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Enhancing links between visual short term memory, visual attention and cognitive control processes through practice: An electrophysiological insight

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ABSTRACT

The operation of attention on visible objects involves a sequence of cognitive processes. The current study firstly aimed to elucidate the effects of practice on neural mechanisms underlying attentional processes as measured with both behavioural and electrophysiological measures. Secondly, it aimed to identify any pattern in the relationship between Event-Related Potential (ERP) components which play a role in the operation of attention in vision. Twenty-seven participants took part in two recording sessions one week apart, performing an experimental paradigm which combined a match-to-sample task with a memory-guided efficient visual-search task within one trial sequence. Overall, practice decreased behavioural response times, increased accuracy, and modulated several ERP components that represent cognitive and neural processing stages. This neuromodulation through practice was also associated with an enhanced link between behavioural measures and ERP components and with an enhanced cortico-cortical interaction of functionally interconnected ERP components. Principal component analysis (PCA) of the ERP amplitude data revealed three components, having different rostro-caudal topographic representations. The first component included both the centro-parietal and parieto-occipital mismatch triggered negativity – involved in integration of visual representations of the target with current task-relevant representations stored in visual working memory – loaded with second negative posterior-bilateral (N2pb) component, involved in categorising specific pop-out target features. The second component comprised the amplitude of bilateral anterior P2 – related to detection of a specific pop-out feature – loaded with bilateral anterior N2, related to detection of conflicting features, and fronto-central mismatch triggered negativity. The third component included the parieto-occipital N1 – related to early neural responses to the stimulus array – which loaded with the second negative posterior-contralateral (N2pc) component, mediating the process of orienting and focusing covert attention on peripheral target features. We discussed these three components as representing different neurocognitive systems modulated with practice within which the input selection process operates.

1. Introduction

The operation of attention to visual stimuli typically follows a sequence of fundamental cognitive processes (Eckstein, 2011; Luck, 2012; Luck & Kappenman, 2012; Nakayama & Martini, 2011) as follows. First, a goal must be activated to guide the allocation of attention. In the case of performing a visual search task, the target's features such as colour and shape need to be stored as a *search template* in visual short term memory (VSTM) to guide attention to task-relevant objects. Second, sensitivity is increased for objects containing features specified by the *search template* so that they have priority among others for further processing. Third, there is a shift of covert spatial attention, triggered towards peripheral locations containing objects potentially sharing task-relevant features with the *search template*. Fourth, attention is adjusted and focused around the relevant object, depending on its size and the proximity of distracting objects. These last two cognitive processes are performed to facilitate the perception and storage in VSTM of task-relevant objects with the intervention of feature-based attention. The fifth step is the comparison and integration of representations of the current observed task-relevant target object and those available in VSTM as part of *search template* (Bennett, Duke, & Fuggetta, 2014; Fuggetta, Bennett, & Duke, 2015). The current study examined the time course of Event-Related Potential (ERP) components which play a role in the processes involved in visual attention. The main purpose of the study was to enhance the understanding of which neurocognitive stages underlying the links between VSTM, visual

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attention and cognitive control processes can be improved through experience and practice.

The first four cognitive processes described above can overall be considered an integral part of the *input selection* construct of attention – the selection of task-relevant inputs for further processing – as defined in a theoretical framework of attention put forward by Luck and Gold (2008). It is important to consider that the domain of input selection has been further distinguished between the *control of selection* – the process that directs attention to task-relevant items – and the *implementation of selection* – the process that enhances the processing of the relevant items and suppress the irrelevant items (Luck & Gold, 2008). The control of selection typically involves prefrontal and parietal cortices, and the implementation of selection typically occurs within the visual cortex that processes the inputs (Luck & Gold, 2008). Input selection usually depends on the executive control system to set the input selection parameters so that it will select the task-appropriate information of the to-be-attended input and suppress the to-be-ignored input.

The fifth step described above – in which representations of the cue are integrated with representations of the target in VSTM – involves an executive-control monitoring mechanism which is in place throughout the sequence of cognitive processes to perform a single rule (i.e. categorisation task). In the current study we used a novel paradigm which combines a match-to-sample task with a memory-guided efficient visual-search task (Bennett et al., 2014; Fuggetta et al., 2015). This paradigm allowed us to assess a wider range of cognitive mechanisms than in traditional visual search paradigms. In performing this paradigm, behavioural responses are slowed and less accurate when a salient target stimulus embedded in a search array of distracters contains different features from with those in the *search template* (i.e. mismatch trials), making the comparison of memory representations more demanding. Adopting Luck and Gold's (2008) framework, the current paradigm can be considered an input selection task, where a single executive control rule is used to perform the categorisation task, but a failure of input selection causes this rule to be applied less efficiently (Luck & Gold, 2008

