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Spatiotemporally dissociable neural signatures for generating and updating expectation over time in children: A High Density-ERP study

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ABSTRACT

Temporal orienting (TO) is the allocation of attentional resources in time based on the *a priori* generation of temporal expectancy of relevant stimuli as well as the *a posteriori* updating of this expectancy as a function of both sensory-based evidence and elapsing time. These processes rely on dissociable cognitive mechanisms and neural networks. Yet, although there is evidence that TO may be a core mechanism for cognitive functioning in childhood, the developmental spatiotemporal neural dynamics of this mechanism are little understood. In this study we employed a combined approach based on the application of distributed source reconstruction on a high spatial resolution ERP data array obtained from eighteen 8- to 12-year-old children completing a TO paradigm in which both the cue (Temporal *vs.* Neutral) and the SOA (Short *vs.* Long) were manipulated. Results show both cue (N1) and SOA (CNV, Omission Detection Potential and Anterior Anticipatory Index) ERP effects, which were associated with expectancy generation and updating, respectively. Only cue-related effects were correlated with age, as revealed by a reduction of the N1 delta effect with increasing age. Our data suggest that the neural correlates underlying TO are already established at least from 8 to 12 years of age.

1. Introduction

The ability to anticipate 'where' and 'when' events may occur stands as a fundamental skill which allows us to selectively orient our attention in space and time (Coull and Nobre, 1998), while ignoring a myriad of other irrelevant environmental stimuli. However, while the mechanisms underlying the orienting of attention in space (*i.e.*, spatial orienting) have been thoroughly investigated in both adults (Corbetta and Shulman, 2002) and children (Amso and Scerif, 2015), the ability to orient attention in time (temporal orienting or TO) has slipped out of core attention research for many years (Nobre, 2001; Nobre and Kastner, 2014). This issue is of pivotal importance given the key role of temporal attention as a gating mechanism to select information for further computational processing, including perception, action, learning, memory and executive control (Correa, 2010).

Actually, attentional selection operates *through* time, but it is also *limited* in time, since it depends on the structural constraints imposed by the limited capacity of the human neurocognitive system. In this sense, investigating the temporal orienting of attention from a developmental cognitive neuroscience perspective may constitute a powerful heuristic for shedding light onto the temporal attention constraints and the dynamics leading to the adult end-state. Moreover, from a clinical perspective, temporal attention has been claimed to be selectively impaired in several developmental disabilities, including dyslexia (Visser, 2014), language disorders (Dispaldro et al., 2013; Dispaldro and Corradi, 2015), Attention Deficit/Hyperactivity Disorder (Carelli and Wiberg, 2012), and autism (Ronconi et al., 2013). Therefore, a better understanding of the neurocognitive underpinnings of TO as a core selective attentional mechanism in typically developing children may open new lines of research to create early, specific intervention strategies for atypical development.

The existing literature on adult individuals shows that TO can be generated by establishing temporal expectancy *a priori* according to environmentally available cues, like a temporally regular structure or a discrete signal providing predictive information about the onset of a task-relevant stimulus. In both cases, TO operates by selectively biasing attentional resources at specific points in time, resulting in faster and better behavioural performance at multiple cognitive levels (Coull and Nobre, 1998; Correa and Nobre, 2008; Correa, 2010).

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Once generated, temporal expectations can be further updated *a posteriori* as a function of (1) the sensory evidence that events actually occur when expected and (2) the elapsing time itself, which intrinsically biases the distribution of attentional and motor resources over time, a phenomenon also known as the Hazard Function or HF (Niemi and Näätänen, 1981; Luce, 1986; Nobre et al., 2007; Coull, 2009a).

In a recent event-related potential (ERP) study we showed dissociable neural signatures for expectancy generation driven by discrete, informative cues and HF-related expectancy updating (Mento et al., 2015). Specifically, the first relies on a larger centro-parietal Contingent Negative Variation (CNV) showing a modulation as a function of target predictability, with the largest CNVs for the targets with the highest predictability, in line with previous literature (Capizzi et al., 2013; Mento, 2013). By contrast, HF-related expectancy updating resulted in a sustained frontal activity, showing increasing amplitude with increasing boost of subjective expectancy as a function of the passage of time. Furthermore, the source reconstruction analyses allowed identification of the origin of the CNV in a left sensorimotor cortical network, while the HF-related ERP activity was mainly generated from the lateral prefrontal cortices. Remarkably, these findings provided converging evidence with the neuroimaging literature showing distinct parietal and frontal functional networks for generating and updating temporal expectancy, respectively (Coull et al., 2000; Vallesi et al., 2009; Vallesi, 2010; Coull, 2011).

