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The Contribution of Various Spatial Modulations to the Management of Exogenous Attention: An N2pc Study

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Abstract: **Introduction**. The mechanisms of exogenous attention, having a high sensitivity to the physical characteristics of sensory signals, provide primary adaptation to the environment. We have suggested that non-local features of the visual scene may have different priorities in attracting exogenous attention. The process of exogenous orientation in the situation of pairwise competition of modulated textures was studied for the first time by isolating the N2pc component. As a result of the study, we established the peculiarities of attention distribution in pairs of spatial features modulated on textures, expanding the idea of the work of exogenous control mechanisms in the visual system. **Methods**. The study involved 32 people aged 18.2 ± 0.4 years with normal vision. The experiment consisted of three parts performed according to the same scheme: the task of the subject was to find the target stimulus (modulated texture) given in the instructions among the decoy (another modulated texture) and distractors. During the experiment, an EEG was recorded in order to analyze the N2pc component. **Results**. Based on the comparison of the N2pc component, it was found that contrast and orientation modulations attract exogenous attention to a greater extent than spatial frequency modulation. The theoretical significance of the results lies in the study of the fundamental mechanisms of exogenous control in the visual system. The results of studying this process can be applied in the development of graphical interfaces, brain–computer systems, as well as in solving a wide range of problems of engineering psychology related to the optimization of human-machine interaction. **Discussion**. Contrast and orientation modulations may have a higher priority for exogenous attention than spatial frequency modulation. In a situation of simultaneous presentation with the latter, contrast and orientation modulations can largely distract attention due to their greater salience. The lower latency of the N2pc component in response to orientation modulation suggests the priority of its processing in comparison with contrast and spatial frequency modulations.

Keywords: attention management, exogenous attention, visual filters, N2pc component, salience, spatial modulation, contrast, orientation, spatial frequency, visual search

Highlights:

- Spatial modulations of different dimensions attract exogenous attention to varying degrees.

➢ Spatial frequency modulation contributes significantly less to visual attention management than contrast and orientation modulations.
➢ Orientation modulation is the highest priority in the competition for attention in comparison with contrast and spatial frequency modulations.

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Introduction

Attention processes allow the brain to overcome the limitations of its processing capabilities, enhancing important visual information and suppressing unnecessary. In order to interact adaptively with the world around us, it is useful to choose the information that is relevant to our goals and ignore what does not apply to them. However, some events should not remain without our attention, even if they are not directly related to current goals. The fundamental research question concerns the mechanisms that control which areas of the visual scene attention will be directed to. On the one hand, the focus of attention can be controlled by the properties of the stimulus, regardless of the goals of the observer. For example, a noticeable new object suddenly appearing in the field of view will attract our attention (Theeuwes, 1994). This control mode is known as exogenous control (or stimulus-driven, involuntary, ascending). Exogenous control mechanisms are sensitive to the physical characteristics of the signals of sensory systems. They provide primary adaptation to the environment, allowing you to navigate and react quickly to sudden events (Klein, 2009). This causes a few features characteristic of this type of orientation. Exogenous attention is fast, resistant to interference and does not require conscious control, and its effects manifest themselves within 100 ms after the attractor (Hopfinger & West, 2006). Exogenous control does not depend on top-down influences, but its effects can be quickly suppressed if the object taken into account does not correspond to the actual task (Theeuwes et al., 2000). On the other hand, the choice of an object for attention may depend on our goals, expectations, or external instructions. For example, the subject can pay attention to an object by following the instructions (Findlay, 1997). This control mode is known as endogenous (or purposeful, conscious, top-down).

It is believed that exogenous attention is attracted by so-called areas of interest, and there may be competition between them. These areas carry the bulk of the information being read, and the result of processing this information is recorded in memory in the form of representations of visual images (Rayner, 2009). With the discovery of D. Hubel functions of striar neurons of the central cortex (Hubel & Wiesel, 1962) fixed the idea that the competition for attention between different parts of the visual scene is based on a comparison of primary (basic) features – brightness gradients, colors, etc. However, striar neurons describe brightness gradients within their relatively small receptive fields, as a result of which the striar neuron model can explain the detection of only a limited number of modulations, for example brightness modulation. But what will be the output of the striar neuron model when contrast modulation is projected onto it, subjectively similar to brightness modulation? If the average brightness of low-contrast and high-contrast areas of the image is equal and does not differ from the average brightness of the image, the linear detector will give zero at the output, and the modulation will not be detected. However, an observer with normal vision effortlessly detects contrast modulation.

