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Early multisensory attention as a foundation for learning in multicultural Switzerland

Turoman Nora

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Département de Radiologie

EARLY MULTISENSORY ATTENTION AS A FOUNDATION FOR LEARNING IN MULTICULTURAL SWITZERLAND

Thèse de doctorat en Neurosciences

présentée à la

Faculté de Biologie et de Médecine
de l'Université de Lausanne

par

Nora Turoman

MSc Université d'Oxford, Royaume-Uni
Psychologue diplômée de l'Université Métropolitaine de Cardiff, antenne de Singapour

Jury

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Prof. Dr. Micah M Murray, Directeur
Dr. Pawel J. Matusz, Co-Directeur
Prof. Dr. sc. Nat. Silvia Brem, Expert
Prof. Monica Gori, Expert
Dr. Duncan Astle, Expert

Thèse n° 276

Lausanne 2020

Programme doctoral interuniversitaire en Neurosciences des Universités de Lausanne et Genève

LEMANIC NEURO SCIENCE DOCTORAL SCHOOL

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Lausanne, le 19.6.2020

pour Le Doyen
de la Faculté de Biologie et de Médecine

Prof. Niko GELDNER
Directeur de l'Ecole Doctorale

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Abstract

Traditional laboratory research on visual attentional control has largely focused on adults, treated one sensory modality at a time, and neglected factors that are a constituent part of information processing in real-world contexts. Links between visual-only attentional control and children's educational skills have emerged, but they still do not provide enough information about school learning. The present thesis addressed these gaps in knowledge through the following aims: 1) to shed light on the development of the neuro-cognitive mechanisms of attention engaged by multisensory objects in a bottom-up fashion, together with attentional control over visual objects in a top-down fashion, 2) to investigate the links between developing visual and multisensory attentional control and children's basic literacy and numeracy attainment, and 3) to explore how contextual factors, such as the temporal predictability of a stimulus or the semantic relationships between stimulus features, further influence attentional control mechanisms. To investigate these aims, 115 primary school children and 39 adults from the French-speaking part of Switzerland were tested on their behavioural performance on a child-friendly, multisensory version of the Folk et al. (1992) spatial cueing paradigm, while 129-channel EEG was recorded. EEG data were analysed in a traditional framework (the N2pc ERP component) and a multivariate Electrical Neuroimaging (EN) framework. Taken together, our results demonstrated that children's visual attentional control reaches adult-like levels at around 7 years of age, or 3rd grade, although children as young as 5 (at school entry) may already be sensitive to the goal-relevance of visual objects. Multisensory attentional control may develop only later. Namely, while 7-year-old children (3rd grade) can be sensitive to the multisensory nature of objects, such sensitivity may only reach an adult-like state at 9 years of age (5th grade). As revealed by EN, both bottom-up multisensory control of attention and top-down visual control of attention are supported by the recruitment of distinct networks of brain generators at each level of schooling experience. Further, at each level of schooling, the involvement of specific sets of brain generators was correlated with literacy and numeracy attainment. In adults, visual and multisensory attentional control were further jointly influenced by contextual factors. The semantic relationship between stimulus features directly influenced visual and multisensory attentional control. In the absence of such semantic links, however, it was the predictability of stimulus onset that influenced visual and multisensory attentional control. Throughout this work, the N2pc component was not sensitive to multisensory or contextual effects in adults, or even traditional visual attention effects in children, and it was owing to EN that the mechanisms of visual and multisensory attentional control were clarified. The present thesis demonstrates the strength of combining behavioural and EEG/ERP markers of attentional control with advanced EEG analytical techniques for investigating the development of attentional control in settings that closely approximate those that we encounter in everyday life.

List of abbreviations

- TAC – task-set contingent attentional capture
- fMRI – functional magnetic resonance imaging
- BOLD – blood-oxygen-level-dependent
- PET – Positron Emission Tomography
- EEG – Electroencephalography
- ERP – Event Related Potential
- LOC – lateral occipital complex
- EN – Electrical Neuroimaging
- GFP – Global Field Power
- DISS – Global Dissimilarity
- TAAHC – Topographic Atomize and Agglomerate Hierarchical Clustering
- GEV – global explained variance
- EF – executive functions
- MSE – multisensory enhancement of attentional capture
- 1P – 1st grade children
- 3P – 3rd grade children
- 5P – 5th grade children
- FSIQ – Full Scale IQ
- WISC-V – Wechsler Intelligence Scale for Children, Fifth Edition
- WPPSI-IV – Wechsler Preschool & Primary Scale of Intelligence, Fourth Edition
- EDA 4-11 – Evaluation Des fonctions cognitives et des Apprentissages de 4 à 11 ans
- TCC – Target Colour-Cue
- NCC – Nontarget Colour-Cue
- AV – AudioVisual
- V – Visual
- DO – Distractor onset
- MR – Multisensory Relationship
- D_V – Target Difference Visual
- D_{AV} - Target Difference AudioVisual
- Pd – Distractor Positivity

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Chapter 1: Introduction

Everyday environments, from the high street to the home, are inundated with information, but our brains have only a limited amount of capacity to process such incoming inputs. Therefore, successful interaction with the environment relies on selective attention, that is, the ability to select information that is relevant to our current goals and ignore that which is not. Over the past decades, research in the field of selective attention has made great strides in understanding the neuropsychological mechanisms of how attentional selection is biased ,or ‘controlled’, by internal factors, such as our current goals, in a top-down fashion, versus external factors, such as salience (the quality of standing out or being prominent in a given environment), in a bottom-up fashion. However, the field’s tendency to rely on adult research subjects and controlled laboratory settings has left some important gaps in knowledge.

It remains poorly understood how selective attention operates in real-world conditions, outside of the research laboratory. In real-world environments, information is routinely presented to multiple senses at a time, and it is known that the brain has a tendency to integrate information across the senses. Little is known about how such integrated, ‘multisensory’, information controls attentional selection. Even less is known about how such control develops from childhood to adulthood, since children’s abilities to control their attentional deployment or integrate information across the senses are not entirely clear. Nonetheless, evidence has mounted that children’s visual attentional control skills are related to fundamental educational skills like literacy and numeracy. However, the link has tended to account more for children’s numeracy skills than literacy skills, and evidence for any causal relationships has been inconclusive. Finally, apart from bottom-up multisensory influences on attentional control, real-world settings also engender top-down influences that may not be related to current goals, but rather to the timing at which information is presented, as well as its semantic meaning. Little to no research has examined the interplay of such diverse top-down and bottom-up influences on attentional control, simultaneously, as they occur in the real world.

The present doctoral thesis aimed to address the above gaps in knowledge while bridging the somewhat disparate cognitive neuroscience research on selective attention, multisensory processing, cognitive development, and education. We did so by investigating the following: 1) the developmental trajectory of attentional control mechanisms in multisensory settings, 2) the links between children’s visual and multisensory attentional control processes and their literacy and numeracy skills, and 3) the influence of contextual factors, such as timing and semantics, on adult attentional control processes in multisensory settings.

1. Visual attentional control in adults

Early explorations of the mechanisms by which attentional selection is executed focused on visual attention in healthy adult populations, and spatial location as a determinant of attentional selectivity. In his seminal study, Posner (1980) demonstrated that a target flash of light that could be presented in one of several locations on a screen was processed faster when preceded by a central cue that pointed to the upcoming location of the flash. However, peripherally presented illuminated cues also sped up target processing when they correctly indicated the upcoming location of a target. These findings suggested that the deployment of (spatial) attention is controlled by: 1) 'endogenous' factors stemming from the individual, such as current goals and expectations, and 2) 'exogenous' factors stemming from the external world, such as salient peripheral events (i.e., events that stand out in their environment). Posner's research (as well as others, see e.g., Broadbent, 1982) suggested that it is the location of the relevant information that guides attentional focus, which then enhances the processing of the attended information. However, in the real world, the location of relevant information is rarely known in advance. For example, when searching for a friend on a crowded city street, or when looking for a mobile phone on a messy bedroom floor, we may know what our target looks like, but not necessarily where it is likely to be located. Treisman and Gelade (1980) adapted such scenarios to the research laboratory by developing the so-called visual search paradigm. In this task, people simply had to respond to a target object that was presented amidst a multitude of distractors. They showed that when the target was defined by a unique feature (a red O amidst green X's and O's), search was fast, but when the target was defined by a conjunction of features (a red O amidst red X's and green O's), search was slow. This, in contrast to Posner's findings, suggested that object features, rather than location in space, could be the main guiding force of attentional selection. Since this study, criticisms have emerged about its dichotomic understanding of search processes (Wolfe, 1998, 2014), and alternative theories have been proposed (Wolfe, 2007, 2014; Duncan & Humphreys, 1989, 1992). However, the visual search task has continued to lend itself to the investigation of mechanisms that control attentional selection.

Though bottom-up stimulus-driven (exogenous) and top-down goal-based (endogenous) factors are conceptually clearly delineated, there has been an ongoing debate as to which factor has priority in controlling selective attention (Theeuwes, 2010). By developing a variant of the visual search task called the 'additional singleton paradigm', Theeuwes (1991) demonstrated that search for a singleton target (i.e., 'the odd one out', a unique diamond shape in an array of circles) will be slower when a distractor with an irrelevant but salient feature (a red circle in an array of white circles) is present in the search array. This finding was taken as evidence that attention will preferentially be captured by the stimulus with the greatest salience. In other words, he argued that bottom-up factors had and advantage over top-down factors in the control of attention. In contrast, Folk et al. (Folk, Remington, & Johnston, 1992) showed that current goals determined attentional selection, even in the case of stimuli that are irrelevant to the current goals. They developed a spatial cueing paradigm, where participants searched for a colour-defined target in a search array, which was preceded by an array of distractors containing one cue that was either also defined by its colour, or by an abrupt onset. They found that attentional capture, indexed by spatial cueing (a difference in response speed to targets in cued versus uncued locations), was evoked only by colour-defined distractors. This prompted them to propose the ‘task-set contingent involuntary orienting’ hypothesis (henceforth referred to as ‘task-set contingent attentional capture’ or TAC) whereby salient but irrelevant objects will only capture attention if they share features with the target and are therefore potentially task-relevant. In other words, top-down factors had primacy in controlling attentional selection. The two conflicting accounts were best reconciled by Bacon and Egeth (1994), with their proposition of different ‘search modes’ being active for each of the two above paradigms. In the additional singleton paradigm, the target could be successfully identified by searching the display for the ‘odd one out’ (so-called singleton-detection mode). Such a strategy would make search ineffective in the faster and more demanding (more potential target stimuli) spatial cueing paradigm, thus necessitating a switch to search by a specific feature (so-called feature-search mode). In a version of the additional singleton paradigm, they demonstrated that singleton-detection mode was ineffective when there were other uniquely shaped distractors in the same search array as the unique target and colour singleton distractor. This suggested that task demands rather than local contrast differences determined whether salient distractors captured attention. Taken together, this study supported the idea that top-down goal-relevance has a primary role in visual attentional control, while the role of bottom-up salience is rather secondary.

The rise of brain imaging and recording methods in studying cognition, such as single-cell electrophysiological recordings in animals, and electroencephalography (EEG), Positron Emission Tomography (PET), and functional Magnetic Resonance Imaging (fMRI) in humans, has further clarified the hierarchical relationship between top-down and bottom-up control factors, while also motivating new, more nuanced models of attentional control. The influential biased competition model of visual attention (Desimone & Duncan, 1995) has argued that, in multi-stimulus contexts, stimuli compete for our brain’s limited attentional resources. In neural terms, stimuli compete for driving the firing of neurons whose receptive fields they are in, which translates into the representation of these stimuli in the visual cortex. Stimuli that ‘win’ the competition at lower levels of the visual processing hierarchy are propagated forward to higher levels. In other words, the stimulus that is selected for perceptual processing will also be the one that will be encoded into short-term memory or that will control visual attentional shifts. Evidence for such a mutually suppressive interaction between stimuli has come from single-cell recordings in the ventral visual system of nonhuman primates. Here, neural firing in response to a preferred stimulus in a receptive field was reduced in the presence of a second stimulus in the receptive field (e.g., Luck et al., 1997; Miller et al., 1993). The competition is primarily biased towards stimuli that are relevant to current behavioural goals. For instance, recordings in primate inferior temporal cortex and V4 demonstrated that, when both goal-relevant and irrelevant stimuli were within a neuron’s receptive field, neural firing was enhanced for goal-relevant stimuli and attenuated for irrelevant stimuli (Chelazzi et al., 1993; Moran & Desimone, 1985). Importantly, in the Moran and Desimone study (1985), the location of the target stimulus was indicated beforehand. Thus, the study demonstrated that allocating attention to a spatial location can resolve the competition for attentional selection, and not merely afford enhanced perceptual processing, as the attentional spotlight theory would suggest. Meanwhile, in the study of Chelazzi et al. (1993), the location of the target stimulus was unknown, but a cue containing its features was presented ahead of a multi-stimulus array containing a target (similarly to Folk et al., 1992). In the delay between the presentation of the cue and the target, nonhuman primate inferior temporal cortex neurons selective for target features showed sustained increases in firing relative to neurons selective for irrelevant stimulus features. This was taken as a neural correlate of the so-called attentional template (Duncan & Humphreys, 1989), that is, a representation of the goal-relevant information in working memory that can guide top-down attentional control. With this, the study suggested that when the target location is unknown, object features guide attentional selection via representations of target features held in working memory. However, bottom-up control factors can also resolve the competition between stimuli. Based on findings that neural firing for preferred stimuli decreases in the presence of similar stimuli in the surround of the receptive field (Allman et al., 1985; Desimone et al. 1985), Desimone and Duncan (1995) suggested that, conversely, the more stimuli stand out from their surroundings, the more firing they evoke, thus ‘winning’ the competition. In line with the above conclusions after Bacon and Egeth (1994), the biased competition model (Desimone & Duncan, 1995) supports that bottom-up salience will resolve the competition in settings where the stimulus is unique in comparison to its surroundings. Whereas, in settings where every stimulus is unique, top-down goal-relevance will resolve the competition between stimuli.

In humans, competition between stimuli in a visual scene, and the biasing of competition by top-down or bottom-up influences depending on the task context, have been supported by studies using PET (e.g., Corbetta et al., 1990, 1991) and fMRI (e.g., Beck & Kastner, 2005, 2007; Kastner et al., 1998). Both of these imaging methods rely on the assumption that task-induced neural activity is related to metabolic changes in the brain, such as the level of blood oxygenation (referred to as BOLD in fMRI specifically; for a more detailed explanation see Barth & Poser, 2011, pp. 1942). fMRI is generally held to have excellent spatial resolution (but poor temporal resolution), which is why fMRI has been instrumental in uncovering the principal brain regions involved in top-down and bottom-up visual attentional control. In a pioneering study, Kastner et al. (1998) showed participants a series of visual images individually and simultaneously, during an fMRI scan. They found that across the visual pathway, simultaneous presentations evoked weaker BOLD responses than individual presentations, confirming competition between stimuli in human visual cortices. Moreover, this difference in activation increased along the hierarchy from V1 to V4 to the temporo-occipital area of the inferior temporal cortex. This finding supports the idea that the outcome of the competition at early levels of information processing is integrated at higher levels of processing. However, evidence was beginning to emerge that areas beyond the visual pathways were also involved in visual selective attention (e.g. Corbetta et al, 1990, 1991). Across the 90's and early 2000's, imaging evidence converged that top-down control of visual attentional selection activated dorsal parietal areas such as the superior parietal lobule and intraparietal sulcus, and well as frontal areas such as the human homologue of the frontal eye field in the prefrontal cortex (e.g., Gitelman et al., 1999; Kastner et al., 1999; Nobre et al., 1997; Wojciulik & Kanwisher, 1999). Evidence had also mounted for the roles of the temporo-parietal junction and various sites in the prefrontal cortex in directing attention to salient stimuli (e.g., Downar et al., 2002; McCarthy et al., 1997; Yamaguchi & Knight, 1991). This work culminated in Corbetta and Shulman's proposition of a dorsal fronto-parietal network of brain regions (chiefly frontal eye field and intraparietal sulcus) responsible for orchestrating goal-based top-down control of attention, and a ventral fronto-parietal network (chiefly ventral frontal cortex and temporo-parietal junction) orchestrating the re-orienting of attention to salient but irrelevant stimuli (Corbetta & Shulman, 2002). Since then, the role of prefrontal areas and dorsal parietal areas in top-down visual attentional control has been further supported (e.g., Bressler et al., 2008; Rossi et al., 2009; Greenberg et al., 2010; Tamber-Rosenau et al., 2011), while the role of the temporo-parietal junction in bottom-up salience-driven control has changed somewhat. Instead of reorienting attention to *any* salient stimuli outside of the current focus, the temporo-parietal junction may only reorient to unattended stimuli that are potentially goal-relevant (e.g., Serences et al., 2005; Corbetta, Patel & Shulman, 2008). These findings provided additional support to the hierarchy of top-down over bottom-up influences on visual attentional control, where goal-relevance determines whether salient stimuli will capture attention.

Complementarily to spatially-resolved fMRI research, EEG with its sub-millisecond temporal resolution, helped situate selective attention mechanisms within the context of more general stages of visual information processing. Here, the event-related potential (ERP) technique has been particularly useful. The EEG represents a scalp-level measurement of summated postsynaptic voltage potentials resulting from neurotransmission predominantly in cortical pyramidal neurons (Woodman, 2010). In order to isolate neural signatures of specific stimulus-locked cognitive processes from the EEG signal, the signal must be averaged over a period of time anchored to a specific stimulus, thus obtaining an ERP. In a stimulus-locked ERP, one can observe a series of voltage deflections, commonly referred to as components (Luck, 2012), which are defined by their latency and topography. In the past 50 years, the ERP approach has helped reveal three mechanisms by which visual attention affects information processing: sensory 'gating' mechanisms, attentional preparatory mechanisms, and the selection of targets among distractors (Figure 1).

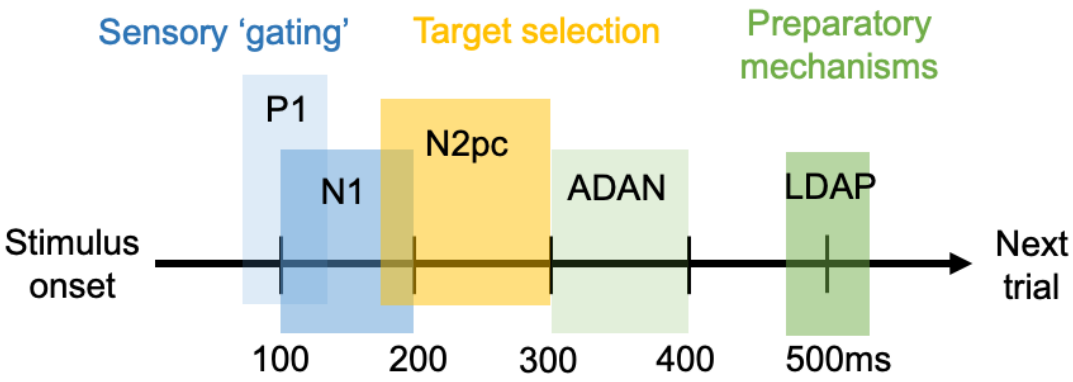


Figure 1. A schematic representing the three mechanisms by which visual attention affects information processing. Colour blocks are presented on a timeline from stimulus onset until the next experimental trial and grouped according to the mechanism that they represent: sensory gating in blue, target selection in yellow, and preparatory mechanisms in green. ERP component names are presented on the colour blocks that represent their latency and mechanism. Height differences between colour fields do not denote amplitude differences and serve purely for visual effect and to accommodate overlap.