Yet, in spite of the increasing number of publications on adults, the neurocognitive mechanisms underlying TO in children are less clear. In a recent study, Johnson and collaborators (Johnson et al., 2015) employed a combined spatio-temporal cueing paradigm and found behavioural evidence that 6–16-year-old children are able to voluntarily orient their attention in space but not in time. However, as the authors argued, the lack of TO effects in their study may be due to the fact that the target was lateralized. Indeed, unlike adults (Coull and Nobre, 1998), the spatial uncertainty of target appearance may have diminished the utility of the time cue in children. In line with this account, Mento and Tarantino (2015) introduced a simplified, child-friendly TO paradigm in which the fixed central presentation of both targets together with the use of a block-wise experimental design and a fully valid CUE-SOA association allowed the demonstration of TO as early as at six years of age, suggesting that dedicated neural mechanisms are already operating at this age.

In the present study, we expanded upon these results by investigating the neural bases of TO from a developmental perspective. To this purpose, we recorded the high-density electroencephalographic (HD-EEG) activity of 8–12-year-old healthy children while administering a child-adapted TO paradigm purposely designed to investigate the neural correlates of TO generation and updating. More specifically, we assessed whether there is evidence of dissociable neural patterns for generating and updating expectation over time in children, and whether this relies on specific spatiotemporal neural signatures.

2. Materials and methods

2.1. Participants

Data were collected from eighteen healthy children [mean age: 9.3 years (SD: 2.05); range: 8–12 years; 8 males; 16 right-handed]. Since preliminary analyses did not show age-related behavioural differences, we initially considered all children as a single group and subsequently ran correlational analyses between electrophysiological components of interest and age. Visual acuity was normal or corrected to normal. All experimental methods had been previously approved by the Research Ethics Committee of the School of Psychology, University of Padua (prot. N. 1179).

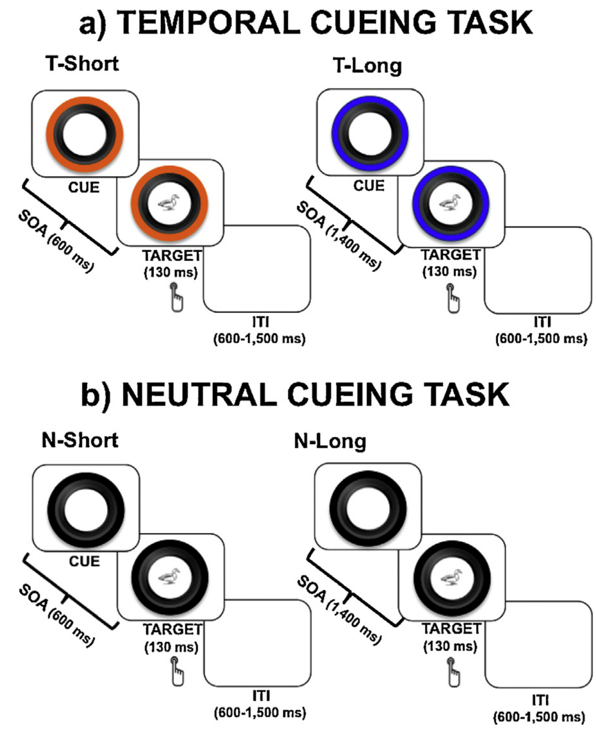

Fig. 1. Experimental paradigm. In the Temporal Cueing task (a) the visual cue provided fixed temporal information concerning the SOA duration, which could be short (left panel) or long (right panel), according to the colour of the cue. By contrast, in the Neutral Cueing task (b) participants never knew in advance the duration of the SOA, which could nevertheless have the same short or long duration as in the Temporal Cueing task.

2.2. Stimuli and task

We employed the same experimental paradigm previously used by Mento and Tarantino (2015) to investigate the behavioural correlates of temporal orienting in children (Fig. 1). Stimuli were presented on a 17-in. monitor at a resolution of 1280 × 1024 pixels. Participants were seated comfortably in a chair at a viewing distance of ~60 cm from the monitor. All participants performed two different cueing tasks within the same experimental session; these consisted of a temporal cueing task and a neutral cueing task, which were administered block-wise rather than trial-by-trial in order to reduce the top-down control required to switch continuously from a predictive to a non-predictive setting, which may result in additional difficulty for children. Importantly, the two tasks were matched for sensorimotor requirements, since the sequence of stimuli and the required responses were always the same, with the only difference between conditions being the level of temporal predictability of the target. In both tasks the trial structure was the same, as described below.

Each trial began with the display of a visual cue in the center of the screen, followed by the presentation of a target stimulus. The visual cue lasted on the screen until target onset and consisted of a picture of a black camera lens surrounded by a circle (total size of the stimulus: 840 × 840 pixels, 144 dpi, 10.62° × 10.54° of visual angle). The target stimulus consisted of a gray-scale picture of an animal, which was displayed centrally within the camera lens (840 × 840 pixels, 144 dpi, 10.62° × 10.54° of visual angle) until the response or a maximum of 3000 ms. The cue-target stimulus-onset-asynchrony (SOA) was manipulated (either 600 or 1400 ms). The Inter-Trial-Interval (ITI) was randomly and continuously