Another confirmation of the insufficiency of the probabilistic summation of the responses of striar neurons for the full perception of visual scenes is found in the reports of patients whose areas of the visual cortex are damaged by stroke. With local damage to the striar cortex, patients are diagnosed with a scotoma – a blind spot in the field of vision (Chandra et al., 2017), while damage to the extrastriar zones leads to various agnosies – subject, facial, opto-motor, etc., while maintaining the overall integrity of the field of vision (Tikhomirov et al., 2021). These facts suggested the presence of mechanisms in the visual system that group the responses of striar neurons in a special way in large areas of the visual field. These mechanisms are now known as second-order visual filters, the first ideas about which were formulated already in the late 80s (Babenko, 1989; Chubb & Sperling, 1989; Fogel & Sagi, 1989; Sutter et al., 1989). These concepts are based on the "filtration – rectification – filtration" scheme, which replaced the model of multiple detectors when explaining the results of experiments with modulated textures. It is important to note that this model in its original form was considered as universal for detecting both contrast modulations and spatial frequency and orientation. In the future, this gave rise to the problem of the specificity of second-order visual mechanisms and raised the question of which mechanism is responsible for distinguishing these types of modulation, given that the observer distinguishes them without additional effort (probably at the preattentive level) (Yavna et al., 2009; Babenko et al., 2020). Currently, there are several studies showing the relative independence of channels detecting various spatial modulations (Kingdom et al., 2003; Cruickshank & Schofield, 2005; Yavna, 2012; Babenko & Ermakov, 2015). In addition, in recent years, data have been obtained indicating that second-order filters can act as a "gate" of attention (Babenko & Yavna, 2018). Being at the exit of the preattentive stage of visual information processing, these structures can control attention from the bottom up, presumably marking the most informative areas. Since each of the presented modulations is simultaneously present in the visual scene, these areas of the visual scene can attract the observer's attention to varying degrees. We attempted to assess the priority of contrast, orientation, and spatial frequency modulations in attracting attention by analyzing the evoked N2pc component fixed in the visual search task. The purpose of the current work is to determine to what extent each of the modulations is a priority for exogenous attention. This task is implemented for the first time by allocating the N2pc component.

The N2pc component is a potential associated with an event that manifests itself contralateral to the place of the visual scene that the subject pays attention to: if the subjects pay attention to the left part of the visual field, N2pc appears in the right hemisphere of the brain, and vice versa. This component got its name in the article by S. Luck and S. Hillyard (Luck & Hillyard, 1994): the letter "N" denotes negative polarity, the digit "2" is the ordinal number of the component (the peak amplitude of N2pc reaches 180–300 ms after the presentation of the stimulus (Luck, 2011)) and "pc" (short for "posterior contralateral") indicates spatial localization, since negativity is formed in the parietal-occipital leads of the contralateral hemisphere. The N2pc component is actively used as a marker of attention recorded by EEG. The first works related to N2pc used the paradigm of parallel-sequential visual search for targets among distractors, in which it was found that although the amplitude of N2pc is the same in both cases, the length of the negative wave is significantly higher in samples with sequential search. This led researchers to the idea that the N2pc component reflects the process of filtering irrelevant information. However, it later turned out that N2pc occurs contralaterally to the presented stimulus even when there are no distractors in its half-field at all. To date, there is evidence according to which only one goal is sufficient for the manifestation of the N2pc component in any of the half-fields (Ilse et al., 2020).