The first ERP component that can be observed over the course of the perception of a visual stimulus is the C1, peaking at 60-90ms post-stimulus onset (Jeffreys & Axford, 1972). The C1 has commonly been taken to reflect responses of primary visual cortex to a stimulus (Clark et al., 1995; Martínez et al., 1999; Di Russo et al., 2003), and it has been shown not to be modulated by spatial attentional processes (Clark & Hillyard, 1996; Martinez et al., 1999). Closely after the C1, the P1 and N1 ERP components are normally observable. The P1 is a positive voltage deflection at lateral posterior sites that typically peaks at 80-130ms post-stimulus onset. It is sensitive to physical stimulus characteristics such as brightness and contrast, and its sources have been suggested to be extrastriate cortex (Di Russo et al., 2001), as well as parietal cortex (Foxe et al., 2005; Murray et al., 2001). The N1, on the other hand is composed of several, negative-going, subcomponents (Di Russo et al., 2001). An early subcomponent peaks at 100-150ms post-stimulus, typically over anterior sites, while later subcomponents peak around 150-200ms post-stimulus. Importantly, unlike the C1, both the P1 and N1 have been shown to be sensitive to spatial selective attention, such that their amplitudes tend to be larger for stimuli in attended locations than for stimuli in unattended locations (Eimer, 1994; Hillyard, Vogel, & Luck, 1998; Hillyard & Anllo-Vento, 1998; Mangun, 1995; Mangun & Hillyard, 1991). Such findings were in line with ideas espoused by research discussed in the context of the biased competition model, where a stronger neural response in visual areas to attended over unattended stimuli was evidence of their (early) selection. Indeed, there was a prevailing idea at the time of sensory enhancement or 'gain control', whereby being in an attended location would increase the 'gain' over stimuli in unattended locations (Hillyard, Vogel, & Luck, 1998) and thus afford them access to limited processing capacities. In this way, the modulations observed in P1 and N1 provided evidence for an early selection model where spatial attention 'gated' further processing. However, ERP components with much later onsets were also shown to respond to spatial attention. For example, in an ERP study, Nobre et al. (2000) cued the location of upcoming visual targets to the right or left visual field in a way that disentangled ERPs to the physical characteristics of the cue from ERPs that would reflect the shifting of spatial attention. With such a design, they identified two components – the ADAN (Anterior Directing Attention Negativity, a frontal negative-going voltage at 300-400ms post-stimulus onset) and the LDAP (Late Direction Attention Positivity, a posterior contralateral positivity at 500ms post-stimulus onset). Both components are thought to reflect preparatory states in the period after the task goal is known and before behaviour is initiated. Specifically, the ADAN has been linked to the production of anticipatory attentional shifts (Nobre et al., 2000; Posner & Petersen, 1990), while the LDAP has been linked with visual cortex excitability in preparation for upcoming events (Harter et al., 1989; Yamaguchi et al., 1994). As such, both of these components index the control of visuospatial attention. However, It has also been suggested that the ADAN and LDAP reflect the functioning of a higher-order attentional control mechanism that may operate across sensory modalities (e.g., Eimer, Van Velzen, Forster & Driver, 2003; Van Velzen, Forster & Eimer, 2002; Seiss et al., 2007; though see van Velzen, Eardley, Forster & Eimer, 2006), supported also by research on EEG oscillations as reviewed by Kayser (2009). Some studies have also observed an EDAN (Early Directing Attention Negativity) component before the ADAN and LDAP, at around 200ms post-stimulus over posterior sites (e.g., Harter et al., 1989; Yamaguchi et al., 1994). However, it has been demonstrated that this component is not directly involved in top-down attentional control (van Velzen & Eimer, 2003).

Crucially, like early behavioural selective attention research, both such early and late ERP activity assumes some advance knowledge of the spatial location of relevant objects, which often is not available in real-world situations. In cases where the location of relevant information is not known in advance, the N2pc component has been instrumental for studying attentional selection. The N2pc is a negative-going voltage deflection around 200ms post-stimulus onset at posterior electrode sites contralateral to stimulus location (Figure 2, Luck & Hillyard, 1994a, 1994b; Eimer, 1996; Girelli & Luck, 1997). Early studies have isolated the N2pc to target stimuli amidst distractors, in visual search contexts (Eimer, 1996), concluding that the N2pc indexes the attentional selection of target stimuli. A more recent stream of studies of the N2pc to cues or distractors that precede targets has helped establish the N2pc as a marker of attentional selection of candidate target stimuli according to their features (e.g., Eimer & Kiss, 2008, 2010; Kiss et al., 2008a; 2008b), and not merely their spatial location (Woodman, Arita & Luck, 2009). Moreover, these studies have established the value of the N2pc in the study of attentional control, by bearing out the behaviourally-observed task-set contingent attentional capture (TAC) effect (Eimer, Kiss, Press, & Sauter, 2009). Using a Folk-like spatial cueing paradigm, Eimer et al. (2009) demonstrated that distractor stimuli that shared the same colour as a subsequently occurring target elicited a reliable N2pc, whereas distractors of a target-nonmatching, though noticeable, colour, did not trigger an N2pc. Such a modulation of N2pc patterned with behavioural results, where reaction time (RT) spatial cueing was enhanced for target-matching distractors and suppressed for target-nonmatching distractors. By supporting the idea that task irrelevant objects can capture attention when they share a feature with the target, the N2pc has helped solidify the notion of a hierarchy of top-down over bottom-up factors in visual attentional control.

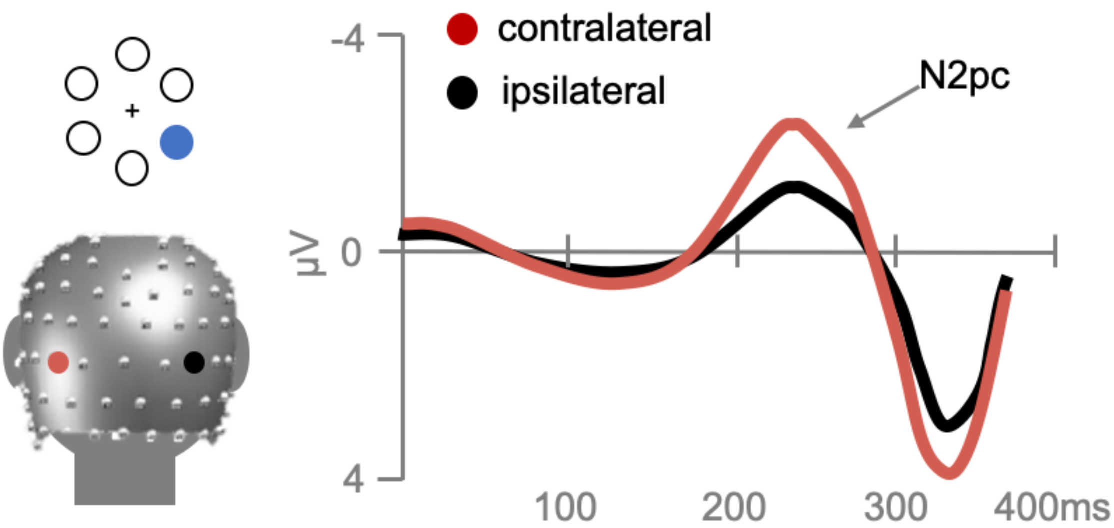


Figure 2. A simplified representation of the N2pc component and the experimental conditions in which it is observable. The rightward panel shows a schematic of a research participant viewing a stimulus array where a blue cue is presented (ahead of a blue target that is not presented here). The posterior electrode sites contralateral and ipsilateral to the cue are highlighted in red and blue, respectively, on the participant's EEG cap. Visible around 200ms, with a negative polarity, the N2pc is reflected in the difference (i.e., the area) between the contralateral and ipsilateral electrode waveforms, again presented in red and black, respectively.

Furthermore, Hopf et al. (2000) have localised the sources of the N2pc. These were an earlier activity in parietal areas (such as posterior parietal cortex, around 180-200ms) and a later activity in occipito-temporal areas (such as the lateral occipital cortex, LOC, around 220-240ms). The latter source, in particular, is in line with previous nonhuman primate research (e.g., Chelazzi et al., 1993) in that it may be construed as a human homologue of the V4 and inferior temporal single-neuron activity observed in primate electrophysiology. With regards to the mechanism underlying N2pc enhancement in response to goal-relevant stimuli and attenuation in response to irrelevant stimuli, a gain control process in visual cortices, such as the above-mentioned LOC, has been suggested. Here, goal-relevant information would produce an enhancement (increased 'gain') in sensory processing areas of the brain, at the expense of irrelevant information, thus 'gating' which information will be selected and relayed for further processing (cf. the biased competition model). However, the gain control account has not been explicitly tested in traditional research in the context of the N2pc.

Despite their invaluable contribution to our mechanistic understanding of attentional control processes, canonical analyses of N2pc present notable limitations. They are summarised here (we discussed them in full in Matusz, Turoman, Tivadar, Retsa, & Murray, 2019). For one, canonical N2pc analyses analyse EEG signal from only 2 electrodes in the entire montage, thus taking into account between 8.7% (in a 23-electrode montage) and 0.78% (in a 256-electrode montage) of the overall measured EEG activity. This is problematic, as it likely results in omission of a large majority of informative brain activity. Some ERP experts argue that increasing electrode numbers injects noise into the measurement, (e.g., Luck, 2005). However, because EEG does not measure electrical activity at its brain source, but rather at the scalp, because of volume conduction (Rutkove, 2007), we can never be certain that a given choice of electrode sites fully captures our effect of interest, and that activity at other sites is irrelevant. Furthermore, canonical N2pc analyses can only reveal average differences in N2pc amplitudes between experimental conditions, but not the brain mechanisms underlying these differences. That is, the same average amplitude of the N2pc, i.e., the difference between the contralateral and ipsilateral electrode, across two experimental conditions can arise from a completely different distribution of values across the scalp, which traditional N2pc analyses cannot detect (for illustration, see Matusz et al., 2019b; Figure 3). In the same study, Matusz et al. presented an alternative analysis approach, called Electrical Neuroimaging (EN), that provided demonstrable advances over the canonical N2pc method. EN encompasses a set of multivariate, reference-independent analyses of global features of the electric field measured at the scalp (Koenig, Stein, Grieder, & Kottlow, 2014; Michel & Murray, 2012; Murray, Brunet, & Michel, 2008; Lehmann & Skrandies, 1980; Tzovara, Murray, Michel, & De Lucia, 2012). In their study, Matusz et al. reanalysed N2pc data from Matusz and Eimer (2013) where N2pc attenuations were found in response to visual-only cues, but not audiovisual cues, that preceded audiovisual targets. These findings were taken as evidence for multisensory attentional templates that guide attentional selection. In Matusz et al. (2019b), applied EN in addition to their previously conducted classic N2pc analysis, to investigate the mechanism underlying such modulations of the N2pc to cues that matched the attentional template partially (visual-only cues) or fully (audiovisual cues).

The main benefit of EN analyses over traditional N2pc analyses is their ability to reveal whether brain response modulations between experimental conditions arise from: 1) differences in response strength within a single brain network, or 2) differential brain networks being active for different conditions. In an EN framework, the strength of the response to an experimental condition over the global scalp field is instantiated by modulations solely in the so-called Global Field Power (GFP). If the above-discussed N2pc modulations by goal relevance were a result of a gain-control mechanism, i.e., a response strength modulation within statistically indistinguishable networks, this would be readily detected as GFP differences between experimental conditions over the N2pc time-window. However, in contrast with the classical gain-control account, Matusz et al. (2019b) suggested that differences in N2pc amplitudes between conditions can be driven by a network- not gain-based mechanisms. As part of EN, differential recruitment of brain generators underlying ERPs can be revealed by analysing the topography of the ERPs in question. As I describe in the Materials and Methods section, clustering algorithms and ‘fitting’ procedures identify periods of stable ERP topography, and therefore, of stable underlying brain network activation, which can then be compared across experimental conditions. With this approach, Matusz et al.et al. (2019b) showed that, over and above differences in GFP, there were differences in scalp topography configurations over the N2pctime-window. This suggested that the neural mechanism of the well-known modulations of N2pc by goal-relevance could be a change in the sets of brain sources that are recruited for processing goal-relevant versus irrelevant stimuli.

Matusz et al. (2019) effectively demonstrated how combining well-understood traditional N2pc analyses with advanced multivariate signal processing techniques, like an EN approach, allows for distinguishing between different cognitive processes in the service of understanding multisensory attentional control, and offers a more in-depth understanding of the brain mechanisms governing these processes. Having methods that are sensitive to the mechanisms underlying well-established ERP effects is important insofar as there remain unanswered questions about the mechanisms of attentional control. It is unclear to what extent our current knowledge about selective attention may be limited to the highly artificial laboratory conditions in which it has been traditionally studied. Most classic attentional research has focused purely on visual attentional processes in closely controlled experimental settings, thus overlooking the complex, multisensory nature of natural environments. Because of this, we currently do not understand how attentional control operates in multisensory settings, nor whether and how attentional control in such settings is influenced by broader contextual factors, such as the timing of stimulus onset, and the semantic meaning inherent in naturalistic stimuli. Even less is known how attentional control processes in such settings develop into their adult form. Children's attentional control processes, especially in real-world conditions, remain under-researched. Importantly, the viability of the N2pc – a marker of *visual* attentional control in *adults* – for assessing attentional control over *multisensory* objects, in *children*, and with varied contextual influences, is uncertain. Likewise, the suitability of EN for answering such questions has never been explicitly tested.

2. Development of attentional control processes

Much of the current knowledge on the mechanisms through which children control their selective attention comes from research into a set of cognitive control-related skills, collectively known as executive functions (EF). The idea of higher-level cognitive functions controlling/managing perceptual processes emerged in 1970's (e.g., Baddeley & Hitch, 1974; Norman & Shallice, 1986), albeit clinicians had been assessing abilities that later came to fall under the umbrella term of EF long before this time (Karr et al., 2018). This led to an ongoing debate as to the structure and organisation of EF (for recent advances in the debate see Fiske & Holmboe, 2019). One of the most popular models of EF (Miyake et al., 2000) has assumed three separate components: working memory (or updating; the ability to keep information in mind and use it to guide behaviour), inhibitory control (or inhibition; ignoring irrelevant information or blocking inappropriate response tendencies), and cognitive flexibility (or shifting; the ability to switch between tasks). These factors have been proposed to be unified by a ‘common EF’ factor (Friedman & Miyake, 2017; Miyake & Friedman, 2012). Most developmental psychology and neuroscience research agrees on some version of the above three factors of Miyake’s model.

EFs have traditionally been localised to prefrontal cortices (Alvarez & Emory, 2006; Diamond, 2002; Goldman-Rakic, 1996). Advances in neuroimaging over the past 20 years have expanded this view, and, as a meta-analysis of neuroimaging studies of EF suggests, it has become widely accepted that frontal and parietal areas jointly contribute to EF skills (Niendam et al., 2012). In developmental research, for working memory, the dorsolateral prefrontal cortex has been implicated most consistently, from infancy (Baird et al., 2002; Diamond, 1991) to early and middle childhood (Perlman et al., 2016). However, the involvement of the parietal cortex has also been implied in more recent research, both in infancy (Bell 2012; Bell & Fox, 1997; Fox & Bell, 1990) and beyond (Buss, Fox, Boas, and Spencer, 2014). Inhibitory control has mostly been linked to the dorsal and ventro-lateral prefrontal cortex (Bunge et al., 2002; Smith et al., 2017), but also parietal cortex and striatum (Bunge et al., 2002; Durston et al., 2002, 2006; Mehnert et al., 2013). The lateral prefrontal cortex has also been implied in cognitive flexibility in children (Aron et al., 2014; Moriguchi and Hiraki, 2009). Clearly, the areas involved in EF, whether generally, or in terms of specific components, overlap with the above-discussed areas associated with attentional control. The idea that these two skills that have traditionally been studied separately, may in fact be closely related, is not new (e.g., Awh & Jonides, 2001; Rothbart & Posner, 2001). Many have considered attentional control to be inextricably linked with working memory (e.g., Amso & Scerif, 2015; Astle & Scerif, 2011; Awh & Jonides, 2001; Kane & Engle, 2002). Developmentally speaking, effective control over attentional selection could be a prerequisite for the development of EF skills (Hendry et al., 2016; Veer et al., 2017). In support of this argument, several longitudinal studies have found that selective attention skills in infancy predict EF skills during early childhood (Holmboe et al., 2008; Johansson et al., 2015; Kochanska et al., 2000). This doctoral thesis focused on attentional control, but findings from EF-related developmental work have been used to inform the present PhD research, due to their neural and conceptual overlap. In the following section, we consider findings from both literatures together.

Behavioural evidence has converged that both EF and attentional control show gradual developmental progression. Children tend to perform worse on experimental tasks designed to measure these skills, and steadily improve by the time they reach adulthood (For studies in the EF domain see e.g., Friedman et al., 2011; Cepeda, Kramer, & Gonzalez de Sather, 2001; Williams, Ponesse, Schachar, Logan, & Tannock, 1999; For studies in the attentional control domain see e.g., Donnelly et al., 2007; Hommel, Li & Li, 2004; Trick & Enns, 1998). Neuroimaging work confirmed this developmental trend. Both Perlman et al.’s (2016) study of 3-7-year-olds and Buss et al.’s (2014) study of 3-4-year-olds found that behaviourally measured demands on working memory patterned with increased activity in dorsolateral prefrontal cortex and parietal cortex, respectively, that increased with age. Similarly, Moriguchi and Hiraki (2011) found that behavioural improvements in shifting between tasks and recruitment of prefrontal cortex both increased from age 3 to age 4. As for the neural mechanism underlying such developmental progression, protracted structural changes in the prefrontal cortex have most commonly been suggested (e.g., Bunge et al., 2002; Casey, Tottenham, Liston & Durston, 2005; Tamnes et al., 2010; 2013; Tsujimoto, 2008), but contributions of parietal areas have also increasingly been recognised. For example, it has long been known that grey matter volume exhibits nonlinear change from childhood to adulthood, with increases until puberty, and decreases following puberty (e.g., Giedd et al., 1999; Jernigan & Tallal, 1990; Jernigan et al., 1991). Of all frontal areas, the prefrontal cortex was demonstrated to be the last region to show such a pattern of change in grey matter volume (Gogtay et al, 2004; Gogtay & Thompson, 2010). However, a recent latent variable modelling study found that *global* grey matter volume, and not individual prefrontal grey matter volumes, contributed to EF skills. Further, and even during reductions in grey matter volume, the structure of white matter frontoparietal connections continues to contribute to EF (Bettcher et al., 2016). Indeed, protracted changes in structural and functional connectivity between frontal and parietal areas regions are also a likely key contributor to children's gradually improving EF and attentional control skills (e.g., Konrad et al., 2005; Baum et al., 2017; Hwang, Velanova & Luna, 2011; Rohr et al., 2016; for reviews of structural and functional changes and links with behaviour, see Fiske & Holmboe, 2019; Kim & Kastner, 2019, pp.224).