Previous research has established that visual search can be improved through experience or practice (An et al., 2012; Clark, Appelbaum, van den Berg, Mitroff, & Woldorff, 2015; Hamame, Cosmelli, Henriquez, & Aboitiz, 2011; Sigman & Gilbert, 2000; Sireteanu & Rettenbach, 1995). In particular, Clark et al. (2015) investigated the neural mechanisms underlying practice-related improvement in behavioural performance on a visual search task with target pop-out arrays. Four ERP components were assessed and found to be modulated with practice. The results showed: (1) increased amplitude of the posterior N1 component suggesting enhancement of early sensory responses to an exogenous visual array (Clark et al., 2015); for review on N1, see (Hillyard, Vogel, & Luck, 1998); (2) an earlier onset and larger amplitude of the second negative posterior-contralateral (N2pc) component, indicating enhanced attentional orienting (Clark et al., 2015), and focusing of covert attention on a peripheral location (Luck et al., 1994); (3) a reduced amplitude of the sustained posterior contralateral negativity component (SPCN), reflecting lower demands of maintaining visual information in working memory and/or target discrimination process (Eimer & Kiss, 2010; Jolicoeur, Brisson, & Robitaille, 2008); (4) an earlier lateralised readiness potential (LRP) (Coles, 1989), related with improvements in motor-response preparation and execution (Clark et al., 2015). However, this investigation did not assess several ERP components related to feature-based attention. Neural mechanisms which support these processes may contribute to the enhanced behavioural performance in visual search tasks with practice.

Here, we primarily aimed to extend previous electrophysiological findings (An et al., 2012; Clark et al., 2015; Hamame et al., 2011) to further enhance the understanding of visual neural mechanisms underlying improvements in behavioural performance with practice. Thus the modulation of perceptual and post-perceptual cognitive processes was investigated in a total of six ERP components that are involved in the operation of attention in vision: (1) the early sensory evoked N1, which reflects early sensory responses to the entire array (Clark et al., 2015); (2) the bilateral anterior P2, which reflects automatic detection of pop-out stimuli (Luck & Hillyard, 1994a, 1994b); (3) the N2pc component, which reflects the process of orienting and focusing covert attention on peripheral target features (Luck et al., 2006, 1994); (4) the bilateral anterior N2 (or N270), observed when subjects actively search for a target that differs from the rest of the array (Luck & Hillyard, 1994a) and for stimuli containing conflicting features (i.e. mismatch trials, for a review see Folstein & Van Petten, 2008); (5) the N2-posterior-bilateral component (N2pb) which is involved in categorising stimuli (Renault, Ragot, Lesevre, & Remond, 1982) and is larger for colour pop-out stimuli (Luck & Hillyard, 1994a); and (6) the post-perceptual mismatch-triggered negativity (MTN) component, which has a bilateral fronto-central and temporo-posterior scalp distribution and appears in a delayed match-to-sample task when the mismatch between the target template in VSTM and the stimulus has at least two dimensions, such as shape and colour (Bennett et al., 2014; Wang, Cui, Wang, Tian, & Zhang, 2004; Wang et al., 2003; Zhang, Wang, Li, Wang, & Tian, 2005).

With the number of ERP components examined in this report it might be the case that they are not independent. With so many under scrutiny, it becomes difficult to know which ones represent distinct neurocognitive processes. Thus a further aim of the study was to identify any underlying structures in the relationship between ERP components that account for unique variance and represent distinct temporal/spatial contributions to the activity observed at the scalp. To explore any such relations, we submitted the amplitude of ERP data to standard principal component analyses (PCA) with rotation. PCA methodology is a well-established exploratory analysis technique that has been used with ERP data for highlighting hidden relations that explain the most variance in a dataset as a whole (Dien, 2012; Kayser & Tenke, 2006).

Correlations between behavioural and electrophysiological measures will be also implemented to examine which neurocognitive processing stages measured with ERPs are the greater contributors to the predicted improvement of behavioural performance (i.e. faster and more accurate responses) with practice. Furthermore, the modulation through practice in the association between ERP components, recorded from same or different rostro-caudal regions of the scalp, will also be assessed. This correlation analysis will further inform us about the role of cortico-cortical interactions of functionally connected regions which might account for the predicted modulation of ERP measures (i.e. earlier onset and larger amplitude of N2pc) in association with enhancement of links between VSTM, visual attention and cognitive control processes through visual-cognitive learning.

2. Method

This study was approved by the local ethical committee of the University of Leicester's Department of Neuroscience, Psychology and Behavior, in accordance with the Declaration of Helsinki. All participants gave written informed consent and received course credit for participating. Participants were fully debriefed about the purpose of the study.

2.1. Participants

An initial group of 30 (22 females, 18–26 years, Mean ± SE 20.31 ± 0.32 years, 26 right handed) undergraduate psychology students from the University of Leicester (UK) with normal or corrected-to-normal visual acuity and colour vision were selected to participate in the study. No participants dropped out between the sessions. All participants reported no use of medication, history of