This component can be considered within the framework of two large theories of attention control: the theory of ascending attention control (bottom-up attention, or exogenous attention) and the theory of descending attention control (top-down attention, or endogenous attention) (Gaspelin & Luck, 2019). The first assumes that salient stimuli attract attention automatically and independently of our knowledge and tasks, the second – that salient elements can be ignored if they do not correspond to the expected signs of the search goal or previous experience. Now, it is obvious that N2pc cannot be considered as a component reflecting exclusively bottom-up processes, since in this case the task assigned to the subject would not matter. However, within the framework of the classic experiment with N2pc, the target is manipulated while maintaining other equal conditions. Thus, although only the subject's task actually changes, and the general characteristics of the visual scene remain unchanged, we can observe a more powerful response of the N2pc component in response to a relevant stimulus than to an irrelevant one (Luck, 2006). Nor can N2pc be attributed to components reflecting exclusively top-down processes due to the large amount of experimental data confirming the influence of physical characteristics of stimuli on the component (Gaspelin & Luck, 2018; Bartolomeo & Malkinson, 2019; Han et al., 2022).

The totality of experimental data suggests that both ascending and descending processes contribute to the formation of N2pc. When two stimuli compete in different half-fields, N2pc is highly likely to be tied to a stimulus that has a high salience. However, this is only true for a situation in which both stimuli have the same relevance. The ascending processes of attention are reflected in the latent period of N2pc, practically without affecting its amplitude in visual search tasks (Bachman et al., 2020). The descending processes of attention modulate the amplitude and duration of N2pc, organizing the process of visual search (Goller et al., 2020).

Methods

The study involved 32 people (25 women and 7 men) with normal or corrected to normal vision, the average age was 18.2 ± 0.4 years.

The study consisted of three parts, the procedure for presenting incentives for each of which was similar. The subject was instructed to report the location of the desired stimulus (target) as soon as possible, presented simultaneously with distracting images (decoy and distractors). The target stimulus and the decoy were always represented by a pair of circles with a diameter of 5.25 angular degrees filled with a texture created by summing randomly arranged vertical Gabor micropatterns with an average wavelength of about 2 mm (λ = 8 pixels). The attractor stimuli (target image and decoy) were modulated by contrast, orientation, or spatial frequency. Distractor stimuli were circles without textures, similar to modulated ones in size and average brightness. Each part of the study was represented by a pair of modulated textures presented simultaneously (contrast modulation – spatial frequency modulation, contrast modulation – orientation modulation, orientation modulation – spatial frequency modulation) and divided into two series (Table 1).

At the beginning of each series, the subject was shown a graphic instruction, on which the target image was depicted on the left, and on the right – a decoy and a distractor. An example of the instruction is shown in Figure 1. The subject was tasked to report the location of the target stimulus as quickly as possible using the "left" and "right" keys. The sequence of successive parts and series of the experiment was randomized. Instructions and incentives were presented on a Philips 240V monitor, with a resolution of 1920 by 1080 pixels at a frame rate of 60 Hz (IPS, diagonal 23"). The subject's head was fixed in the frontal-chin rest at 60 cm from the screen. The procedure for presenting instructions, stimuli, and recording responses was written in Python 3 using the PsychoPy library.

Table 1

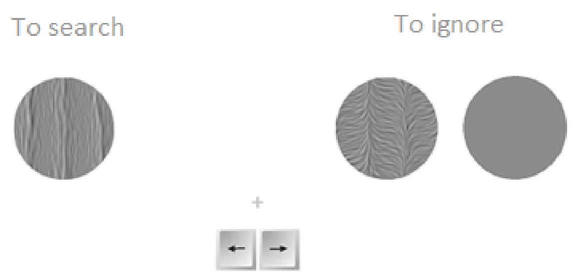
Experiment design

	Series 1 (100 trials)		Series 2 (100 trials)	
	Aim	Decoy	Aim	Decoy
MC – MSF	MC	MSF	MSF	MC
MC – MO	MC	MO	MO	MC
MO – MSF	MO	MSF	MSF	MO

Note: The Aim is a texture, the determination of the location of which is the task of the subject; *the Decoy* is a distracting texture presented simultaneously with the Aim; *MC* is a texture modulated by contrast; *MSF* is a texture modulated by spatial frequency; *MO* is a texture modulated by orientation.