How changes in brain structure and connectivity contribute to age-based improvements in task performance is unclear. Mechanistically, children's weaker attentional skills may partly come from slowly maturing interactions between top-down visual attention and memory processes, as shown, e.g., by benefits in volitional use of retro-cues to aid memory retrieval, arising after the age of 7 (Shimi et al. 2014a). Alternatively, increased distractibility, or weaker inhibition of external distractors, may be the main contributor, as suggested by an examination of visual search performance from childhood to old age (Hommel, Li & Li, 2004). The distraction account seems to be supported by the only extant child-friendly adaptation of Folk et al.' spatial cueing paradigm (Gaspelin, Margett-Jordan & Ruthruff, 2015). This study showed that 4-year-olds' attention was captured by target non-matching distractors three times as strongly as adults' attention. Even when controlling for children's overall slower processing speed, TAC-like effects were still observed in 4-year-old children, but they were heavily attenuated compared to young adults. In Gaspelin et al.'s study, there was no concurrent EEG measurement to test any possible modulations of N2pc by target-matching cues. Nonetheless, N2pc's have otherwise been identified in children. For example, Couperus & Quirk (2015) demonstrated that children aged 9-12 showed a reliable N2pc to lateral feature-defined targets, as do adults. Yet, children's N2pc showed a larger amplitude and delayed onset. Notwithstanding, the observed contralateral negativity in children can indeed be considered a nascent N2pc, as it was present over the same posterior contralateral sites as in adults (here, electrode pair P7/8), while also having a similar duration (~100ms). Other studies have confirmed the presence of N2pc in children in response to singleton targets (Sun, 2017), and to goal-relevant objects stored in short-term memory (Shimi et al., 2015). However, there does not appear to have been a study on *distractor* N2pc's in children. In adults, it was exactly research on distractor N2pc's that helped confirm the priority of goal-relevance over stimulus salience in visual attentional control. Since such research has yet to be conducted on children, it remains unclear whether children rely more on goal-relevance or stimulus salience in their control of attention, and when in childhood does adult-like prioritisation of goal-relevance emerge. One of the motivations of the current PhD research was to elucidate the developmental trajectory of visual attentional control mechanisms. For this reason, we introduced combined a spatial cueing task with a concurrent EEG measurement to obtain N2pc's to distractors.

3. The multisensory nature of information as a source of attentional control

Historically, much of the research into perceptual and cognitive processing has focused on the functional properties of each sense in isolation. Such a modular view has been instrumental to our understanding of the fundaments of perception (e.g., Evans & Whitfield, 1964; Hubel & Wiesel, 1962; Mountcastle, 1957), but has nonetheless overlooked that information in real-world environments, outside of controlled laboratory settings, typically stimulates multiple senses at a time, rather than each sense in isolation. Traditionally, sensory organisation was thought of as a hierarchy where information from lower-level sensory-specific cortical areas was propagated forward to higher-order 'polysensory' or 'heteromodal' areas in association cortex, where inputs from the former were integrated (e.g., Barth et al., 1995; Benevento et al., 1997; Bignal, Singer & Herman, 1967; Bruce, Desimone & Gross, 1981; Felleman & Van Essen, 1991). Since then, an ever-growing number of cortical areas where neurons processed converging inputs from multiple senses – thus, 'multisensory convergence zones' – have been discovered. Such areas included the superior temporal sulcus (reviewed in Beauchamp, 2005), parietal areas such as the superior parietal lobule (e.g., Molholm et al., 2006) and intraparietal sulcus (e.g., Bremner et al., 2001; Bolognini et al., 2010), and frontal and prefrontal areas like the ventrolateral prefrontal cortex and premotor cortex (Graziano, Yap & Gross, 1994; Fogassi et al., 1996; Sugihara et al., 2006; for reviews see e.g.: Calvert & Thesen, 2004; Driver & Noesselt, 2008). Multisensory convergence zones have also been found in primary visual and auditory cortices (Laurienti et al., 2002; Martuzzi et al., 2007; Schroeder et al., 2003; Schroeder & Foxe, 2002; Wang et al., 2008), and subcortical areas such as the superior colliculus, basal ganglia, and thalamus (Meredith & Stein, 1983, 1986; Meredith et al., 1987; Nagy et al., 2006; Mesulam & Mufson, 1982). For example, Stein et al. recorded single neurons in the deep layers of the cat superior colliculus, a region containing neurons that respond to inputs from only one sense, and neurons that respond to multiple types of sensory input. When auditory and visual stimuli were presented alone versus together, response amplitudes in multisensory neurons were larger than the sum of the responses of unisensory neurons ('superadditive' responses). Conversely, when stimuli were presented outside of a neuron's receptive field, responses either did not interact, or they were smaller than the sum of unimodal resoponses (‘subadditive’ responses; Meredith & Stein, 1986). Such nonlinear neural responses to multisensory stimuli provided a signature of the integration of unisensory inputs into a multisensory representation (or multisensory integration, MSI), and established important guidelines for multisensory research to come (Alais, Newell & Mamassian, 2010). Moreover, these principles helped solidify the idea that multisensory processing is more than just pooling information from different senses. With regards to nonlinear responses, Stein and Stanford (2008) have stated that the magnitude of MSI reflects the salience of a stimulus, and that one of the main outcomes of MSI is enhancing the salience of biologically meaningful events.

The growing body of evidence for multisensory convergence in primary sensory and subcortical areas cast serious doubt on the traditional hierarchy, where convergence was thought to be constrained to later activated, ‘higher-level’ areas. A further challenge to the traditional functional account was the mounting evidence for MSI occurring already at the level of primary sensory cortices. Early animal studies saw activations in the cat visual cortex by auditory stimuli (e.g., Fishman & Michael, 1973; Spinelli, Starr & Barrett, 1968). However, newer studies using EEG methods have demonstrated that MSI can occur within the first 100ms after stimulus onset; sometimes as early as 40ms post-stimulus (e.g., Giard and Peronnet 1999; Fort et al. 2002; Foxe et al., 2000; Molholm et al., 2002; reviewed in de Meo et al., 2015). Such an early onset would presumably be too rapid to reflect the involvement of higher-order areas later down the processing hierarchy (see Lamme & Roelfsema, 2000; Luck et al., 1997). Separately, numerous neuroimaging studies have borne out that primary sensory brain regions can respond to inputs from other sensory modalities and to multisensory inputs (e.g., Amedi et al., 2002; Saito et al., 2006; Calvert et al., 1999; 2001; Kayser et al., 2007), and have suggested that interactions between inputs from different senses take place in these low-level areas (e.g., Ghazanfar et al., 2005; Lakatos et al., 2007; Martuzzi et al., 2007; and more recently e.g., Cappe et al., 2010; Lacey & Sathian, 2014; 2014; Raij et al., 2010). Further, feedback projections between convergence areas and primary sensory cortices were found (e.g., Falchier et al., 2002; Rockland & Ojima, 2003; Schroeder & Foxe, 2002), as were lateral connections between primary sensory cortices (e.g., Cappe & Barone, 2005; Ghazanfar & Schroeder, 2006; Falchier et al., 2002; Fu et al., 2003). Collectively, these findings suggested a differential sensory organisation than previously thought, and thus, a potential need to recontextualise research in psychology and neuroscience in a new multisensory framework.

There has long been interest in the behavioural benefits afforded by inputs from multiple senses. A wave of related research spanning decades has demonstrated the wide-ranging behavioural benefits of multisensory as opposed to unisensory information (for reviews see e.g., Calvert, Spence & Stein, 2004; Murray & Wallace, 2012; Stein, 2012). Perceptual benefits of enhanced detection and recognition of multisensory pairings have been demonstrated numerous times (e.g., Doyle & Snowden, 2001; Vroomen & de Gelder, 2000; Lovelace et al., 2003; Pérez-Bellido et al., 2013; Schnupp, Dawe & Pollack, 2005; Molholm et al., 2004). Over and above facilitating traditionally unisensory effects, converging multisensory inputs have also been known to produce wholly novel perceptual outcomes. For example, McGurk effect occurs when the sound of a syllable (‘ba’) is dubbed onto a video of a speaker articulating a different syllable (‘ga’), typically resulting in the perception that the speaker is saying a third syllable (‘da’; McGurk & MacDonald, 1976; 1978). More than a curious ‘illusion’, the McGurk may reflect the brain’s use of information from different senses to estimate an unknown property; here, what the speaker was saying. Indeed, inputs to multiple senses often carry redundant information, and it has been shown that the perceptual system weighs each modality’s inputs by reliability to obtain unknown information (e.g., Alais and Burr, 2004; Ernst & Bulthoff, 2004), and then integrates these inputs in aa statistically optimal fashion (Ernst & Banks, 2002). Rather than multisensory processes being mechanistically ‘special’ and serving to enhance unisensory processes, it is more likely that they are an adaptive norm, underlying all of perception and related cognitive processes, that previous, simplistic, paradigms have neglected (van Atteveldt et al., 2014). Such a change in perspective poses particularly interesting questions for models of attentional control. If MSI is indeed as fundamental as suggested theoretically, and empirically, with its early onset and putative source in low-level cortices, could it thus be impervious to the influence of top-down control mechanisms?

There has been substantial interest in the intersection between multisensory processes and attentional control processes over the past two decades (for reviews see Talsma et al., 2010; Koelewijn et al., 2010; Navarra et al., 2010), and particularly in the extent to which MSI is independent of top-down attentional control (e.g., Alsius et al., 2005; 2014; Buchan & Munhall, 2012; Fairhall & Macaluso, 2009; Tiippana et al., 2011; Fernández et al., 2015). Early results on bottom-up attentional control showed no clear enhancements in orienting to multisensory over unisensory stimuli (Santangelo et al., 2006; Ward, 1994; Spence & Driver, 1999). For example, in an adaptation of the Posner paradigm, Santangelo et al. (2006) found that audiovisual cues and either audio-only or visual-only cues elicited comparable visual attentional capture. However, in a later study, Santangelo and Spence (2007a) showed that multisensory cues can indeed be more effective at capturing attention than unisensory cues, but only when visual attention is taxed by a demanding task. Here, participants either performed only a task where they judged whether a briefly presented target was shown at the top or bottom of the screen, or, additionally, on 70% of trials, also a task where they had to identify a letter within a central rapid serial visual presentation array. Crucially, in the dual-task condition, only the audiovisual cues showed reliable RT spatial cueing effects, as opposed to visual-only or audio-only cues, indicating that only audiovisual cues re-oriented attention to the secondary task (see also Santangelo & Spence, 2007b; Santangelo et al., 2008). However, the work of Alsius et al. (2005; 2014) provided somewhat contradictory evidence with the use of a McGurk-related task and a detection task. They found that behavioural illusory McGurk responses strongly decreased when visual attention was taxed in the dual-task condition (Alsius et al., 2005), and that such reductions were followed by reductions in auditory N1 and P2 components (Alsius et al., 2014). Taken together, these results suggest that taxing visual attention weakens the effects of MSI, at least for some types of stimulus categories.

Over the years, evidence has converged that top-down attention is important (though not always necessary de Meo et al., 2015) for multisensory effects to emerge. Much of this evidence (including Alsius et al., 2005; 2014; reviewed in Fernández et al., 2015) resulted from paradigms using stimuli which are imbued with semantic meaning – faces/mouths and voices of a speaker – as opposed to the meaningless tones and shapes used in early work. It is possible that semantic factors inherent in speech contexts obscured the relationship between MSI and attentional control. As we will discuss later in Section 6, semantic meaning provides an important scaffold for integrating sensory inputs into objects, and as such are known to interact with MSI effects (reviewed in Doherman & Naumer, 2008). Notably however, Matusz and Eimer (2011) managed to avoid any semantic confounds while disentangling whether bottom-up control of attention by multisensory stimuli is secondary to top-down goal-relevance, as in the case of visual stimuli. They devised a multisensory adaptation of Folk et al.' spatial cueing paradigm, specifically the version of the task with colour-defined cues, where a simultaneous tone was presented together with the visual cue on half of all trials. Experiment 2 in this study incorporated the demanding visual-attention task aspect by designating a unique colour-defined identity to every distractor element (that was not the cue or target), thus necessitating a feature-search mode for the detection of the target stimulus. They found that target-matching visual-only cues elicited strong attentional capture, while nonmatching cues did not, consistent with well-established TAC effects (Figure 3). Interestingly, audiovisual cues elicited larger attentional capture than did visual-only cues, regardless of whether they matched the target by colour or not. Thus, the addition of a co-occurring sound enhanced the attentional capture elicited by visual stimuli – an effect that was in that study referred to as multisensory enhancement of attentional capture (MSE). That task-irrelevant multisensory stimuli captured attention independently of their adherence to the strong, feature-specific top-down task-set directly challenges the traditional hierarchy of attentional control processes. More broadly, these results suggest that purely unisensory attentional research may be limited in explaining real-world, multisensory, attentional control.

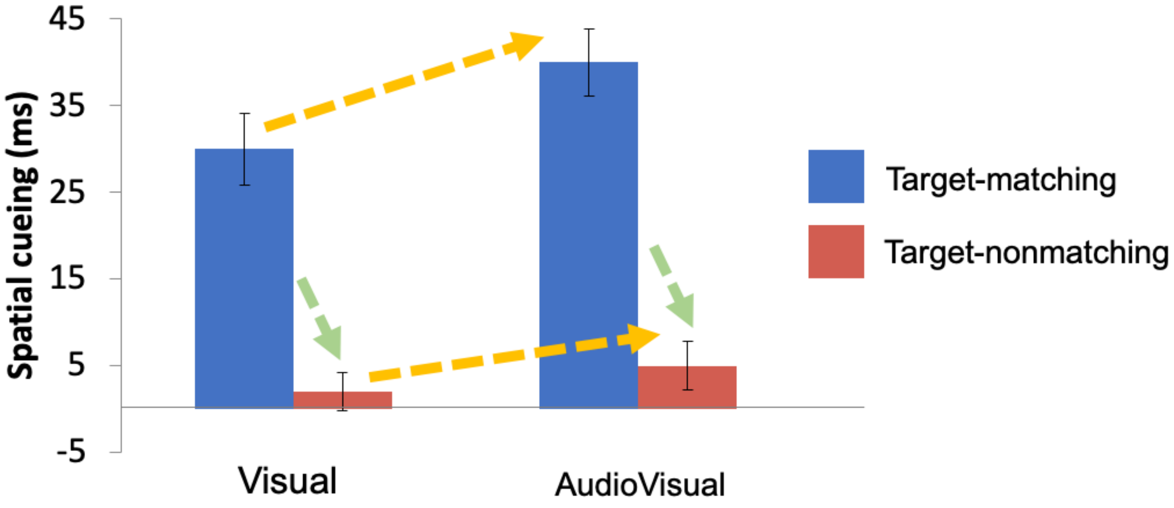


Figure 3. A simplified presentation of the TAC and MSE behavioural capture effects in Matusz and Eimer's (2011) Experiment 2. Bars represent behavioural capture as measured by spatial cueing (in milliseconds), and error bars represent the standard error of the mean. Light green arrows illustrate TAC effects, which are visible as the spatial cueing difference between Target-matching cues and Target-nonmatching cues. Yellow arrows illustrate MSE effects, which are visible as the spatial cueing difference between Visual and AudioVisual cues.

Given that audiovisual distractors, like visual-only distractors, were behaviourally found to capture attention, and given the success of the N2pc as an index of *visual* selection of candidate target objects, it was reasonable to ask whether the N2pc could also index attentional selection of multisensory objects. However, little research has been devoted to investigating the viability of the N2pc for investigating attentional control over multisensory stimuli. The N2pc has been used in multisensory paradigms; for example, Matusz and Eimer (2013) employed the N2pc in their study on multisensory attentional templates. Here they showed that searching for visual targets triggered a reliable N2pc to visual distractors but searching for audiovisual targets was followed by an attenuated N2pc to the same visual distractors. The attenuated N2pc was explained by there only being a partial correspondence between the distractor to which the N2pc was measured and the target defined by both visual *and* auditory features. However, this paradigm did not include an audiovisual distractor condition. If there had been such a condition, the attenuation could have possibly been eliminated, due to a full match with the multisensory attentional template. Alternatively, it could have been even greater, given that multisensory bottom-up effects can have difficulty persisting in N2pc's (cf. van der Burg et al., 2011). In the only other multisensory study that employed the N2pc, van der Burg et al (2011) measured ERPs in response to visual distractors presented alone (visual-only) or together with a tone (audiovisual). An N2pc was observed in response to audiovisual but not visual-only distractors. However, the duration of this N2pc was uncharacteristically short (20ms) compared to N2pc durations in the literature (~100ms, e.g., Astle, Nobre & Scerif, 2010; Luck & Hillyard, 1994; Sawaki & Luck, 2010). Crucially, the mean amplitudes between audiovisual and visual distractor-induced N2pc's were never statistically compared, thus providing no evidence as to the reliability of the purported MSE by audiovisual distractors in this study. With this, neither of the two extant multisensory studies using the N2pc have provided sufficient support for multisensory modulations of the traditional N2pc to distractor stimuli. Because of this, it remains unclear whether the traditional hierarchy of top-down over bottom-up influences in attentional control persists in multisensory settings. In order to elucidate the latter, more research is needed to ascertain whether the N2pc can equally act as an index of visual and multisensory attentional capture by task-irrelevant stimuli.

4. Development of multisensory processes and their links with attentional control

While we still do not fully understand how adults control their attention towards multisensory objects, we know even less about how children do so, and whether similar control mechanisms are used at different points in development. There has been a debate as to the developmental trajectory of multisensory processing, with some research suggesting that multisensory capabilities are present early in life, while others - that they develop only later, after sufficient experience (reviewed in Dionne-Dostie et al., 2015, and in Murray et al., 2016). In support of the early integration account, infants are known to extract stimulus characteristics such as temporal synchrony (Bahrick & Lickliter, 2000; Lewkowicz, 1992; Lewkowicz, Leo & Simion, 2010) and intensity (Lewkowicz & Turkewitz, 1980) from birth, and use them to detect correspondences between sensory inputs, such as successfully matching faces with voices (Bahrick, 2001). Further, infants can use haptically acquired information about an object's shape and texture to discriminate visually presented objects (Steri, 2003; Sann & Steri, 2007).

Opposingly, the late integration account argues that sensory systems work independently at birth, necessitating experience to develop and work in concert efficiently. Animal studies have demonstrated that early environmental experience is key for successful development of MSI (Wallace & Stein, 2007; Wallace, Perrault, Hairston & Stein, 2004). A study in human infants that suffered visual deprivation due to congenital cataracts has corroborated this, by showing that an early lack of visual experience constrains later audiovisual integration once sight is restored, with effects persisting into adulthood (Putzar et al., 2007). In further support, it has long been known that senses develop at different rates in utero, with touch developing first (Hooker, 1952), followed by hearing (Hepper & Shahidullah, 1994) and then vision, largely postnatally (Atkinson, 1983). Gori et al. demonstrated that developing senses may scaffold each other in estimating such unknown properties, before 'learning' to respond in an integrated fashion around age 8 (Gori et al., 2008, 2012, see also Ernst, 2008). Using a child-friendly adaptation of Ernst and Banks' (2002) task, Gori et al. (2008) measured visual-, haptic- and multisensory visuo-haptic size discrimination skills in children aged five to ten. Briefly, children were asked to judge whether a 'standard' block was taller or shorter than a 'probe' block that varied in height. On visuo-haptic trials, the visually- and haptically-perceptible sizes of the standard were unequal. For adults and 10-year-old children, visual information, which was revealed to be a more precise estimator of size, was guiding size judgments, while for 5-year-old children, less precise haptic information guided size judgments. Moreover, when the points where participants estimated the probe and standard to be equal were compared across all the available ages, adult patterns were found to emerge by age 8, but not before. Based on these results, they concluded that children cannot integrate visual and haptic information in a statistically optimal (adult-like) fashion before age 8. In a follow-up study using a temporal bisection task, they demonstrated a similar pattern of results, and a similar age limit, for optimally integrating audiovisual information (Gori et al., 2012).

