magnetic stimulation data, the loci of sensitivity to symmetry are above the retinotopic (i.e., V1 and V2) structures (Cattaneo *et al.*, 2011; Sasaki *et al.*, 2005; Tyler *et al.*, 2005). An early effect of symmetry on ERPs was reported by Norcia *et al.* (2002); however, neither the patterns nor the stimulus presentation methods in that study were comparable to methods used in the present experiment. Considering both the early and the late negativities as vMMNs, emergence of the successive components suggests a cascade of memory-related processes. This possibility fits the idea that mismatch responses are correlates of hierarchically organized error signals; i.e., the difference between a model predicting the characteristics of ongoing stimulation and bottom-up processes elicited by the actual stimulation (Winkler & Czigler, 2012). VMMNs in the earlier and later latency ranges had similar surface distributions. Therefore it is unlikely that the early and late vMMNs are due to the structural hierarchy of the visual system. Instead, we consider the later component as a manifestation of recurrent activity. So far there were only few attempts to localize vMMNs. These studies identified the prestriate cortex as generator of vMMN (Czigler *et al.*, 2004; Kimura *et al.*, 2010; Sulykos & Czigler, 2011). According to MEG study the MOG (middle occipital gyrus) is an important cortical area which of activity reflected the sensory memory – based visual change-detection processes (Urakawa *et al.*, 2010). Furthermore Yucel *et al.* (2007) reported a deviant related extensive network (occipital-fusiform, posterior parietal, prefrontal and subcortical regions). In these regions unattended

deviants elicited BOLD activation which decreased with difficulty of demanding visuomotor tracking task.

Emergence of vMMN to random deviants and the lack of vMMN to symmetric deviants are analogous to an effect in auditory modality. Within a series of legal syllables in a language, an irregular syllable elicited mismatch negativity, but a legal deviant in a series of irregular ones did not (Steinberg *et al.*, 2011). Accordingly, violation of an existing category resulted in automatic detection processes; however, in the absence of categorization, there were no such processes. It seems that the role of category-related representation in the two modalities is similar.

In conclusion, the results of the present study show that bilateral vertical symmetry is a prominent stimulus category and that stimuli violating the rule of successive appearance of such patterns elicit deviant-related components, even if the stimulus patterns are unrelated to the ongoing behavior.

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Abbreviations: ANOVA, analysis of variance; ERP, event-related potential; vMMN, visual mismatch negativity

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