Figure 1

Example slide instructions

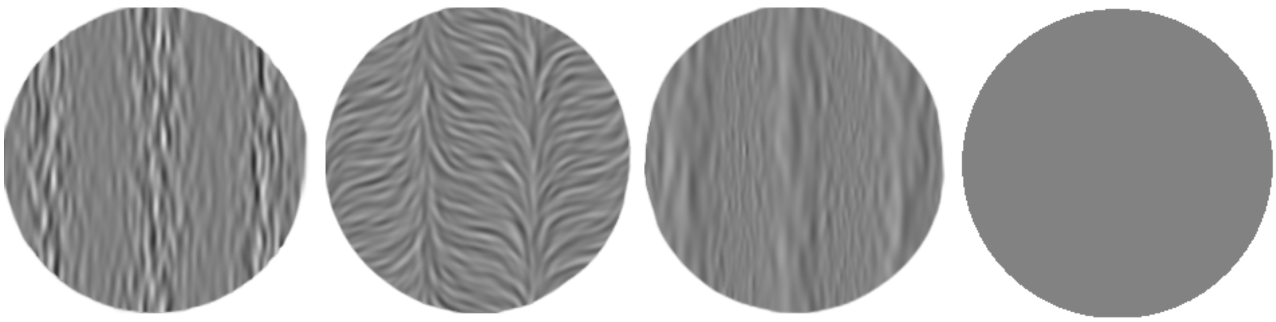


Here the Aim is a texture modulated by spatial frequency (MF), the Decoy is a texture modulated by orientation.

Each series consisted of 100 presentations. Each presentation began with a demonstration of a fixing point that lit up on the screen for 1000–2000 ms. Then 12 stimulus images were presented for 500 ms: 6 on the left and right. The stimulus images were placed at random positions within two windows on the left and right sides of the screen (Figure 3). One of the stimulus images was always the target texture, another was the distracting texture (decoy); each texture could be presented from the left and right with equal probability. The rest of the images were presented by distractors. Subjectively, the target texture and the decoy looked like circles with vertical stripes, the distractors looked like homogeneous gray circles identical to each other. Examples of incentives are shown in Figure 2. Each subsequent presentation was launched immediately after the response of the subject using the "left", "right" and "space" keys (no response). For each presentation, the response of the subject and the time spent were recorded. Each episode ended with an instruction to rest for 40 seconds, after which a new instruction was presented, in which the texture that was the target in the previous series became the decoy, and the target, respectively, became the texture that acted as the decoy. Thus, both series were performed similarly to each other, differing only in the instructions.

Figure 2

Images used as stimuli



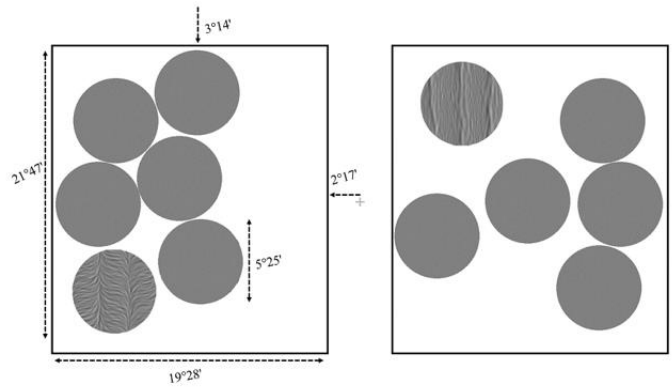
From left to right: contrast modulation (MC), orientation modulation (MO), spatial frequency modulation (MSF), distractor.

EEG recording was carried out monopolarly (Fz was used as an indifferent electrode) using the NV-40 digital amplifier of Neurobotics LLC in the parietal-occipital leads PO7/PO8 at a sampling frequency of 1000 Hz. The frequency band of the amplifier was limited to 30 Hz from above, 0.5 Hz from below. Synchronization of the graphics and EEG output was carried out using a light flux sensor through an analog synchronization channel of the amplifier. The post–stimulus epochs of the EEG were averaged separately for each subject, the target–decoy pair and the side from which the target stimulus was presented. The epochs associated with the erroneously determined position of the target stimulus were removed from the analysis, as well as epochs in which the response of the subject was delayed by more than 1 second.