Other work (e.g., Nardini et al., 2008; 2010) has supported the idea that facilitation of behavioural responses by MSI has an onset after the age of 8 years. By contrast, multisensory benefits for learning and memory have been reported from age 5 onwards. Specifically, incidental learning benefits by audio-visual interactions have been reported in children as young as 5 (Broadbent et al., 2018a; 2018b). In the latter study, Broadbent et al. (2018b) administered a child-friendly task involving line drawings of animals to assess the role of uni- and multisensory cues on vigilance and incidental learning of category membership. Here, learning was 'incidental' in that category membership of the presented animal stimuli (family 1 or family 2) was not important to the task. Children aged 5, 7, and 9 completed the task, along with a test of their category knowledge 24h later. Across all age groups, better retention of category membership was observed after exposure to multisensory than unisensory cues. This result suggested that redundant information that is presented across the senses can be used, even before age 8, to improve learning. Similarly, Birch and Belmont (1965) have found that the ability to match information across the senses was related to reading skills in primary school children aged 5–12.

While there is still some debate as to when in development do adult-like multisensory processing capacities emerge, it is entirely unclear whether children are more or less susceptible to attentional capture by multisensory stimuli than adults. If children are indeed less adept at controlling their attention, and more prone to distraction, as suggested by extant research (see Section 2), the increased salience of multisensory stimuli may make children especially prone to distraction by such stimuli – both more so than adults, and over and above distraction by unisensory stimuli. In the developmental field, there has been a surprising dearth of research into the dynamic interplay between developing multisensory integration skills and *developing* unisensory attentional skills. A couple of studies from our group have recently challenged the classical view that children simply have weaker attentional control skills than adults. First, Matusz et al. (2015) compared 7-year-olds, 11-year-olds, and young adults (20 years old) on their ability to locate 1 of 2 target coloured shapes (e.g., a green circle). During this visual search task, a peripheral distractor of a target-matching or target-nonmatching colour could be presented visually, auditorily, or audiovisually. Matusz et al. also manipulated the difficulty of the task by presenting three or no additional distractors in the search array along with the target object. Crucially, when the task was easy, all age groups showed interference with the search task by audiovisual distractors (e.g., a green circle with the spoken label 'green'), indicating that attention was captured by distractors. However, when the task was difficult, interference by audiovisual distractors was observed in 11-year-olds and young adults, but not in 7-year-olds. This result suggested that young children’s limited attentional capacities were mostly ‘spent’ on the difficult task, leaving less to allocate to the salient multisensory distractor. More broadly, this suggested that young children’s weak attentional control could actually shield them from distraction in real-world contexts, rather than making them perform worse than adults, as suggested by visual attentional research. A follow-up study using number stimuli showed a similar developmental trajectory in the specific interference effects that multisensory stimuli have on young compared to older children and young adults (Matusz et al., 2019a). However, in these particular paradigms, the multisensory information in the distractors was always semantically congruent with the visual target identity. That is to say that the information inherent to the distractors was relevant to the task, even though the distractors themselves were not. Thus, these two studies can speak only to the role of multisensory processes dependent on top-down attention, and it remains unclear if children may be particularly sensitive to salient abstract stimuli like ‘beep-flashes’. Further, and more importantly, both of the above studies measured distractors’ interference with the primary task, rather than distractor processing per se. Thus, it remains unclear whether multisensory information in the environment can capture children’s attention more or less than adults’ attention. Are young children protected from distraction by multisensory stimuli, as the above studies would suggest? Or, would they be even more distracted than adults if the distractors were not imbued with (task relevant) semantic meaning? Teasing out how children’s attention is engaged by multisensory stimuli is important insomuch as multisensory stimuli make up real world environments, including those where children learn. One of the main foci of the present thesis was to clarify the mechanisms behind children's attentional control by multisensory stimuli, and the developmental trajectory thereof, in the service of understanding their links with school learning.

5. Implications for education

The idea of real-world multisensory environments that has been evoked frequently thus far is perfectly embodied in the example of typical school classroom. Learning environments, like the classroom, are characterised not only by competing within-sensory inputs, necessitating unisensory control. Most of these unisensory inputs are congruent in the spatio-temporal and semantic information they provide and may thus be integrated to form multisensory objects. However, developmental research in its current state has no clear answer as to when children are able to optimally integrate such inputs. It is likewise unclear at which point in development does attentional control over such multisensory inputs reach adult-like levels. Further, not enough is known about how control skills function during various points in childhood, whether or not these skills may be considered adult-like. Arguably, through developmental research on attentional and multisensory processes, we have learnt much more about when such processes become fully developed or adult-like than how they operate during given periods of development. Perhaps this is rightfully so, as studying development means studying how cognitive processes change rather than studying children's processing per se (Karmiloff-Smith, 1992). However, characterising children's attentional control processes in real-world settings may be equally as important as knowing when it reaches adult capacities inasmuch as the way in which children control their attention may influence their educational attainment.

Distraction by visual-only and auditory-only real-world content has been found to hinder learning (visual: Fisher, Godwin & Seltman, 2014; Godwin & Fisher, 2011; auditory: Massonnié, Rogers, Mareschal & Kirkham, 2019). Proficiency in visually-assessed EF/attentional control skills like self-regulation, short-term memory span, and conflict monitoring have been positively related to academic achievement (e.g., Cragg & Gilmore, 2014; Gawrilow et al., 2014; Bull, Espy & Wiebe, 2008; Steele et al., 2012; Isbell et al., 2018). Interestingly, however, such control skills have sometimes shown stronger correlational links with numeracy than literacy (e.g., Bull et al., 2008), and the evidence for *causal* links has been mixed (for review see Merkeley, Matusz & Scerif, 2018). Multisensory processing has largely been left out of such investigations. Notably, however, Brem et al. (2010) have showed that the reaching of an adult-like state of specific reading networks depends on children's learning of audiovisual letter-sound pairings, and this multisensory mapping ability has been shown to predict reading outcomes years later (Bach et al., 2013). Similarly, the ability to match information between the senses at infancy has been demonstrated to be a better predictor of later reading skill than the ability to match information within a single sensory modality (Rose et al., 1999). Problems with forming such audiovisual letter-sound pairings have even been proposed as a critical contributor to developmental dyslexia (Birch and Belmont, 1964, Blau et al., 2010), where children present persistent difficulties with reading, despite unimpaired intelligence (Shaywitz, 1998).

We have noted in Section 4 that there is mounting evidence of multisensory benefits for memory and learning in children. Another example is the work of Heikkilä et al. (2015; Heikkilä, & Tiippana, 2016) which has shown that presenting visual and auditory stimuli during memory encoding could improve subsequent unisensory recognition in children aged 8–12. In these studies, the multisensory pairings were fully task-relevant. On the other hand, we know from other integrative work (Astle & Scerif, 2011) that attention often precedes memory and learning. For this reason, it is important to test how fully goal-irrelevant multisensory stimuli (i.e., distractors) engage attention, and whether such attentional control can contribute to predicting learning and educational achievement. Based on the research reviewed in this section, we have strong bases to believe so – the main question is when.

Curiously, it is not just attentional control that may influence educational outcomes, but schooling experience, in turn, may influence the development of attentional control skills. That schooling is a catalyst for developing cognitive control has been repeatedly suggested by findings of increases in IQ with education (e.g., Ceci, 1991; Husén & Tuijnman, 1991; Brinch & Galloway, 2012) that were too rapid to be accounted for by maturation alone (Cliffordson & Gustafsson, 2008). Further support has come from reports of strong improvements in EF skills during the period when most children enter formal schooling, that has thus been dubbed the ‘5-to-7-year shift’ (e.g., Burrage et al., 2008; Brod, Bunge and Shing, 2017; Roebers et al., 2011). Recently, Brod and colleagues (2017) used a longitudinal cut-off design, comparing children in the same age-group (5-to-6-year-olds) where some were enrolled in first grade and others were still in kindergarten because of fixed school entry dates, and retesting them a year later. At each timepoint, they administered two tasks – one assessed purely behaviourally, and the other assessed during an fMRI scan. Children who had started school had better behavioural performance at the first timepoint and more improvements in performance by the second timepoint than their peers who were still in kindergarten. As for the fMRI measures, recruitment of the posterior parietal cortex increased for both groups over the course of a year, however, the increase was larger for children that had been enrolled in first grade a year before. Since both behavioural and neural measures of EF skills improved more dramatically for children that had already received some formal instruction, the authors concluded that formal education interacts with age-related improvement of EF. We do not know how such findings translate to naturalistic contexts, as the influence of schooling on attentional control in multisensory settings has yet to be directly investigated. Indirectly, the two studies by Matusz et al. discussed above suggest that the development of attentional control skills need not be uniformly linear when the multisensory nature of the environment and the child’s schooling experience are taken into account. In their 2015 study, they show that, when the experimental task was difficult, 11-year-olds were more distracted by auditory-only distractors than either 6-year olds or adults. This suggested that distractibility, when not tested only in vision, can differ at different levels of experience. Next, in their educationally-relevant study (Matusz et al., 2019a), the interference effects could well be accounted for by differences in experience. To recapitulate, in this study, young adults, 11-year-olds, and 6-year-olds had to search for a target digit (e.g., the number nine) in a visual search array which could have three or no additional distractors, while a peripheral distractor digit could be presented visually (the number six), auditorily (spoken label “six”), or audiovisually (then number six with a spoken label “six”). When the target and audiovisual distractor identity were congruent (target – nine, distractor – nine), RTs were generally facilitated (statistically reliable for 6-year-olds and adults, but not 11-year-olds). However, when the target and audiovisual target identities were different (target – nine, distractor – six), adults incurred costs on their RT’s, but young children did not (costs were not statistically reliable in 11-year-olds). This suggested that children with less schooling experience were less familiar with written numerals, which in turn protected them from distraction by conjunctions of written numerals and their familiar auditorily-presented names.

Understanding how typically developing children control their attention in multisensory contexts, the developmental trajectory of such control, and its links with educational attainment, are the first steps towards understanding why some children may struggle with school learning. It has been estimated that between 4% and 17% of primary school pupils have a specific learning disorder such as dyslexia or dyscalculia (e.g., Shalev & Gross-Tsur, 2001; Elliott & Grigorenko, 2014; Shaywitz, 1998). Typically, the diagnosis of such school learning problems occurs after failing to achieve age-appropriate educational milestones, if at all. With this, gaps in development and quality-of-life emerge between within-norm and struggling learners, with the latter group being at risk of weaker overall achievements in school (Torgesen, 2002), greater vulnerability to mental health problems (Valås, 1999), and poor employment outcomes in adulthood (De Beer et al., 2014). Over the past years, there has been great progress in understanding the neurocognitive mechanisms and brain correlates of specific literacy (Ozernov-Palchik & Gaab, 2016) and numeracy problems (Price & Ansari, 2013), but developing effective screening tools and interventions has remained a challenge. Though the generalizability of attentional control training to specific educational skills has proven to be debatable (for review in numeracy see Merkeley, Matusz & Scerif, 2018), recent tentative evidence has shown that multisensory processes can be effective screening tools for cognitive problems (Murray et al., 2018; Denervaud et al., 2020). It was the hope of the work presented in the current thesis that including multisensory factors would not only advance the understanding of the links between attentional control skills and educational attainment, but also bring the field closer to developing tools that would help struggling learners.

6. Predictability and semantics in attentional control in multisensory environments

Laboratory-based research that has informed most of our present knowledge on attentional control mechanisms has typically involved simplified stimuli (e.g., geometric shapes, pure tones), presented in highly controlled contexts (e.g., darkened sound-attenuated booths) as part of experimental tasks that may not resemble daily activities. A typical selective attention paradigm may include an array of visual shapes, and a clear set of instructions specifying identity and/or the location of the target. By contrast, real-life contexts in which attention occurs are structured along multiplex levels of organisation, ranging from statistical stimulus regularities to semantic meaning, all of which influence attention to and processing of multisensory objects that make up such contexts (Soto-Faraco et al., 2019). In fact, some see 'context' itself as the "immediate situation in which the brain operates… shaped by external circumstances, such as properties of sensory events, and internal factors, such as behavioural goal, motor plan, and past experiences" (van Atteveldt et al., 2014). van Atteveldt et al. (2014) reviewed evidence to support that MSI itself is dependent on contextual factors such as temporal predictability, past experience, and behavioural goals. Indeed, relevance to behavioural goals has been the most researched top-down control factor in the study of attentional processes (Nobre & Kastner, 2014). However, it may be but one of several forms of top-down influence by contextual factors onto attentional selection (summarised in Gazzaley & Nobre, 2012; Ten Oever et al. 2016). Two such factors that deserve special attention are the temporal organisation and semantic meaning of stimuli within a given context.

Spatial and temporal structure of the external environment are types of information that seem to be routinely used to build expectations and predictions, and such predictions can be of great use for behaviour. Evidence has converged that when the spatial location of an upcoming target stimulus is presented as a pre-cue, this information is stored in working memory and used as a base to generate expectations which, in turn, shape subsequent top-down attention and action (e.g., Coull et al., 2000; Coull & Nobre, 1998; Nobre, Coull, Frith & Mesulam, 1999; see also Gazzaley & Nobre, 2012, p.2). Information from long-term memory, such as the typical location of an object in real-world visual scenes, has also been shown to speed up orienting to that object; joint activation of both the fronto-parietal network and the hippocampus confirmed that such search is guided by information in memory (Summerfield et al., 2006; see also 'contextual cueing' by e.g., Chun, 2000; Chun & Jiang, 1998, 2003). Being able to predict the temporal and spatial occurrence of behaviourally relevant stimuli demonstrably improves behavioural outcomes, such as the speed and accuracy of responses (e.g., Correa et al., 2005; Coull et al., 2000; Green & McDonald, 2010; Miniussi et al., 1999; Naccache et al., 2002; Rohenkohl et al., 2014). A couple of these studies included ERP investigations of the effects of temporal predictability on visual attention, and found that both early components like the P1 (Doherty et al., 2005; see also Dassanayake et al., 2016), and late components like the LDAP were sensitive to predictable onsets of stimuli (Green & McDonald, 2010). In the context of language, studies have shown that the brain uses the onset of a speech sound, following a predictable delay after its corresponding lip movement, to decode meaning from syllables (ten Oever & Sack, 2015), sentences (Luo & Poeppel, 2007) and across competing streams of information (Zion Golumbic, Poeppel, & Schroeder, 2012). More generally, successive stimulus onsets that appear along a predictable rhythm have repeatedly been found to improve perception and behavioural performance (Jones et al., 1981; 2002; 2006; Sanabria et al., 2011; though also temporal cues: Ten Oever et al., 2014).

The behavioural benefits of the temporal predictability of stimuli have motivated some to suggest that stimulus onset predictability is a salient characteristic, and may therefore capture attention (Southwell, 2017). Indeed, the predictability of regularly repeated stimuli has been shown to enhance attention to stimulus locations and features (e.g., Chalk, Seitz & Seriès, 2010; Summerfield et al., 2006; Zhao et al., 2013). However, an opposing theory has suggested that the successive repetition of stimuli should decrease rather than enhance responsiveness to such stimuli. The repetition suppression account has argued that, from the single-neuron level to the level of hemodynamic changes across groups of millions of neurons, repeated stimulus presentations evoke attenuated neural response amplitudes compared to novel stimuli (Grill-Spector, 2006; Henson, 2003; Miller et al., 1991). More recently, such attenuating effects have also been ascribed to predictions (Summerfield et al., 2008; Auksztulewicz & Friston, 2016; Smout et al., 2019), and specifically temporal predictions (Costa-Faidella et al., 2011). Given that these two opposing accounts have yet to be reconciled, and that most research (except the work on language) across these domains has focused on uniquely visual or auditory stimuli, it remains unclear how temporal predictability may influence attentional control in real-world multisensory settings.

Semantic meaning is inextricably embedded in real-world settings, and like statistical stimulus regularities, humans quickly learn semantic relations between sensory inputs, such as that between the sight of a cat and a meowing sound (e.g., Beierholm, Quartz & Shams, 2009; Parise, Spence & Ernst, 2012). The notion that semantic information is a basic organising principle for sensory information has been borne out by electrophysiological results showing that the processing of semantic categories can elicit ERPs already around 100-150ms after the presentation of a stimulus (De Lucia et al., 2010; Dell'Acqua et al., 2010; Doniger et al., 2001; Murray et al., 2006; Simanova et al., 2010). There is plentiful evidence that semantically congruent audiovisual stimuli (sight of a cat coupled with a meowing sound) elicit improved behavioural responses over stimuli where the inputs are incongruent (sight of a cat coupled with the sound of a plate breaking, e.g., Chen & Spence, 2010; Iordanescu et al., 2008; Laurienti et al., 2004; Molholm et al., 2004; Yuval-Greenberg & Deouell, 2007; for review see Doehrmann & Naumer, 2008). Such enhancements may result from the experience that most real-world multisensory objects are made up of semantically congruent sensory pairings. Since semantically meaningful objects predominate real-world settings, the brain likely benefits more from semantic multisensory processes than those including meaningless multisensory stimuli, like the beeps and flashes normally used in laboratory research. For example, research by Murray and colleagues in the field of object memory has showed that semantically congruent multisensory pairings were better remembered than meaningless multisensory pairings (Murray et al., 2004; 2005; Matusz et al., 2015; Thelen et al. 2015, reviewed in Matusz, Wallace & Murray, 2017).

With regards to attentional control over multisensory stimuli, the research interest has been more modest but still present (e.g., Iordanescu et a., 2008; 2010; Mastroberardino et al., 2015). In a seminal study, Iordanescu et al (2008) employed a visual search paradigm where participants had to search for a target image (e.g., a picture of a dog) amongst three other images denoting real-world objects. They demonstrated that target detection was faster in the presence of an accompanying sound that was semantically congruent with the target image (the sound of a dog barking) than when the sound was congruent with another, distractor, image shown on the screen, or with an image that was not shown on the screen. In a follow-up study, Iordanescu et al (2010) showed that multisensory semantic congruence sped up not only behavioural responses, but also the initial rapid eye movement (saccade) toward the target, and subsequent saccades during search for the target. Further, Mastroberardino et al. (2015) found better behavioural performance and differential activation of fronto-parietal attentional control networks for stimuli that were preceded by goal-irrelevant semantically congruent multisensory pairings. Although all of these studies suggest that multisensory semantic congruence guides and facilitates attention, none of them included a comparison with non-semantic multisensory stimuli. Therefore, it is impossible to disentangle whether the observed behavioural and brain responses were driven more by the multisensory or semantic qualities of the stimuli that were used.

What the above work collectively shows is that experience-based expectations and predictions about stimulus onset and semantic meaning are routinely used to achieve goals and benefit behaviour. This is in line with predictive coding and Bayesian approaches, whereby the brain utilises predictions/expectations from higher-level cortices, generated by experience with the environment, to 'evaluate' information entering from lower-level cortices and calibrate decision-making and action (e.g., Friston, 2005; Friston & Stephan, 2007; Rao & Ballard, 1999; reviewed in Clark, 2013 and Summerfield & Egner, 2009; Erns & Banks, 2002; Knill & Pouget, 2004; Schroeder et al., 2010). Despite the intuitiveness of such a framework, the interplay between simultaneously occurring behavioural goals, spatiotemporal predictions, and semantic predictions in real-world multisensory settings remains largely unclear (see Ten Oever et al., 2016). In order to ascertain the various, potentially interacting, influences that could affect attentional control in multisensory settings, the present thesis employed an experimental paradigm that emulates real-world conditions while retaining a sufficient degree of experimental control to systematically manipulate all the factors of interest.