For each subject, the average d–wave curve for each "target-decoy" pair was calculated, representing the millisecond difference in VP for counter- and ipsilateral presentations of the target stimulus. Individual difference curves were averaged, confidence intervals ($\alpha = 0.05$) were constructed for the results of averaging. Then, for each target–decoy pair, the average power of the N2pc component was calculated, expressed in the sum of all statistically significant negative values of the d-wave ($p < 0.05$).

Figure 3

Sizes of incentives and demonstration windows in angular degrees



The frames and dotted lines are shown for clarity. The stimulus content corresponds to the part of the study "MO (orientation modulation) – MSF (spatial frequency modulation)" (see Table 1). The Aim, Decoy and distractors are in random positions within the demonstration windows.

Results

Figure 4 shows the difference waves of the SSP mismatch for contra- and ipsilateral targets in the leads P07/PO8 in the time interval of 155–300 ms with the upper and lower bounds of the student confidence interval ($\alpha = 0.05$). The left shows the N2pc component in response to the MC as a goal, and the MO as a decoy, the graph on the right reflects the N2pc in response to the opposite situation.

N2pc in response to the condition "MC – target, MO – decoy" is registered at the level of statistical significance ($p < 0.05$) from 191 to 275 ms, reaching its peak (–0.69 ± 0.27 mv) at 243 ms.

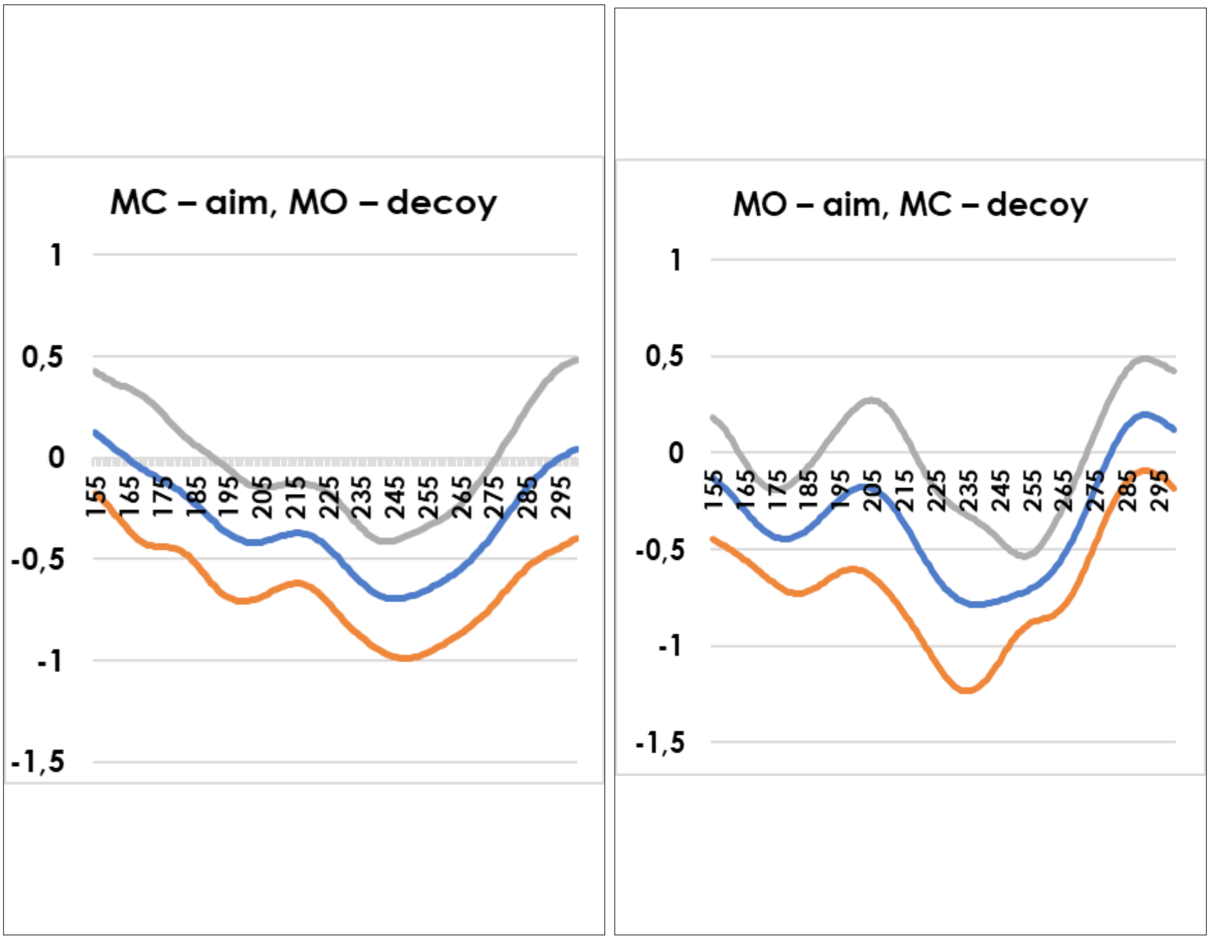
In the inverse problem, when orientation modulation was the target, and the decoy was represented by a texture modulated by contrast (the condition "MO – target, MC – decoy"), the N2pc component was recorded at the level of statistical significance ($p < 0.05$) at two time intervals: from 164 to 188 ms with a peak (–0.44 ± 0.24 mv) at 175 ms, and from 219 to 272 ms with a peak (–0.72 ± 0.18 mv) at 253 ms.

The total power of the N2pc component in the condition "MC – target, MO – decoy" was –55.08 ± 11.44 mv, for the inverse problem ("MO – target, MC – decoy") the power was –55.70 ± 13.51 mv. There were no statistically significant differences in the power index of the N2pc component for this pair of modulated textures.

Let's turn to the next pair of modulated textures. Figure 5 shows graphs of N2pc registered in leads P07/PO8 in the time interval of 155–300 ms with the upper and lower bounds of the student confidence interval ($\alpha = 0.05$). On the left, the N2pc component is presented in response to the MC as a target paired with a decoy in the form of a texture modulated by spatial frequency. The graph on the right reflects N2pc in response to the reverse situation.

Figure 4

N2pc in Po7/Po8 on a contrast modulated target (left) and an orientation modulated target (right)



The red and gray lines indicate, respectively, the lower and upper limits of the confidence interval for the d-wave. On the abscissa axis – time in ms, on the ordinate axis – the potential difference in mv.

N2pc in response to the condition "MC – target, MO – decoy" is registered at the level of statistical significance ($p < 0.05$) from 193 to 256 ms, reaching its peak (–0.60 ± 0.34 mv) at 244 ms. The average power of the N2pc component in significant areas of the d-wave was –42.25 ± 11.90 mv.

In the inverse problem (the condition "MO – target, MC – decoy"), there was no significant increase in negativity in the contralateral leads.

Consider the last pair of modulated textures. Figure 6 shows graphs of N2pc registered in leads P07/PO8 in the time interval of 155–300 ms with the upper and lower bounds of the student confidence interval ($\alpha = 0.05$). On the left is the N2pc component in response to the MO as a target paired with a decor in the form of a texture modulated by spatial frequency. The graph on the right reflects N2pc in response to the reverse situation.