7. Research aims of the current thesis

The present thesis is divided along the following main points of interest, each with its specific research questions stated below:

Aim 1. Clarifying the developmental trajectory of attentional control mechanisms in multisensory conditions.

    a) When during development does visual attentional object selection become controlled by top-down visual and bottom-up multisensory control processes?

    b) Does multisensory control of visual attention emerge before or after visual top-down control?

    c) Are traditional measures of attentional control (behavioural and/or ERP) useful in studying more naturalistic attentional control, gauged by multisensory stimuli, and across the lifespan? If not, can multivariate EEG measures offer complementary or even more robust tools?

Aim 2. Characterising children's attentional control processes at different points of schooling and identifying their links with scholastic achievement.

    a) How do children process task-irrelevant multisensory distractors vis-à-vis visual distractors, and what are the brain mechanisms governing such attentional processes?

    b) How do these mechanisms differ across different levels of school experience?

    c) Between visual and multisensory attentional control, which is more important for learning to read and for learning basic mathematics?

Aim 3. Investigating the influence of contextual factors on adult attentional control processes in multisensory conditions.

    a) Does the predictability of the onset of task-irrelevant stimuli influence attentional control? If it does, how so?

    b) Does the multisensory relationship between auditory and visual distractor features influence attentional control? If it does, how so?

To investigate the above interests, a so-called ‘naturalistic laboratory’ approach was applied, which incorporates key parameters of natural environments, such as their multistimulus and multisensory nature, into rigorous laboratory paradigms (see Matusz, Dikker, Huth, and Perrodin, 2019). Throughout this thesis, Matusz and Eimer’s (2011) multisensory version of Folk’s spatial cueing paradigm was used to assess attentional control mechanisms, as it allowed a direct and systematic comparison between known visual control processes and lesser known multisensory control processes. The paradigm was further adapted to fit school-aged child populations, through minor simplifications and the introduction of a game-like narrative (described in full in Chapter 2). Importantly, both adults and children across different levels of schooling completed the same, child-friendly, version of the task. In so doing, we could directly compare how both adults and children at different levels of schooling controlled their attention towards visual and audiovisual objects, as well as differences in such control processes across age-groups. Finally, for Aim 3, the above paradigm was expanded to include manipulations of distractor stimulus onset predictability and semantic meaning. Since this manipulation increased both task complexity and testing time, only adults were assessed. Top-down visual attentional control was assessed through the presence of TAC, i.e., attentional capture by objects with target-matching features but non nonmatching features, even if such objects are goal-irrelevant. As a measure of bottom-up control of attention by multisensory stimuli, we probed the occurrence of MSE, i.e. increases in attentional capture for audiovisual distractors regardless of target-matching. For all cohorts, the behavioural paradigm was combined with a simultaneous EEG measurement, and the EEG data thus gathered were analysed in line with traditional N2pc analysis methods as well as within an EN framework. Links between behavioural and brain measures of attentional control processes and children’s literacy and numeracy skills were assessed with the use of a robust correlation technique known as skipped correlation. To be precise, indices of TAC and MSE as behavioural measures, and template map durations over the N2pc time-window as brain measures, were correlated with a set of scores on a standardized age-appropriate test of literacy and numeracy.

In general, adults were expected to replicate the well-established TAC effect in behaviour as well as the MSE effect observed by Matusz and Eimer (2011). In children, and specifically for Aim 2, behavioural TAC and MSE were considered as evidence of adult-like processing. We expected to find TAC in older child groups, but not the youngest (see Gaspelin et al. 2015), and for MSE, there were no clear predictions in children. For the traditionally measured N2pc in adults (posterior contralateral electrodes on the scalp, like PO7/8), we expected a reliable N2pc for target-matching distractors and attenuated or even eliminated N2pc for non-target matching distractors. Again, for Aim 2, such was the pattern of N2pc results that was considered adult-like. There were no strong predictions for MSE in N2pc, as the only study to date on N2pc to audiovisual stimuli during a demanding visual attention task showed weak evidence for audiovisual distractors (van der Burg et al. 2011). Equally, there were no strong predictions for TAC or MSE effects in children’s N2pc’s, for two reasons. First, the oldest children in our study were younger than the youngest children where the N2pc was reported (Couperus & Quirk 2015). Second, the N2pc in the current paradigm was recorded to distractors, and not targets, as in all previous studies, which may have further created sub-optimal conditions for its detection. In turn, the sensitive multivariate nature of EN analyses was expected to reveal modulations of brain response strength (via GFP) or of network recruitment (via topographical analyses of DISS) by visual and/or multisensory control in adults, and at least in older groups of children. For Aim 2, in the EN framework, adult-like processing would constitute GFP amplitudes comparable to those seen in adults, and the presence of adult topographical configurations in child ERP signals. In terms of links with education, we only had a general expectation that visual attentional control would be related to numeracy and less so with literacy, based on the available research that has shown such links (e.g., Bull, Espy & Wiebe, 2008; Steele et al., 2012). For Aim 3, we expected that both the onset of the distractors, and the multisensory relationship between distractor features would modulate adults' attentional capture. There were no strong predictions as to whether these contextual factors would further modulate MSE or TAC effects, as these factors have yet to be tested in concert. Specifically, semantically meaningful links between auditory and visual distractor features were expected to produce larger behavioural capture, and increased N2pc and EN measures of attentional control, over and above pure simultaneity-based links between distractor features. For distractor onset, there were two possible outcomes. In the case that predictable stimuli were being 'enhanced' due to the rhythmicity of their onset, larger behavioural capture, and increased N2pc and EN measures of attentional control would be observed for predictable compared to unpredictable onsets. Alternatively, if predictable stimuli were being 'suppressed', driven by a repetition suppression-like mechanism, reduced behavioural capture, and reduced N2pc and EN measures of attentional control would be observed for predictable compared to unpredictable onsets.

Chapter 2: Materials and Methods

1. Participants

1.1. General participant information

Participants of all ages had normal or corrected-to-normal vision and normal hearing, and had no history of sensory problems (e.g., related to vision or audition), neuropsychological problems (e.g., epilepsy), neurodevelopmental disorders (e.g., autism, ADHD), or learning difficulties (e.g., dyslexia), as indicated by parental report for children, or by direct report for adults. Before participating in the study, all adult participants and parents/caregivers of child participants signed an informed consent form, and children verbally assented to take part in the study. All research procedures were approved by the Cantonal Commission for the Ethics of Human Research (CER-VD).

1.2 Developmental Study

A total of 115 primary school children participated in the study, 28 of whom were enrolled in fifth grade, 46 in third grade, and 41 in first grade of primary school in the canton of Vaud, Switzerland. Here, children enter formal education, i.e., 1st grade at ages 4-5. However, the first two grades are considered as kindergarten, and educational goals therein mainly include socialisation, building work habits, and acquiring foundational skills in literacy, numeracy, etc. (CIIP, 2012). Then, at 3rd grade, children are effectively 6-7 years old, and at 5th grade, 8-9 years old. For brevity, each child group will be referred to by the central tendency of their respective groups (see below), thus: '5-year-olds' for 1st grade children, '7-year-olds' for 3rd grade children, and '9-year-olds' for 5th grade children. Children were recruited from local schools, nurseries, public events and entertainment facilities. Recruitment took place in the period from March 2017 to May 2019. Of the total number of children recruited, 18 were excluded for failure to initiate the testing session or failure to complete the task with above chance-level accuracy (50%), thus excluding 1 9-year-old ,6 7-year-olds, and 11 5-year-olds respectively. Finally, 5 additional participants (1 9-year-old, 2 7-year-olds, and 2 5-year-olds) were excluded because of unusable EEG signals due to excessive noise even after a two-step preprocessing detailed below. Therefore, the final child sample consisted of 92 children. 9-year-olds (*N* = 26, 10 male, M_{age}: 8y 10mo, *SD:* 5mo, range: 8y 1mo – 10y 1mo), 7-year-olds (*N* = 38, 18 female, M_{age}: 6y 10mo, *SD:* 4mo, range: 6y 1mo, 7y 9mo), and 5-year-olds (*N* = 28, 13 female, M_{age}: 5y, *SD:* 4mo, range: 4y– 5y 7mo). We based our sample sizes on the only extant study that employed a comparable spatial cueing paradigm in children (Gaspelin et al., 2015). Using G*Power 3.1 (Faul, Erdfelder, Buchner & Lang, 2009), we calculated that the power for their Cue Relevance x Cue validity 2-way interaction in 5-year-olds was 0.98, with a sample size of 39 and effect size of 0.1 in the case of raw reaction times. This was the most comparable interaction and age group with our study, in that it was an analogue to our TAC effects and our 5-year-old group. We expected that this effect would be easier to detect in older children. A post-hoc power analysis on our present data revealed comparable statistical power for testing our hypothesised TAC effects in behaviour, with 0.97 in 5-year-olds (sample size of 28, effect size of 0.1), 0.99 in 7-year-olds (sample size of 38, effect size of 0.2), and 0.99 in 9-year-olds (sample size of 26, effect size of 0.4).

1.3 Adult Study

The adult sample consisted of 39 adult volunteers (14 male, M_{age}: 27y 6mo, *SD:* 4y, range: 22–38y). Adult participants were recruited via word of mouth and study flyers distributed at the Lausanne University Hospital Centre (CHUV) and the University of Lausanne. Although previous studies with comparable behavioural tasks normally involved smaller adult samples (Eimer, Kiss, Press & Sauter, 2009; Matusz & Eimer, 2011), here we aimed for a sample size that was consistent with the child groups. We calculated the power of Matusz and Eimer's (2011, Experiment 2) Cue Colour x Spatial Cueing interaction and Tone Presence x Spatial Cueing interaction, as these effects were analogues to our hypothesised TAC and MSE effects in behaviour. The power of the Cue Colour x Spatial Cueing interaction was 0.99 with a sample size of 22 and an effect size of 0.6, while the power of the Tone Presence x Spatial Cueing interaction was 0.92 with a sample size of 22 and an effect size of 0.1. A post-hoc power analysis on our present data revealed sufficient statistical power for testing our hypothesised TAC effects (0.99 for a main effect of Cue Colour size of 39, effect size of 0.9) and MSE effects (0.99 for a main effect of Cue Modality, sample size of 39, effect size of 0.2) in behaviour. Next, the power necessary to detect TAC effects in N2pc was based on the results of a power calculation on the Cue Condition x Contralaterality interaction from Eimer et al. (2009). This interaction reached a power of 0.99 with a sample size of 12 and an effect size of 0.6. We, again, conducted a post-hoc power analysis on our Experiment 2 N2pc data and found that there was sufficient statistical power to detect TAC in N2pc (0.99 for a main effect of Cue Colour size of 39, effect size of 0.4). The power of MSE and contextual effects in N2pc could not be estimated as no previous studies have investigated such effects in distractor-locked N2pc's.

2. Materials and procedures

All participants were tested at the Lausanne University Hospital Centre (CHUV). As the two studies involved similar but, nonetheless, distinct testing procedures and materials, we describe them separately.

2.1. Developmental Study

2.1.1. General procedures

Children took part in two testing sessions – the attention task combined with the EEG session, and a neuropsychological testing session. The EEG session lasted between 1h and 1h30mins, including briefing, obtaining consent, practicing the experimental task, the experimental task itself, and breaks. The experimental task was a child-friendly version of Matusz and Eimer's (2011) audiovisual adaptation of Folk et al.'s (1992) spatial cueing paradigm, combined with a simultaneous EEG recording. Briefly, the task involved searching for a target diamond shape in an array of diamond shapes, which was preceded by a visual or audiovisual distractor that could either match the target by colour or not (Figure 4A). The neuropsychological testing session lasted approximately the same amount of time but took place on a different day than the EEG session. Neuropsychological testing involved assessing children's baseline IQ and their educational achievements, in counterbalanced order. We describe the tools and related procedures below. All test items during this session were administered in French. After completing both sessions, children received a 30 Swiss franc voucher for a media store and parents/caregivers' travel costs were reimbursed.

2.1.2. Baseline cognitive functioning

Full Scale IQ (FSIQ) items from the Wechsler Intelligence Scale for Children, 5th edition (WISC-V) for 9-year-old and 7-year-old children, and FSIQ items from the Wechsler Preschool & Primary Scale of Intelligence, 4th edition (WPPSI-IV) for 5-year-old children were used to assess general cognitive skills. No child had an FSIQ score under 85, which would warrant exclusion.

2.1.3. Educational achievement

Assessment of children's school learning skills focused on literacy and numeracy, which were measured using the Evaluation of cognitive functions and learning (In French: Evaluation des fonctions cognitives et apprentissages; EDA 4-11) testing battery. Different items from the EDA 4-11 were used to compute age group-appropriate scores of children's educational achievements. It should be noted that the administration of certain items had to be modified to reconcile the differences in school instruction between the local Swiss school system and the French system that the EDA 4-11 was standardized for. We describe the changes where appropriate.

For 9-year-olds, there were two separate measures of literacy, that is, Reading and Comprehension. These measures were computed as follows:

- Reading – the number of words correctly read in an age-appropriate text,
- Comprehension – a composite score based on correctly answered questions about the content of the read text.

The numeracy measure was a composite score of items belonging to the Mathematics measure, that assessed the following skills:

- Counting – counting down from 24
- Mental calculation – solving equations without the help of supplies. Here, equations that involved multiplication were not administered, as multiplication is only introduced very gradually, rather towards the end of this school grade. Instead, one point was given for every multiplication item if the participant solved the preceding, non-multiplication items, correctly
- Numerical awareness – correctly identifying digits, and writing the appropriate digits in response to dictated number words

- Basic arithmetic – Solving equations on a worksheet. Again, equations that involved multiplication were not administered, and one point was given for every multiplication item if the participant solved the preceding, non-multiplication items, correctly.
- Problem-solving - solving mathematical problems based on images in a workbook (e.g., ‘If one lollipop costs 8 CHF and one candy costs 6 CHF, how much do you need to buy all the lollipops and sweets?’)
- Size estimation – identifying the largest and smallest number in an array of numbers, stating which of two spoken numbers is larger
- Place value – stating how many tens there are in a three-digit number
- Value estimation – marking the position of given numbers on a line marked with 0 at the start and 100 at the end

For 7-year-olds, the literacy measure, i.e., Reading, was a composite score based on the successful reading of letters, words (monosyllabic and disyllabic), syllables, digraphs, trigraphs, nonwords, and sentences, in that order. The numeracy measure, i.e., Mathematics, was a composite score of items that measured the following skills:

- Counting – counting up from 5, where beyond 15 was sufficient
- Mental calculation – solving equations without the help of supplies
- Numerical awareness – correctly identifying digits, and writing the appropriate digits in response to dictated number words
- Basic arithmetic – Solving equations on a worksheet. This task involved transforming given equations into column form before solving them, which is not yet taught at the 7-year-old level. Therefore, we did not impose this rule on participants.
- Problem-solving – solving mathematical problems based on images in a workbook (e.g., 'There are five lollipops on the picture. If you eat three, how many are left?’)
- Size estimation – stating which of two written numbers is larger, and which of two spoken numbers is larger
- Value estimation – marking the position of given numbers on a line marked with 0 at the start and 100 at the end

For 5-year-olds, Phonological skills were assessed as a proxy for literacy, through nonword repetition. Numeracy was a composite score of the following measures:

- Counting – counting as long as the participant can, where beyond 10 was sufficient
- Quantification – showing a given number of fingers
- Enumeration – counting a number of objects on an image in a workbook
- Cardinality – stating the number of objects on an image, without counting them one by one
- Number recognition – correctly naming digits

2.2. Adult Study

Adults took part only in an EEG session. However, this session took approximately 3h, as it was comprised of four experimental tasks. All four experimental tasks were variations of

Matusz and Eimer's (2011) adaptation of the Folk et al.'s spatial cueing paradigm. The first two tasks involved non-semantically related colour-pitch combinations as in the original study, while the last two involved colour-pitch combinations that were semantically congruent (the factor of Multisensory Relationship in Figure1.B). Such a semantic relationship between colours and sounds was created using a training task that was based on the association task in Sui, He & Humphreys (2012; see also Sun, Fuentes, Humphreys & Sui, 2016). Further, Experiments 1 and 3 involved cue onsets variable in duration, while Experiments 2 and 4 involved cue onsets that had a constant timing (the factor of Distractor Onset in Figure 4.B). As a pilot study revealed sufficient proficiency at the experimental task (over 50% accuracy) after a few trials, unlike children, adults did not practice the task before its administration. Adult participants were not compensated for their participation.

3. Experimental task

3.1. General task properties

As in the original task used by Folk et al. (1992), all participants searched for a colour predefined target (e.g., red bars) in a search array, and assessed the target's orientation (vertical vs. horizontal). The search array was always preceded by an array containing distractors ("cues"). Distractors were visual and audiovisual stimuli that could match the target colour (red set of dots) or not match the target colour (blue set of dots), as in the original Matusz and Eimer (2011) study (Exp.2).

Each experimental trial consisted of the following sequence of arrays: base array, followed by cue array, followed by a fixation point, and finally a target array (Figure 4A). The base array contained four differently coloured sets of closely aligned dots, each dot subtending 0.1° × 0.1° of visual angle. Each set element could be one of four possible colours (according to the RGB scale): green (0/179/0), pink (168/51/166), gold (150/134/10), silver (136/136/132). In the cue array, one of the base array elements changed colour to either a target-matching colour, or a target-nonmatching colour that was not present in any of the elements before. The remaining three cue array elements did not change their colour. The cues and the subsequent target "diamonds" could have either a blue (RGB values: 31/118/220) or red (RGB values: 224/71/52) colour. The target array contained four bars (rectangles) where one was always the colour-defined target. The target colour was counterbalanced across participants.

The two cue colours were randomly selected with equal probability before each trial, and the colour change was not spatially predictive of the subsequent target location (same cue – target location on 25% of trials). On half of all trials, cue onset coincided with the onset of a pure sine-wave tone, presented from two loudspeakers on the left and right sides of the monitor. Sound intensity was 80 dB SPL, as measured using an audiometer placed at a position adjacent to participants' ears.

Experimental and training tasks were conducted in a dimly lit, sound-attenuated room, with participants seated at a distance of 90 cm from a 23" LCD monitor with a resolution of 1080 × 1024 (60-Hz refresh rate, HP EliteDisplay E232). All visual elements were approximately equiluminant (~20cd/m2). The luminance of each element colour was determined by filling the computer screen with one colour at a time and measuring the luminance with a luxmeter placed at a position adjacent to participants' eyes. Each colour was measured three times, and the measurement values per colour were averaged to create a composite luminance value per colour. Next, these values were averaged across colours, and transformed from lux to cd/m2 in order to facilitate comparison with the results of Matusz & Eimer (2011). Elements were spread equidistally along the circumference of an imaginary circle against a black background, at an angular distance of 2.1° from a central fixation point. Target orientation (horizontal or vertical) was randomly determined on each trial; responses were made by pressing one of two horizontally aligned round buttons (Lib Switch, Liberator Ltd.) that were fixed onto a tray bag on the participants' lap. Participants were told to answer as quickly and accurately as possible. The full experimental session consisted of 8 blocks of 64 trials each, resulting in 512 trials in total. If participants did not respond within 5000ms of the target presentation, the next trial was initiated, otherwise the next trial was initiated immediately after a button press. Feedback on accuracy was given after each block, followed by the 'progress (treasure) map' which informed participants of the number of blocks remaining until the end, and during which participants could take a break and, in the case of children, parents/caregivers could enter the testing room.