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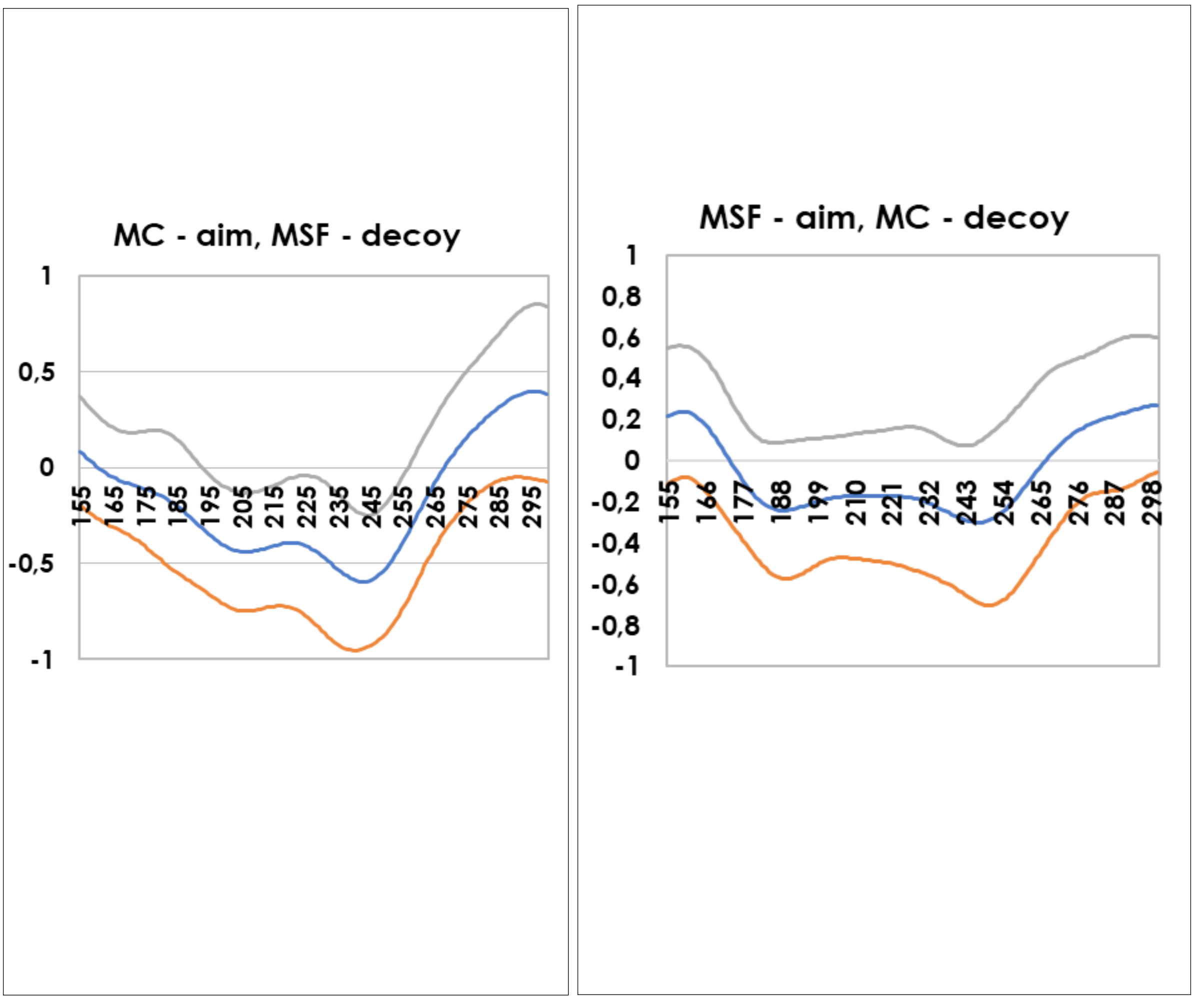
Figure 5

Difference waves in Po7/Po8 leads to a target modulated by contrast (left) and a target modulated by spatial frequency (right)



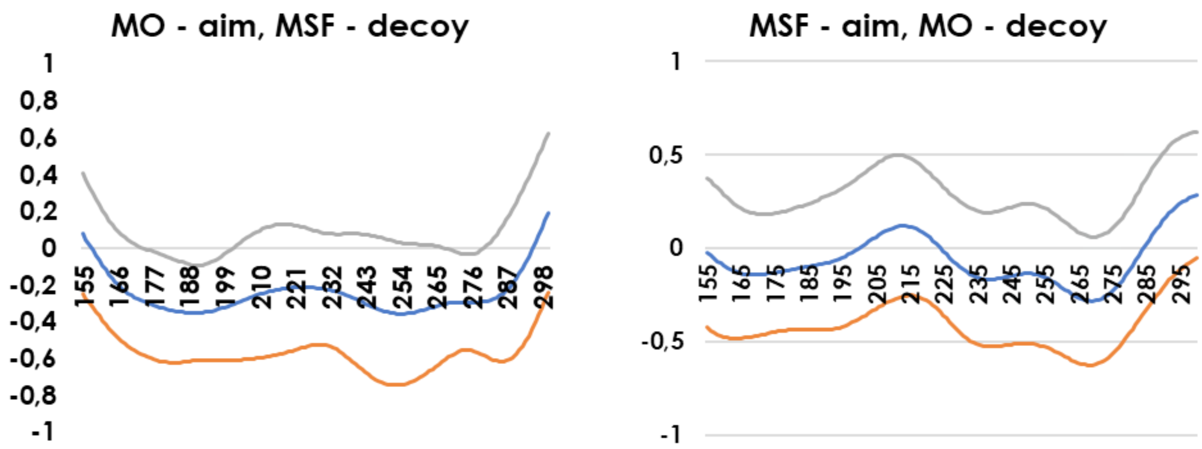
The red and gray lines indicate, respectively, the lower and upper limits of the confidence interval for the d-wave. On the abscissa axis – time in ms, on the ordinate axis – the potential difference in mv.