Consequently, there were four overall cue conditions: TCCV (target colour-cue visual), NCCV (nontarget colour-cue, Visual), TCCAV (target colour-cue, AudioVisual), NCCAV (nontarget colour-cue, AudioVisual), These conditions translated into a 2 x 2 stimulus design, with factors: Cue Colour (target colour-cue - TCC vs. nontarget colour-cue - NCC), Cue Modality (Visual - V vs. AudioVisual - AV), and Cue-Target Location (Same vs. Different).

3.2. Developmental Study

The task was adapted to be more age-appropriate and engaging for children in the following ways. First, we introduced a game-like narrative, where participants had to help a pirate captain find treasure on a deserted island and moved along a treasure map after each completed block. Second, target bars were reshaped into "diamonds" to make them more attractive to children. The original uniformly coloured targets (Matusz & Eimer 2011, Exp.2) were given diamond-like appearance by adding triangle shapes on the short sides of the bars and increasing and decreasing the luminance of certain sides of the bars by 20% (see Target array in Figure1.A). Third, the number of elements in all arrays was reduced from 6 to 4 by removing 2 elements on the meridian, so that the perceptual load on children's attention is lower (e.g. Matusz et al. 2015).

There were other differences compared to the original Matusz and Eimer (2011) paradigm, in that the base array in the Developmental Study varied pseudorandomly in duration across trials (between 100, 250 and 450ms). This manipulation served to avoid any possible building of predictions based on stimulus regularity that could influence top-down attentional control (Schwartze et al., 2011). However, the plausibility of such temporal predictability effects on top-down attentional control was systematically investigated in the Adult Study (see below). Further, to familiarise children with the task, a practice block of 32 trials at 50% of regular task speed was administered. Finally, during the experimental task itself, stickers on diamond-shaped sheets were offered during breaks in order to maintain motivation in younger child participants.

3.3. Adult Study

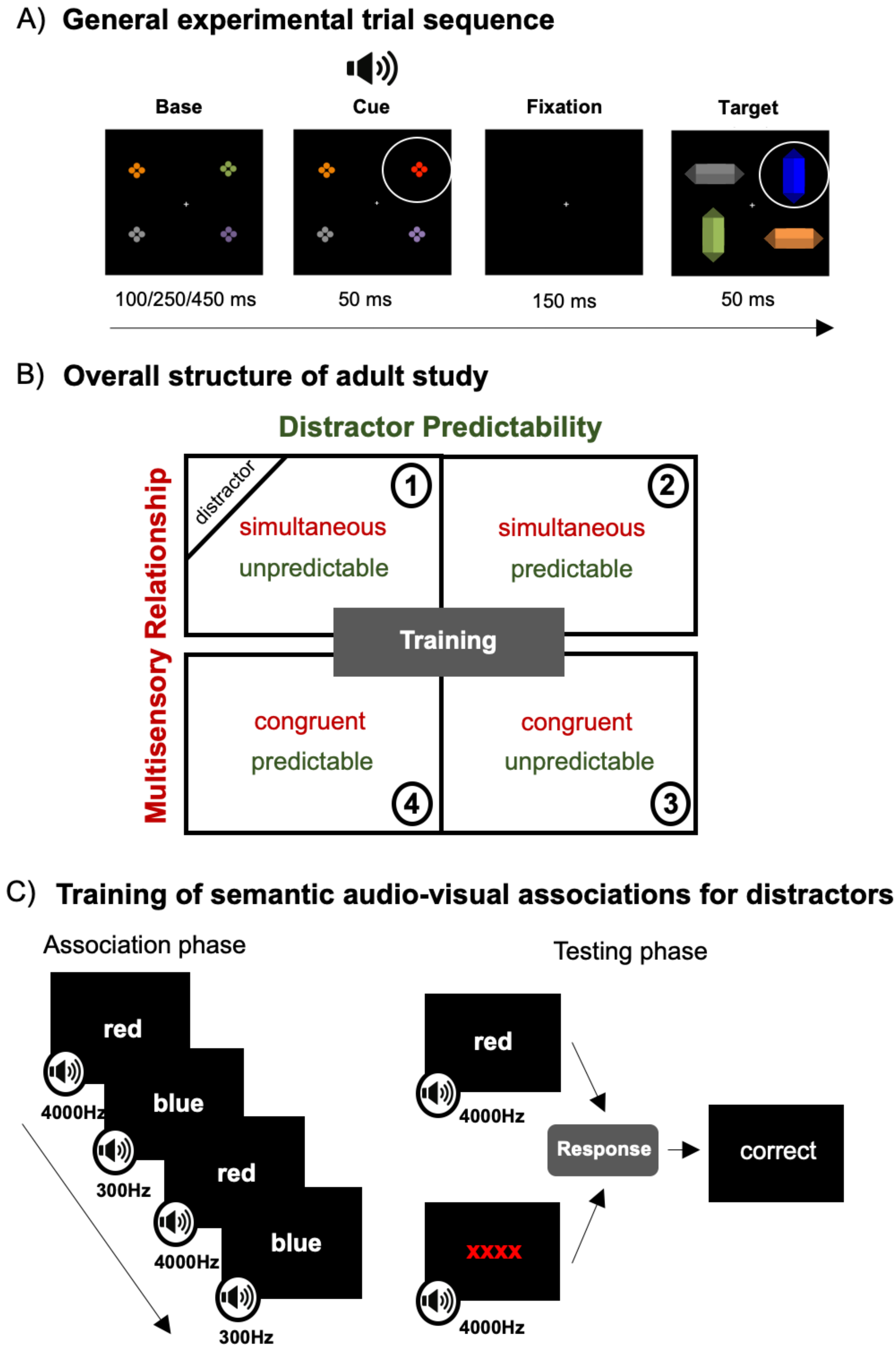
The main difference between the Adult Study and the Developmental Study was the introduction of the two factors, Distractor Onset and Multisensory Relationship, manipulated across the four experimental tasks. To first address the Onset Duration factor, the base array duration was systematically manipulated across experimental tasks. That is, in Experiments 2 and 4, base array duration (and therefore cue onset) was kept constant at 450ms, as in the original Matusz and Eimer (2011) paradigm, while in Experiments 1 and 3, base array duration (and therefore cue onset) was varied between 100, 250 and 450ms (Figure1.B). This way, the strength of attentional capture by temporally predictable distractors could be compared with the capture elicited by unpredictable distractors, and if and how these visual and audiovisual distractors differ on that dimension. Second, to address the Multisensory Relationship factor, the sound frequency was set to 2000Hz in Experiments 1 and 2, as in the Matusz and Eimer (2011) paradigm, and alternated between 4000Hz (high-pitch) or 300Hz (low-pitch) in Experiments 3 and 4. Then, a Training was presented after Experiment 2, in order to induce in participants a semantic-level association between a specific cue colour and a specific pitch (Figure 4C). This way, the strength of attentional capture by colour-pitch combinations related by their simultaneous presentation could be compared with the capture elicited by colour-pitch combinations related by their semantic congruence.

With the above manipulations, the total number of trials in the Adult Study was four times larger than that in the Developmental Study (512 x 4 = 2,048 trials in total). Thus, the Adult Study design had 5 different factors. These were Cue Colour, Cue Modality, and Cue-Target Location, with two new factors: Distractor Onset (DO; Predictable vs. Unpredictable) and Multisensory Relationship (MR; Simultaneity vs. Congruence). In relation to the Developmental study, the ‘adult control’ data used there were effectively data from Experiment 1. Like the experimental task used in the Developmental Study, Experiment 1 involved a base array of variable duration (Distractor Onset was Unpredictable), and the colour and pitch of the cues were purely simultaneous (Multisensory relationship was Simultaneity). Another similarity is that the data for Experiment 1 were collected within the first 1h-1h30, akin to the total length of the children’s EEG session.

3.2.1. Training

The Training in the Adult Study consisted of an Association phase and a Testing phase. In the Association phase, participants were shown alternating colour word–pitch pairs. Specifically, each pair consisted of a word, denoting a cue colour, that was presented on the centre of the screen at the same time as a spatially diffuse pure tone that was either high (4000Hz) or low (300Hz) in pitch. Both the colour word and sound were presented for 2 seconds, after which a central fixation cross was presented for 150ms, followed by the next colour word-pitch pair. Colour words were paired with sounds according to two possible pairing options. In one pairing option, the high-pitch tone was associated with the word 'red' and the low-pitch tone with the word 'blue', and in another pairing option, the high-pitch tone was associated with the word 'blue' and the low-pitch tone with the word 'red' (Fig.1C, Association phase). Pairing options were counterbalanced across participants. Therefore, if the first pairing option was selected, a presentation of the word 'red' with a high-pitch tone would be followed by a presentation of the word 'blue' with a low-pitch tone, which would again be followed by the former pair, etc. There were ten presentations per pair, resulting in a total of 20 trials. Colour words were chosen instead of actual colours to ensure that associations were based on semantic meaning rather than a linking of basic stimulus features (for examples of such taught crossmodal correspondences see e.g., Ernst, 2007). Colour words were shown in participants' native language (speakers: 19 French, 8 Italian, 5 German, 4 Spanish, 3 English). Participants were instructed to observe and try to memorise the pairings as best as they could, as they would be subsequently tested on how well they learnt the pairings.

The strength of colour-pitch associations was assessed in the Testing phase. Here, participants were shown colour word-pitch pairings (as in the training) as well as colour-pitch pairings (a string of x's in either red or blue paired with a sound, Fig.1C, Testing phase). Based on the pairing option that participants were 'taught' in the Association phase, pairings could be either matched or mismatched. For example, if 'red' was paired with a high-pitch tone in the Association phase, in the Testing phase, the word 'red' (or red x's) paired with a high-pitch tone would match, while the word 'red' (or red x's) paired with a low-pitch tone would be mismatched. Participants had to indicate whether a given pair was matched or mismatched by pressing an appropriate button on the same response setup as in the experiments. In a similar paradigm used by Sui, et al. (2012), people were able to reliably associate low-level visual features (colours and geometric shapes) with abstract social concepts such as themselves, their friend, and a stranger. Following their design, in the Testing phase each pairing was shown for 250ms, of which 50ms was the sound (instead of the stimulus duration of 100ms that Sui et al. used, to fit our stimulus parameters), followed by an 800ms blank screen where choices were to be made, and feedback on performance after each answer was given. Before each trial, a fixation cross was shown for 500ms. Each participant performed three blocks of 80 trials, with 60 trials per possible combination (colour word – sound matching, colour word – sound nonmatching, colour – sound matching, colour – sound nonmatching). A final summary of correct, incorrect, and missed trials was shown at the end of testing phase. Participants whose correct responses were at or below 50% had to repeat the testing.



A) General experimental trial sequence

B) Overall structure of adult study

C) Training of semantic audio-visual associations for distractors

Figure 4. A) An example trial of the General experimental task is shown, with four successive arrays and their durations. The white circle around the target location (here the target is a blue diamond) and the

corresponding cue location serves to highlight, in this case, a non-matching cue colour condition, with a concomitant sound, i.e., NCCAV. B) The order of tasks in the Adult Study, with the corresponding conditions of Multisensory Relationship (MR) in red, and Distractor Onset (DO) in green, shown separately for each experiment. C) Events that were part of the Training of the Adult Study. *Association phase*: an example pairing option (red – high pitch, blue – low pitch) with trial progression is shown. *Testing phase*: the pairing learnt in the Association phase would be tested using a colour word or a string of x's in the respective colour. Participants had to indicate whether the pairing was correct via a button press, after which feedback was given.

4. EEG acquisition and preprocessing

A 129-channel HydroCel Geodesic Sensor Net connected to a NetStation amplifier (Net Amps 400; Electrical Geodesics Inc., Eugene, OR, USA) was used to record continuous EEG data sampled at 1000Hz. Electrode impedances were kept below 50kΩ, and electrodes were referenced online to Cz. First, offline filtering involved a 0.1 Hz high-pass and 40 Hz low-pass as well as 50 Hz notch and a second-order Butterworth filter (–12 dB/octave roll-off, computed linearly with forward and backward passes to eliminate phase-shift). Next, the EEG was segmented into peri-stimulus epochs from 100ms before cue onset to 500ms after cue onset. An automatic artefact rejection criterion of ±100 µV was used for adult EEG data, and of ±150 µV for child EEG data, along with visual inspection. The use of different artefact rejection criteria between children and adults was based on a suggestion of Shimi, Nobre and Scerif (2015) that, due to physiological differences and EEG spectral power differences between children and adults, these two groups may require different criteria to prevent discarding clean EEG signal. The specific choice of criteria was based on previous ERP research on adults (e.g., Murray, Nobre & Stokes, 2011; Matusz et al., 2019b) and developing populations (e.g., Melinder et al., 2010; Shimi et al., 2014b). Epochs were then screened for transient noise, eye movements, and muscle artefacts using a semi-automated artefact rejection procedure. For children, additionally, only EEG data from trials with correct responses, and from blocks with over 50% accuracy were used, to fit behavioural data. Data from artefact contaminated electrodes across all groups were interpolated using three-dimensional splines (Perrin et al., 1987). Average numbers of epochs removed were as follows: 11% in adults (across all experiments), 11% in 9-year-olds, 8% in 7-year-olds, and 14% in 5-year-olds. Average numbers of electrodes interpolated per participant were as follows: 8 in adults (6% of the total electrode montage; across all experiments), 11 in 9-year-olds (8% of the total electrode montage), 10 in 7-year-olds (8% of the total electrode montage), and 12 in 5-year-olds (10% of the total electrode montage).

Cleaned epochs were averaged, baseline corrected to the 100ms pre-cue time interval, and re-referenced to the average reference. Next, an additional 50Hz notch filter was applied. All of the above steps were done separately for ERPs from the four cue conditions, separately for cues in the left and right hemifield. To analyse cue-elicited lateralised ERPs, single-trial data from all conditions with cues presented on the left were relabelled to have electrodes over the left hemiscalp represent activity over the right hemiscalp, and vice versa. After relabelling, the "mirror cue-on-the-right" single-trial data and the veridical "cue-on-the-right" data were averaged together, creating a single average

ERP for each of the 4 cue conditions. This way, the contralaterality that would normally be represented by separate ERPs, was preserved within each averaged ERP, with contralateral and ipsilateral hemiscalp activations present within each averaged ERP. As a result, we obtained 4 different ERPs: TCCV (target colour-cue, Visual), NCCV (nontarget colour-cue, Visual), TCCAV (target colour-cue, AudioVisual), NCCAV (nontarget colour-cue, AudioVisual). All preprocessing and EEG analyses, unless otherwise stated, were conducted using CarTool software (available for free at www.fbmlab.com/CarTool-software/; Brunet, Murray, & Michel, 2011).

5. Data analysis design

5.1. General analysis procedures

5.1.1. Behavioural analyses

Analyses across both the Developmental and Adult study were focused on reaction-time (RT) spatial cueing effects, which were calculated by subtracting the mean RTs for trials where the cue and target were in the same location (from the mean RTs for trials where the cue and target location differed, separately for each of the four cue conditions. Error rates were also analysed, in the form of percentages. Before the analysis, RT data were cleaned using slightly different procedures between the developmental and Adult Study.

In general, RT data was analysed using the analysis of variance (ANOVA) technique. However, error data was not normally distributed and was thus analysed using various nonparametric tests. Specifically, the Kruskal–Wallis *H* test, which is considered the nonparametric version of a one-way ANOVA with two or more balanced or unbalanced groups (Field, 2013), was used to analyse if error rates differed significantly between the four age-groups in the Developmental study and between experiments in the Adult study. Friedman and Durbin tests were used to analyse differences between experimental conditions within each age group in the Developmental study, and for each experiment separately in the Adult study, as both of these measures are considered nonparametric versions of a repeated-measures ANOVA (see e.g., Conover, 1999). The difference between the two tests is that the Durbin test is optimized for 'balanced incomplete designs', such as our adult error data, where no errors were made for some conditions but not for others. In the case that there are no zero-values in a design, the Durbin test reduces to a Friedman test. Therefore, we applied a Durbin test to the adult data, and separate Friedman tests to the child data. We note that, unlike their parametric counterpart, the Friedman and Durbin tests do not allow the testing of interactions, or the inclusion of between-subject factors. All analyses, including post-hoc paired *t*-tests, were conducted using SPSS for Macintosh 26.0 (Armonk, NY: IBM Corp).

5.1.2. N2pc analyses

The N2pc is a well-studied and well-understood correlate of attentional selection in visual contexts and in adult populations. However, it is unknown whether the N2pc also indexes attentional selection by multisensory stimuli, which real-world settings are made up of. It is also unclear whether the N2pc elicited by visual as well as audiovisual captures modulations of top-down attention by contextual factors inherent to real-world settings, such as semantic relationships across the senses (for visual-only research, see, e.g. Wu et al. 2013) and stimulus onset predictability (for visual-only study, see, e.g., Burra & Kerzel, 2013). Finally, the sensitivity of the N2pc to such real-world factors has yet to be explored in child populations. In order to systematically compare such lesser known N2pc effects against those that are well-known, we began our ERP analyses across age groups by conducting a canonical N2pc analysis on the contralateral and ipsilateral average ERPs elicited across the 4 cue conditions. Additionally, these analyses helped us better bridge previous and present traditional N2pc results with our EN analyses of the N2pc, as EN analyses offer a decisive advance over canonical N2pc analyses, as discussed in the Introduction.

5.1.3. Electrical neuroimaging analyses

ERP data were also analysed within an EN approach, using data from the entire 129-channel electrode montage. EN analyses, as all other analyses, differed for the Developmental and Adult Study. However, both involved the application of a set of general measures, which are outlined in the Introduction. We describe these measures in more detail below, followed by the differences in their application between the Developmental and Adult study.

The first general EN measure is Global Field Power (GFP). Mathematically, it reflects a moment-to-moment measure of the root mean square, or standard deviation, of potential [µV] across the entire electrode montage (see Lehmann & Skrandies, 1980; Murray, Brunet, & Michel, 2008). More simply, it represents the standard deviation of voltage potential across the whole montage. As such, it can be understood as a measure of the strength of the global brain response to an experimental condition. Therefore, if two ERPs elicited by different experimental conditions differ in GFP, it follows that they elicited responses of different strength. Because the GFP can be displayed as a single waveform, just like any other waveform, it lends itself to statistical analyses that mirror those normally conducted on ERPs, such as ANOVAs or *t*-tests.

As Murray and colleagues (2008) point out, GFP can reveal how strong the measured ERP potential is on average across the scalp. What it cannot reveal is where, on the scalp field, the potential is higher and where it is lower. This distribution of the voltage potential across the scalp may be referred to as a topographical map, and differences in topographical maps between two experimental conditions are indexed by the aforementioned measure of Global Dissimilarity (DISS). Mathematically, DISS equals the root mean square of the squared differences across two conditions between the potentials at each electrode (versus the average reference), each of which is first scaled by the instantaneous GFP (see Lehmann & Skrandies, 1980; Murray, Brunet, & Michel, 2008). Unlike GFP, DISS does not provide a set of values per experimental condition that can be statistically compared. Rather, DISS indexes the ‘distance’ between two topographical maps, independently of their strength. Furthermore, if two ERPs differ in topography, they also differ in the configurations of underlying brain sources (Lehmann, 1987; Vaughan Jr, 1982). For this reason, the differential recruitment of brain generators underlying ERPs can be revealed by analysing the topography of the ERPs in question. However, topography changes over the course of an ERP, in a systematic way. One topographical map can be stable for tens to hundreds of milliseconds, before changing to a new configuration that, again, lasts tens to hundreds of milliseconds (see “functional microstates”, e.g., Michel, Seeck & Landis, 1999; Michel et al., 2011; Michel & Koenig, 2018). Therefore, to understand specifically how different brain generators are recruited between experimental conditions, we must identify periods of stable patterns of ERP topography, and thus, periods of stable activity of underlying brain generators.

A hierarchical clustering method called Topographic Atomize and Agglomerate Hierarchical Clustering (TAAHC) is typically used to analyse EEG/ERP topography within an EN approach. In a procedure we will refer to as ‘segmentation’, TAAHC first identifies a sequence of topographical maps in the group-averaged ERP data across all conditions. Initially, each map in the dataset belongs to one cluster. Next, over a series of iterations, the number of clusters becomes progressively smaller. Each remaining cluster is assigned groups of maps whose mathematical mean (centroid) represents a ‘template map’ that labels that cluster. Unlike traditional hierarchical clustering methods, TAAHC does not merge the clusters on each iteration, thus inflating clusters’ size on each iteration. This is particularly well-suited to the analysis of EEG/ERP topography due to the need to reliably detect relatively short-duration periods of stable topographic activity in such data (Murray, Brunet, & Michel, 2008). Each cluster accounts for a portion of the global explained variance (GEV) in the grand-averaged ERP data, and on each iteration, the cluster with the smallest GEV is identified, dissolved, and freed of its maps, which then get reassigned to new clusters. The ‘free’ maps are reassigned to the cluster whose centroid they are best spatially correlated with. Spatial correlation is essentially the Pearson’s product-moment correlation coefficient between two voltage potential distributions, i.e., topographical maps, and is directly related to DISS (Murray et al., 2008; Matusz et al., 2019b). This procedure in principle ends with the entire dataset characterised by one cluster, which is not informative. The optimal number of clusters constitutes the smallest number of template maps accounting for the largest amount of variance in the group-averaged ERP data between conditions. This optimal number can be identified using several criteria, including a modified Krzanowski–Lai criterion as well as the Cross Validation index, and Dispersion (Murray et al., 2008).

Once the optimal configuration of clusters in the group-averaged data is identified, its validity in describing the *single-subject* data can be statistically assessed. This is typically done by ‘fitting’ the single-subject ERP data back onto the template maps revealed by the segmentation procedure. In this step, each datapoint of each single subject’s ERP data over a chosen time-window is labelled by the template map present over that time-window with which it is best spatially correlated. This fitting procedure can be used to obtain a variety of different dependent measures that can be subjected to standard statistical analyses, such as ANOVA and *t*-test (Murray et al., 2008). For the purpose of the present studies, we focused on template map durations (in milliseconds). Unless otherwise stated in the results, map durations were statistically different from 0ms (as confirmed by post-hoc one-sample *t*-tests), meaning that they were reliably present across the time-windows of interest. Throughout the results, Holm-Bonferroni corrections were used to correct for multiple comparisons between map durations. Comparisons passed the correction unless otherwise stated.

5.2 Developmental study

5.2.1. Behavioural analyses

Before RT spatial cueing data and error data were analysed, RT data were cleaned per the following. First, blocks with mean accuracy below chance level (50%) were removed, resulting in removal of 15% of all blocks (3% for 9-year-olds, 7% for 7-year-olds and 37% for 5-year-olds). In adult controls, all blocks were used due to high overall accuracy (>95%). Next, child RT data from the remaining blocks, and adult control data, were cleaned following the procedure of Gaspelin and colleagues (2015). Specifically, incorrect and missed trials were discarded, as were trials with RTs below 200ms and above 5000ms. Moreover, 2.5 *SDs* from individual participant's mean RTs were also discarded. Thus, 26% of all trials were removed (6% in adult control data, 28% in 9-year-olds, 29% in 7-year-olds and 40% in 5-year-olds). As part of an additional, control analysis, clean RT data were corrected for children's general cognitive slowing by dividing each individual's RT's per condition by their average overall RT, and then converting it to a percentage.

'Raw' mean RT data and corrected RT data were submitted to separate mixed-design four-way repeated-measures ANOVAs with one between-subject factor of Age group (adults vs. 9-year-olds vs. 7-year-olds vs. 5-year-olds), and three within-subject factors: Cue Colour (TCC vs. NCC), Cue Modality (V vs. AV), and Cue-Target Location (Same vs. Different). Next, data for each age-group were submitted to separate repeated-measures ANOVAs with within-subject factors: Cue Colour, Cue Modality, and Cue-Target Location. Error data was analysed using separate three-way Friedman tests for each child group, with factors Cue Colour, Cue Modality, and Cue-Target Location. In the case of adult control data, we conducted a three-way Durbin test instead, with factors Cue Colour, Cue Modality, and Cue-Target Location.

5.2.2. N2pc analyses

In the Developmental Study, we conducted two sets of N2pc analyses to address two different research questions. We describe the two analyses separately in detail.

5.2.1.1.'Normative' analysis. The aim of the first analysis was to identify the age of the emergence of adult-like attentional control mechanisms in childhood. For this purpose, all ERP analyses in developmental groups first followed a 'normative' analysis framework, where the parameters were those typically used for canonical analyses of the N2pc in adult visual attention research.

The first step in this normative analysis involved extracting the mean amplitudes for each of the 4 cue conditions within the 180-300ms post-stimulus onset time-window, prescribed by the adult literature (e.g., Luck & Hillyard, 1994; Eimer, 1996; Eimer & Kiss, 2008; Eimer 2014), separately for the contralateral and the ipsilateral posterior electrodes. Regarding electrode pair choice, EGI 129-channel equivalents of the canonical PO7/8 electrodes (e.g., Eimer, Kiss, Press & Sauter, 2009; Kiss et al., 2008a, 2008b) were electrodes e65 and e90. We used these criteria to extract mean amplitudes for each of the 8 ERPs (4 cue conditions for ipsilateral and contralateral electrode each) for each of the developmental groups as well as for the adult controls (data from Adult Study Experiment 1). We then submitted these mean amplitude values to separate 3-way repeated-measures ANOVAs, with within-subject factors: Cue Colour (TCC vs. NCC), Cue Modality (V vs. AV), and Contralaterality (Contralateral vs. Ipsilateral).

Next, we analysed the same data choosing the electrode sites and time-window for extraction of mean amplitude values using a more data-driven approach. Here, the parameters were again based on the EEG data from the Adult Study Experiment 1. We first computed a contralateral-ipsilateral difference ERP for each individual participant by subtracting the voltage amplitudes over the contralateral hemiscalp from voltage amplitudes over the ipsilateral hemiscalp. We did so for the experimental condition that best resembled the contexts in which the N2pc was traditionally observed, i.e., where the distractor matched the target colour (and the engaged sense), the TCCV condition. Individual ERPs for this condition were grand averaged. To obtain an N2pc time-window from the grand-averaged TCCV difference ERP, we used an EN measure called Global Dissimilarity (DISS), which is a measure of difference in configuration of two electric fields (Murray, Brunet & Michel, 2008). Comparing DISS between experimental conditions, with the help of other related measures (see below), can help reveal whether different sets of brain networks are active for different conditions. Displaying DISS over time for a single condition, as in the current case, can reveal periods of stability and change in the topography of an ERP, and with that, in the active networks of intracranial sources. If DISS is displayed as a waveform, peaks denote periods of changes in ERP topographic activity, and throughs denote stable periods of ERP topographic activity. Our N2pc time-windows were obtained by identifying such throughs in the post-cue time-period of the grand averaged TCCV ERP, under the assumption that the N2pc is orchestrated by a single stable network of brain sources (chiefly LOC, see Hopf et al., 2000).

The resulting time window was 154-300ms (147ms duration). Next, to identify the appropriate electrode sites, in the grand-averaged TCCV ERP, we identified the locations on the scalp with the highest negative voltage amplitudes over the above N2pc time-windows using an automatic setting in the CarTool software. The resulting electrodes were e59/e91 (contralateral/ipsilateral, respectively). We then extracted voltage amplitudes from the above electrodes in the above time-window for each of the four age groups, and submitted the data to separate 3-way repeated-measures ANOVAs, with within-subject factors: Cue

Colour (TCC vs. NCC), Cue Modality (V vs. AV), and Contralaterality (Contralateral vs. Ipsilateral) .

5.2.1.2. *'Descriptive' analysis*. The second set of ERP analyses on developmental data served to clarify how attentional control skills function during various stages of childhood. In contrast with the normative approach, here, the focus was on investigating the mere existence and nature of lateralised N2pc-like responses to visual and audiovisual cues at school entry and beyond. Whether such responses resembled adult N2pc's, in their onset/duration or scalp sites where they were present, was of little importance for this analysis. Such an analysis was borne out of evidence that, while children show N2pc-like responses to target objects, their N2pc's are markedly different than those of adults, for example, in amplitude and/or onset latency (Couperus & Quirk, 2015; Sun et al. 2018; Shimi et al. 2015). For this reason, applying adult criteria to the study of child ERPs can result in an omission or misinterpretation of relevant effects. Therefore, as part of descriptive N2pc analyses, we probed each child age group's ERP data for the electrode sites and time-window in which the N2pc would be best detected in a data-driven fashion. Like in the data-driven part of the normative analyses, we first computed a grand-averaged contralateral-ipsilateral difference ERP for the TCCV condition. Next, to obtain N2pc time-windows, for each group's grand-averaged TCCV difference ERP, we identified the post-cue time-period in which the DISS measure was stable. The resulting time windows were as follows: 144-271ms (127ms duration) in 9-year-olds, 151-275ms (125ms duration) in 7-year-olds, and 110-310ms (192ms duration) in 5-year-olds. Then, to identify the appropriate electrode sites for each group, in each group's grand-averaged TCCV ERP, we identified the locations on the scalp with the highest negative voltage amplitudes over each group's respective N2pc time-windows using an automatic setting in the CarTool software. The resulting contralateral-ipsilateral electrode sites were as follows: e68/e94 in 9-year-olds, e68/e94 in 7-year-olds, and e50/e101 in 5-year-olds. Mean amplitude values extracted from each group's respective electrode sites and time-window were submitted to separate three-way repeated-measures ANOVAs, with factors: Cue Colour (TCC vs. NCC), Cue Modality (V vs. AV), and Laterality (Contralateral vs. Ipsilateral).

5.2.3. Electrical neuroimaging analyses

In children, in order to obtain *global* EN measures of *lateralised* N2pc effects, we computed a difference ERP, by subtracting the voltages over the contralateral hemiscalp and the voltages over the ipsilateral hemiscalp, separately for each of the 4 cue conditions. This resulted in a 59-channel lateralised ERP (as the midline electrodes from the 129-electrode montage were not informative). Next, this difference ERP was mirrored onto the other side of the scalp, recreating a "fake" 129 montage (with values on midline electrodes set to 0). It was on these mirrored "fake" 129-channel lateralised difference ERPs that we performed the global EN response strength-based and topography-based analyses on, across the 4 cue conditions, for younger groups and adult controls.

The first step in our child EN analyses involved using GFP to investigate whether modulations of cue-elicited lateralised ERPs by top-down visual and bottom-up multisensory control mechanisms were a result of differential response strength within statistically indistinguishable brain networks. For the normative approach, we extracted the average GFP amplitudes measured within the canonical adult N2pc time-window of 180-300ms post-cue. We then submitted each age group's averages to separate 2 x 2 repeated-measures ANOVAs with Cue Colour (TCC vs. NCC) and Cue Modality (V vs. AV) as within-subject factors. For the descriptive approach, we extracted average GFP amplitudes measured within each age group's own N2pc time-window and submitted the extracted data to the same 2 x 2 repeated-measures ANOVA.

Next, we investigated whether there were differences across the 4 cue-elicited lateralised difference ERPs that were driven by changes in electric scalp field topography. Such changes would forcibly indicate that top-down visual control and/or multisensory bottom-up control modulate spatially-selective brain responses by activating distinct configurations of brain sources.

5.3.2.1. Normative analysis. For normative topography-based analyses, we applied the segmentation procedure to the entire post-cue period of the group-averaged adult control ERP data and identified the optimal number of clusters that explained most of the variance in the data. Next, we tested to what extent the stable patterns of EEG activity ('template maps') seen in adults were present within child ERPs, and how this involvement differed by age group. That is, the single-subject ERP data of each age group was 'fitted back' onto the clusters identified in the adult group-averaged difference ERPs. The final output for each participant was the number of timeframes (in milliseconds) that each adult topographical map characterised each child's ERP over the canonical adult N2pc time-window. These map durations (in milliseconds) were submitted to separate three-way 2 x 2 x 4 repeated-measures ANOVAs in each age group, with factors: Cue Colour (TCC vs. NCC) and Cue Modality (V vs. AV), and Map (Map1 vs. Map2 vs. Map3 vs. Map4) followed by post-hoc t-tests. Maps with durations under 10 contiguous timeframes were not included in the analyses. Greenhouse-Geiser corrections were applied where necessary to correct for violations of sphericity.

5.3.2.2. Descriptive analysis. Descriptive EN analyses involved the same analysis steps as the normative analysis, except that the 'fake' ERP data across the entire post-cue epoch were segmented separately for each age group, after which, each age group's 'fake' data were submitted to a 'fitting' onto the optimal configuration of clusters for that age group, using each age group's own N2pc time-window. The resulting template map durations (in milliseconds) over each group's N2pc time-window were submitted to separate three-way repeated-measures ANOVAs in each age group, with factors: Cue Colour (TCC vs. NCC), Cue Modality (V vs. AV), and Map (different levels due to different numbers of maps in each age group: 9 in 9-year-olds, 5 in 7-year-olds, and 8 in 5-year-olds). Again, maps under 10 contiguous timeframes were not included in the analyses, and Greenhouse-Geiser corrections were used to correct for violations of Sphericity.

5.2.4. Correlational analyses.

Relationships between behavioural and EEG/ERP measures of attentional control and children's educational scores were investigated using correlational analyses employing Pearson's skipped correlation coefficient and Spearman's skipped correlation coefficient. Our choice of method was motivated by the documented advances that skipped correlations have over conventional correlations when data are nonnormally distributed, as were our educational scores. Pearson correlation tends to be the most widely used correlation technique despite its known limitations. It is overly sensitive to outliers, and highly affected by the magnitude of the slope of datapoints, the magnitude of residuals, heteroscedasticity, etc. (Wilcox, 2012a, b). An oft-used alternative to Pearson correlation, Spearman correlation, is less sensitive to univariate outliers, i.e., data-points with extreme values in one of the compared variables (Rousselet & Pernet, 2012). However, bivariate outliers, with extreme values in two variables, can create the illusion of an association between compared variables (Rousselet & Pernet, 2012; Wilcox, 2004, 2005). Generally, children's brain and behavioural data tend to be quite variable, and we could not exclude the possibility of univariate or bivariate outliers in any of our data. The way in which skipped correlations are computed accounts for such drawbacks (for a detailed description see Pernet, Wilcox & Rousselet, 2013; Rousselet & Pernet, 2012; Wilcox, 2004; though see Schwarzkopf, De Haas & Rees, 2012 for an opposite view). Briefly, the centre of the data (usually the sample mean, see Wilcox, 2004, pp.134) is computed using a robust estimator of multivariate location and scatter, called the minimum covariance determinant (Rousseeuw, 1984; Hubert, Rousseeuw & Van Aelst, 2008). Next, outliers are identified by orthogonally projecting each data point onto lines that join each data point to the minimum covariance determinant and discarding those that fall outside of the interquartile range. Then, on the remaining data, Pearson's and Spearman's correlations and associated *t*-values are computed. In a proof-of-concept, Pernet, Wilcox, and Rousselet (2013) demonstrated the superiority of skipped correlations in detecting true effects in cases when data were nonnormally distributed. Indeed, the method appeared most successful in cases of distant, bivariate outliers, as it removed them effectively, while taking the removal into account.

To apply skipped correlations to our data, we used the opensource robust correlation Matlab toolbox that Pernet and colleagues (2013) developed, which is publicly available at: https://sourceforge.net/projects/robustcorrtool. Behavioural measures used in correlations were indices of task-set contingent attentional capture (TAC) and multisensory enhancement of capture (MSE) that were calculated using the formulae below (1 for TAC and 2 for MSE, respectively):

$$\left(\frac{TCCVinval - TCCVval}{TCCVval}\times 100 + \frac{TCCAVinval - TCCAVval}{TCCAVval}\times 100\right) - \left(\frac{NCCVinval - NCCVval}{NCCVval}\times 100 + \frac{NCCAVinval - NCCAVval}{NCCAVval}\times 100\right) \tag{1}$$

$$\left(\frac{TCCAVinval - TCCAVval}{TCCAVval} \times 100 + \frac{NCCAVinval - NCCAVval}{NCCAVval} \times 100\right) - \left(\frac{TCCVinval - TCCVval}{TCCVval} \times 100 + \frac{NCCVinval - NCCVval}{NCCVval} \times 100\right) \tag{2}$$

EEG measures were template map durations across cue conditions, over a given N2pc time-window. Because correlational analyses were conducted as part of the descriptive approach, template maps were each age-group's own maps that characterised each age-group's own N2pc time-window. Educational scores were divided into literacy and numeracy measures, per the items discussed in the Materials and procedure section above. To reiterate, for 9-year-olds, there were two literacy measures – scores on Reading and on Comprehension, while the numeracy measure was a composite score on Mathematics items. For 7-year-olds, the literacy measure was a composite score on Reading items, and the numeracy measure was a composite score on Mathematics items. Finally, for 5-year-olds, Phonological skills were the literacy measure, while the numeracy measure was a composite score on Numeracy items. Correlations were conducted separately for each age group, and for each combination of a behavioural or EEG measure and a literacy or numeracy score. The correlation results outputs provided correlation coefficients ($r_{skipped}$ and $\rho_{skipped}$) and confidence intervals, but not display p-values. Therefore, we obtained these measures from tables of critical values for Pearson and Spearman correlation coefficients from Weathington, Cunningham and Pittenger (2012; tables B.7 and B.8, respectively). Holm-Bonferroni corrections were applied to correct for multiple comparisons. All correlations, unless otherwise stated, passed the correction.

5.3. Adult study

5.3.1 Behavioural analyses

As in the Developmental study, RT data were cleaned, before analyses, using the following procedures. Incorrect and missed trials were discarded, as were RTs below 200ms and above 1000ms, following Matusz & Eimer (2011). As a result, 5% of trials across all experiments were removed. Next, RT spatial cueing data were submitted to a four-way 2 x 2 x 2 x 2 repeated-measures ANOVA with factors: Cue Colour (TCC vs. NCC), Cue Modality (V vs. AV), Multisensory Relationship (MR; Simultaneity vs. Congruence), and Distractor Onset (DO; Unpredictable vs. Predictable). Here, Cue-Target location was not included as a factor in order to ensure sufficient statistical power given the addition of MR and DO as factors. However, Cue-Target location was used as a factor for analysing error data, where we conducted 3-way Durbin tests for each experiment, with factors Cue Colour, Cue Modality, and Cue-Target Location.