N2pc in response to the condition "MO – target, MSF – decoy" is recorded at the level of statistical significance ($p < 0.05$) at two time intervals: from 174 to 201 ms with a peak (–0.35 ± 0.25 mv) at 191 ms, and from 268 to 280 ms with a peak (–0.30 ± 0.25 mv) at 275 ms. The average power of the N2pc component for this condition was –22.27 ± 5.75 mv.

In the inverse problem (the condition "MSF – target, MO – decoy"), no statistically significant N2pc component was found in response to the target texture.

Figure 6

Difference waves in Po7/Po8 leads to a target modulated by orientation (left) and a target modulated by spatial frequency (right)



The red and gray lines indicate, respectively, the lower and upper limits of the confidence interval for the d-wave. On the abscissa axis – time in ms, on the ordinate axis – the potential difference in mv.

Discussion

The design of our study suggests equal relevance of stimuli acting as visual search goals: in each part of our experiment, the subject performed the same task, and the procedure for presenting stimuli was organized according to the same algorithm. In our opinion, there is no reason to assume that the subjects could experience influences that encourage them to subjectively distinguish some textures from others. The only factor modulating endogenous attention in our experiment was the instruction that meets the basic methodological requirements for experiments with N2pc registration (Luck, 2006).

We found that in the "contrast modulation – orientation modulation" pair, N2pc has a shorter latency period when the target of visual search is an orientation-modulated texture. This corresponds to the result obtained in the pair "orientation modulation – spatial frequency modulation". In this problem, the N2pc component also manifested early enough in response to an orientation-modulated texture as a target, with a peak (–0.35 ± 0.25 mv) at 191 ms. According to the conclusions formulated in a number of studies, the latent period of the N2pc component is associated with the physical characteristics of the visual scene: the salient stimulus is able to quickly attract the observer's attention even before the endogenous control mechanisms are activated, which is reflected in the early occurrence of the N2pc component (Bachman et al., 2020;

Mudrik & Deouell, 2022). Based on this, we can assume that orientation modulation is more noticeable both against the background of contrast modulation and against the background of spatial frequency modulation.

We found no manifestations of the N2pc component in response to spatial frequency modulation as a target. There was no statistically significant increase in negativity between contra- and ipsilateral leads either in the task when spatial frequency modulation was presented in conjunction with contrast modulation as a decoy, or in the task in which orientation modulation was the decoy. However, the absence of the N2pc component in itself is not an indicator of the absence of attention bias, since stimuli presented as distractions can reduce the N2pc component, leaving the target stimulus detectable (Zivony et al., 2018). We tend to interpret the result obtained by us as evidence of the upward influences of the textures-decoys, manifested due to their greater (relative to the texture modulated by spatial frequency) salience. In the inverse problems, when the spatial frequency modulation was the decoy, and the contrast and orientation modulations, respectively, were the goals, the N2pc component was registered at the significance level $p < 0.05$.

Conclusion

Based on the results obtained, we can draw the following conclusions:

1. Textures modulated by contrast and orientation attract attention significantly more than textures modulated by spatial frequency.

2. Textures modulated by contrast and orientation are probably detected due to exogenous control mechanisms. A direct confirmation of this hypothesis is the relatively low latency of the N2pc component.

The results obtained will significantly expand the understanding of the mechanisms of image formation and can be used in solving applied problems in the field of information technology and education.

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Conflict of Interest Information

The author has no conflicts of interest to declare.