5.3.2. N2pc analyses

In the Adult Study, N2pc analyses involved several steps. First, we performed a canonical analysis with mean amplitude values extracted from PO7/8 electrode equivalents (e65/90) over the 180-300ms time-window. A second type of analysis involved extracting mean amplitudes from clusters of electrodes contralateral and ipsilateral to stimulus presentation. Though less popular in the context of the N2pc such cluster approaches have been used in other attentional ERP research (e.g., Beer & Röder, 2004; Lange, Rösler & Röder, 2003; Lange & Röder, 2006, for application in N2pc see e.g., Weymar, Löw, Öhman, & Hamm, 2011; Wieser, Hambach, & Weymar, 2018), For the current cluster approach , we extracted mean amplitude values from two electrode clusters comprising PO7/8 equivalents e65/90 and their six immediate surrounding neighbours (e58/e96, e59/e91, e64/e95, e66/e84, e69/e89, e70/e83), over the canonical 180-300ms post-cue time-window. In both the canonical single-electrode and electrode-cluster approaches, analyses were conducted on the mean amplitude of the N2pc difference waveform, which was obtained by subtracting the average of amplitudes in the ipsilateral posterior-occipital cluster from the average of amplitudes in the contralateral posterior-occipital cluster. This step helped mitigate the loss of statistical power that could result from the addition of new contextual factors. N2pc means were thus submitted to a four-way 2 x 2 x 2 x 2 repeated-measures ANOVA with factors Cue Colour (TCC vs. NCC), Cue Modality (V vs. AV), MR (Simultaneity vs. Congruence), and Distractor Onset (DO; Unpredictable vs. Predictable), analogously to the behavioural analysis.

5.3.3. Electrical neuroimaging analyses

5.3.3.1. Developmental analogue analysis. In adults, we also investigated potential differences across visual and audiovisual conditions in GFP and topography. Analogously with analyses in children, GFP from “fake” 129-channel lateralised difference ERPs was extracted over the canonical 180-300 N2pc time-window and submitted to a 2 x 2 x 2 x 2 repeated-measures ANOVA with factors Cue Colour (TCC vs. NCC), Cue Modality (V vs. AV), as well as the two new factors, MR (Simultaneity vs. Congruence), and Distractor Onset (DO; Unpredictable vs. Predictable). Topographical analyses followed the same analysis protocol as the child normative approach. That is, the ‘fake’ 129-channel data across all of the adult experiments were submitted to the segmentation over the entire post-cue period. Next, the data were fitted back over the 180-300ms period. Finally, the resulting number of timeframes (in milliseconds) was submitted to the same repeated-measures ANOVA as the GFP data above.

5.3.3.2. Exploratory Adult analysis. In an exploratory analysis in adults, we probed the influence of contextual factors on nonlateralized ERP signals, given previous evidence that semantic information and temporal expectations can modulate nonlateralized ERPs within the first 100-150ms post-stimulus (e.g., Dell’Acqua et al., 2010; Dassanayake et al., 2016). The same four-way repeated-measures design as in the behavioural adult analyses and canonical N2pc adult analyses was applied onto non-lateralised whole-montage ERP data. However, unlike behavioural measures, ERPs are sensitive to the physical differences in visual and audiovisual stimuli. Specifically, on audiovisual trials, the cue-induced ERPs would be contaminated by brain response modulations induced by Cue Modality, with these modulations visible in our data already at 40ms post-cue. Consequently, any direct comparison of visual-only and audiovisual ERPs, would index at least auditory processing per se and perhaps also capture of attention by audiovisual stimuli. Such confounded sound-related activity is eliminated in canonical N2pc analyses through the contralateral-minus-ipsilateral subtraction. Thus, to eliminate such a confound for exploratory EN analyses, we calculated new difference ERPs, first between TCCAV and NCCAV conditions, and then between TCCV and NCCV conditions. Such difference ERPs, just as the canonical N2pc difference waveform, subtracted out the sound processing confound in visually-induced ERPs. These difference ERPs produced a new factor that indexed the enhancement of visual attentional control by sound presence, that we henceforth refer to as Target Difference. For this level of analysis, all EN analyses were conducted on these difference ERPs, and included the factor Target Difference with two levels: D_{AV} (TCCAV – NCCAV difference) and D_V (TCCV – NCCV difference). Greenhouse-Geiser corrections were applied where necessary to correct for violations of sphericity.

As part of exploratory adult analyses, multivariate analyses of voltage and GFP data were conducted using the STEN toolbox 1.0 (available for free at https://zenodo.org/record/1167723#.XS3lsi17E6h) using a 3-way repeated-measures ANOVA with factors: MR (Simultaneity vs. Congruence), DO (Unpredictable vs. Predictable), and Target Difference (D_{AV} vs. D_V). Follow-up tests involved further ANOVAs and pairwise t-tests. To correct for temporal and spatial correlation (see Guthrie & Buchwald, 1991), we applied a temporal criterion of >15 contiguous timeframes, and a spatial criterion of >10% of the 129- channel electrode montage at a given latency for the detection of statistically significant effects at an alpha level of 0.05. Next, a topographic analysis was conducted, involving a segmentation of the ERP difference data across the post-cue and pre-target onset period (0 - 300ms from cue onset), and a clustering of the data to obtain template maps. Next, the data was fitted to the traditional N2pc time-window (180-300ms) and analysed using the same analysis design as for GFP, that is MR x DO x Target Difference repeated-measures ANOVA. Additionally, any time-periods that indicated significant condition differences in the GFP data were further explored via an additional fitting procedure.

Chapter 3: Results

1. Developmental study: Evidence for top-down visual attentional control (TAC) and bottom-up multisensory attentional control (MSE)

This part of the analysis was concerned with the developmental trajectory of, and the characterisation of children's top-down visual and bottom-up multisensory attentional control mechanisms. These mechanisms were assessed behaviourally, using N2pc, and the EN measures GFP and topography. The latter three EEG measures were all investigated in a normative manner to probe for the emergence of adult-like mechanisms in children, and a descriptive manner to investigate children's mechanisms independently of adults. Across these seemingly disparate analyses, the presence of top-down visual and bottom-up multisensory attentional control mechanisms was uniformly indexed by TAC and MSE, expressed as modulations by the factor of Cue Colour and Cue Modality, respectively. Thus, in behaviour, TAC and MSE were could be seen in modulations of Target-Cue Location by Cue Colour, and of Target-Cue Location by Cue Modality. In N2pc, these were modulations of Contralaterality by Cue Colour and Contralaterality by Cue Modality. In GFP, these were the main effects of Cue Colour and Cue Modality. Finally, in topography, these were modulations of Map by Cue Colour and Map by Cue Modality. To foreshadow our results, we review the presence of TAC and MSE across age-groups and different analysis modalities in the table below.

Table 1

Overview of results attesting to the presence of TAC and MSE

Effect	**Adult controls**	**9-year-olds**	**7-year-olds**	**5-year-olds**
		Behaviour (RTs)		
TAC	✓	✓	✓	X
MSE	✓	X	X	X
		N2pc		
TAC	✓	X	X	X
MSE	X	X	X	X
		GFP		
TAC	X	X	X	X
MSE	X	X	X	X
		Topography		
TAC	✓	✓*	✓*	✓*
MSE	✓	✓*	✓*	X

Note. * denotes that the TAC and MSE effects have been obtained in Descriptive analyses, and therefore cannot be considered adult-like.

1.1. Behavioural analyses

1.1.1. Raw RTs

Mean RTs sped up progressively from 5-year-olds (1309ms) through 7-year-olds (1107ms) and 9-year-olds (836ms) to adults (594ms), which was reflected in a significant main effect of Age, $F_{(3,\ 127)} = 94.7$, $p < 0.001$, $\eta_p^2 = 0.7$ (Figure 5). Here, 5-year-olds were reliably slower than 7-year-olds ($t_{(33)} = 4.4$, $p < 0.001$), who were slower than 9-year-olds ($t_{(32)} = 5.7$, $p < 0.001$), who were in turn, slower than adults ($t_{(32.5} = 5.1$, $p < 0.001$). However, Age did not modulate any other factors (all *F's* < 2, *p*'s > 0.1, where the only interaction that reached an $F > 1$ was Age x Cue Colour, $F_{(3,\ 127)} = 1.9$, $p = 0.1$; for full results see Appendix 1). Nonetheless, to adequately investigate differences between adults and children, and the developmental trajectory of attentional control processes, we analysed the raw RT data from each age group separately.

1.1.1.1. Adults. Firstly, in adults, there was a significant main effect of Cue Colour, $F_{(1,\ 38)} = 36.9$, $p < 0.001$, $\eta_p^2 = 0.5$, driven by faster responses on trials with target colour-cues (TCC, 607ms) than on trials with nontarget colour-cues (NCC, 618ms). Adults also showed generally faster responses on trials with sounds (AV, 605ms) than with no sounds (V, 620ms), $F_{(1,\ 38)} = 76.1$, $p < 0.001$, $\eta_p^2 = 0.7$. Overall behavioural capture effects in adults were reliable, i.e. responses were faster for trials where the cue and target location were the same (600ms) versus when they were different (624ms), $F_{(1,\ 38)} = 110.9$, $p < 0.001$, $\eta_p^2 = 0.8$.

Further, as in the original Matusz and Eimer's (2011) study, the adults' overall behavioural capture effects differed depending on the colour of the cue, as shown by a 2-way Cue-Target Location x Cue Colour interaction, $F_{(1,\ 38)} = 161.5$, $p < 0.001$, $\eta_p^2 = 0.8$ (this is the TAC effect). This effect was driven by statistically significant behavioural capture effects for the TCC condition (48ms, $t_{(38)} = 16.7$, $p < 0.001$), but not the NCC condition (1ms, $t_{(38)} = 0.2$, $p = 0.8$; Figure 5 top left panel, and Figure 6A top left panel). Again, as in the original 2011 study, behavioural capture effects also differed when elicited by visual and audiovisual distractors, as shown by a two-way interaction between Cue-Target Location and Cue Modality, $F_{(1,\ 38)} = 4.9$, $p = 0.03$, $\eta_p^2 = 0.1$ (this is the MSE effect). This effect was driven by larger behavioural capture effects elicited by AV (26ms, $t_{(38)} = 10.8$, $p < 0.001$) than by V cues (21ms, $t_{(38)} = 8.9$, $p < 0.001$; Figure 5 top left panel, and Figure 6A, top left panel). The Cue Colour x Cue Modality interaction ($F < 1$) was not significant, and neither was the Cue-Target Location x Cue Colour x Cue Modality interaction ($F < 3$, $p > 0.1$; for full results see Appendix 1). These results demonstrated that adults showed both reliable TAC and MSE in behaviour, replicating Matusz and Eimer (2011).

1.1.1.2. 9-year-olds. Like adults, 9-year-olds, responded faster on TCC trials (843ms) than on NCC trials (865ms), $F_{(1,\ 25)} = 28.4$, $p < 0.001$, $\eta_p^2 = 0.5$. Their overall behavioural capture effects were also reliable, with faster RTs for trials where the cue and target location were the same (839ms) versus when they were different (870ms), $F_{(1,\ 25)} = 68.9$, $p < 0.001$, $\eta_p^2 = 0.7$. Overall speeding up of responses on AV compared to V trials now showed the level of a nonsignificant trend ($F_{(1, 25)}$ = 0.3, p = 0.08, η_p^2 = 0.1). However, the main question was whether behavioural capture effects in 9-year-old children would be modulated by the cues' matching of the target colour, as well as the audiovisual nature of the cues. Notably, like in adults, did indeed show TAC, as evidenced by a 2-way interaction between Cue-Target Location and Cue Colour, $F_{(1, 25)}$ = 19.5, p < 0.001, η_p^2 = 0.4. This interaction was driven by significant capture effects for the TCC distractors (56ms, $t_{(25)}$ = 8.3, p < 0.001), but not for the NCC distractors (6ms, $t_{(25)}$ = 0.9, p = 0.7; Figure 5 top right panel, and Figure 6A, top right panel). However, in contrast with adults, 9-year-olds did not show MSE, with no evidence for visually-elicited capture effects enlarged on AV vs. V trials, i.e., no 2-way Cue-Target Location x Cue Modality interaction, $F_{(1, 25)}$ = 1.4, p = 0.3. Other interactions failed to reach statistical significance (All F's < 2; full results in Appendix 1). With this, we can conclude that 9-year-olds showed reliable TAC, but not MSE, in behaviour.

1.1.1.3. 7-year-olds. In 7-year-olds, like in adults, responses were faster for trials with TCC cues (1112ms) than for NCC cues (1138ms), $F_{(1, 37)}$ = 18.7, p < 0.001, η_p^2 = 0.3, and were also faster for trials with AV cues (1111ms) than V cues (620ms), $F_{(1, 37)}$ = 8.6, p = 0.006, η_p^2 = 0.2. Further, overall capture effects were again reliable, with faster responses on cue-target location same (1109ms) versus different (1140ms) trials, $F_{(1, 37)}$ = 14, p < 0.001, η_p^2 = 0.4. Just as in the two older groups, 7-year-olds, did show TAC, as shown by a Cue-Target Location x Cue Colour interaction, F = 6.4, p = 0.02, η_p^2 = 0.2. This was driven by reliable cueing effects elicited by TCC distractors (55ms, $t_{(37)}$ = 4.8, p < 0.001), but not by NCC distractors (7ms, $t_{(37)}$ = 0.6, p = 1; Figure 5 bottom left panel, and Figure 6A, bottom left panel). However, as in 9-year-olds, 7-year-olds' visually-induced attentional capture effects did not show MSE, with no 2-way Cue-Target Location x Cue Modality interaction failing to reach significance, $F_{(1, 37)}$ = 2.1, p = 0.2. Other interactions also did not reach statistical significance (All F's < 2; full results in Appendix 1). It thus appeared that 7-year-olds, like 9-year-olds before them, showed reliable TAC, but not MSE.

1.1.1.4. 5-year-olds. In 5-year-olds, as in the other age groups, we observed reliable overall attentional capture effects $F_{(1, 27)}$ = 14, p < 0.001, η_p^2 = 0.4, driven by faster responses for cue-target location same (1312ms) versus different (1343ms) trials. However, there was no evidence for either of the two key interactions, specifically, the Cue-Target Location x Cue Colour interaction ($F_{(1, 27)}$ = 1.4, p = 0.2), or the Cue-Target Location x Cue Modality interaction ($F_{(1, 27)}$ = 0.4, p = 0.5). In further contrast with the older age groups, overall RTs were not affected by the colour of the cue, as shown by a nonsignificant main effect of Cue Colour, $F_{(1, 27)}$ = 2.6, p = 0.1. In one final contrast, faster responses on AV versus V trials showed only a nonsignificant trend, $F_{(1, 27)}$ = 3.5, p = 0.07, η_p^2 = 0.1. No other interactions reached statistical significance (All F's < 2). The 5-year olds, therefore, did not show reliable TAC nor MSE in behaviour.

1.1.2. RTs corrected for children’s cognitive slowing

Following analyses of raw RTs, we tested if the behavioural capture effect modulations observed across the age groups were preserved when RTs were corrected for children’s overall cognitive slowing. All of the child groups showed the same patterns of results as in the raw RT analyses. That is, 9-year-olds and 7-year-olds showed TAC but not MSE, and 5-year-olds did not show TAC or MSE. For brevity, we have relegated the full results of these statistical analyses to Appendix 1. These analyses demonstrated that, even after having corrected for children’s overall cognitive slowing, no children exhibited MSE, and only older children exhibited TAC.

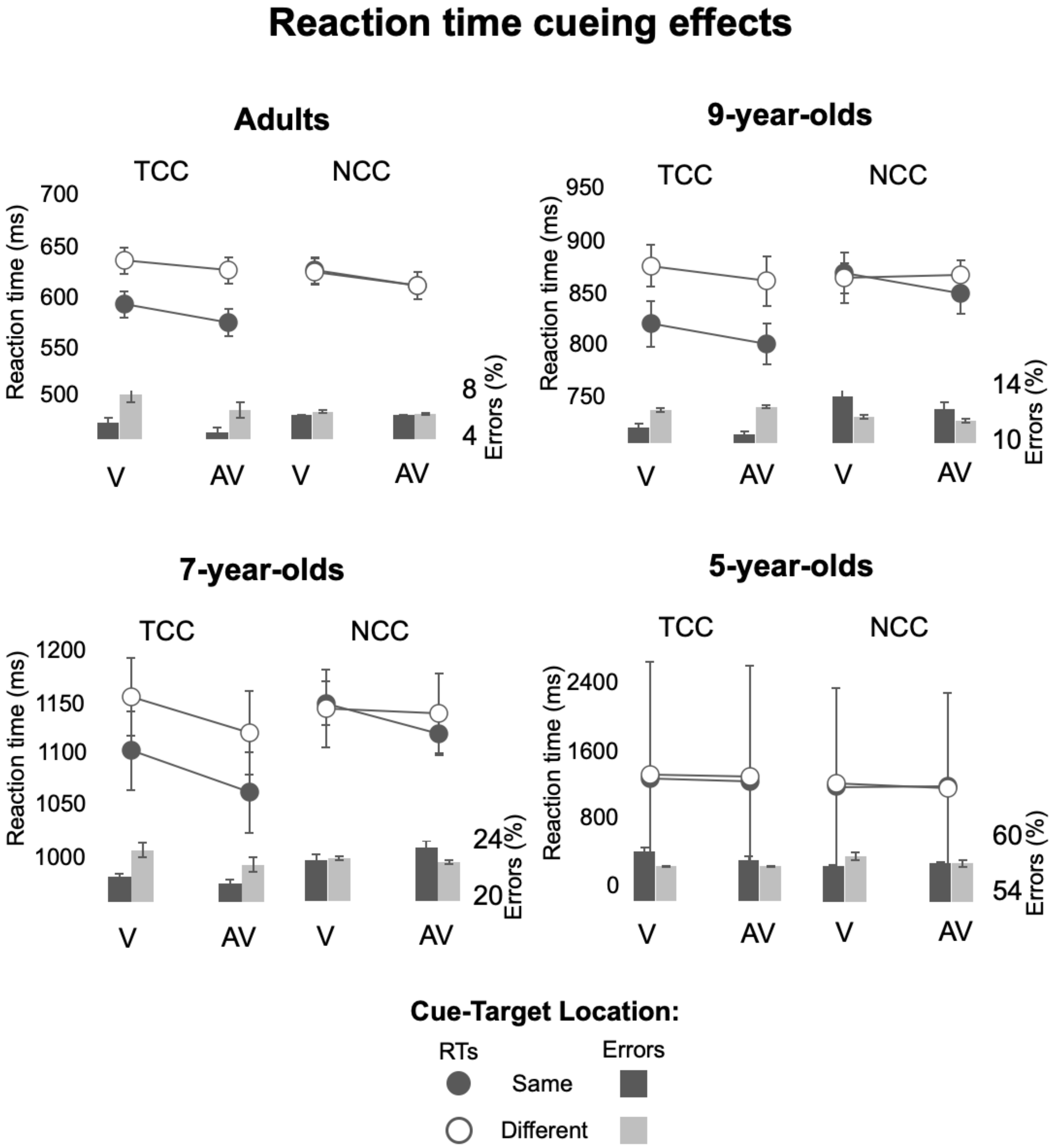
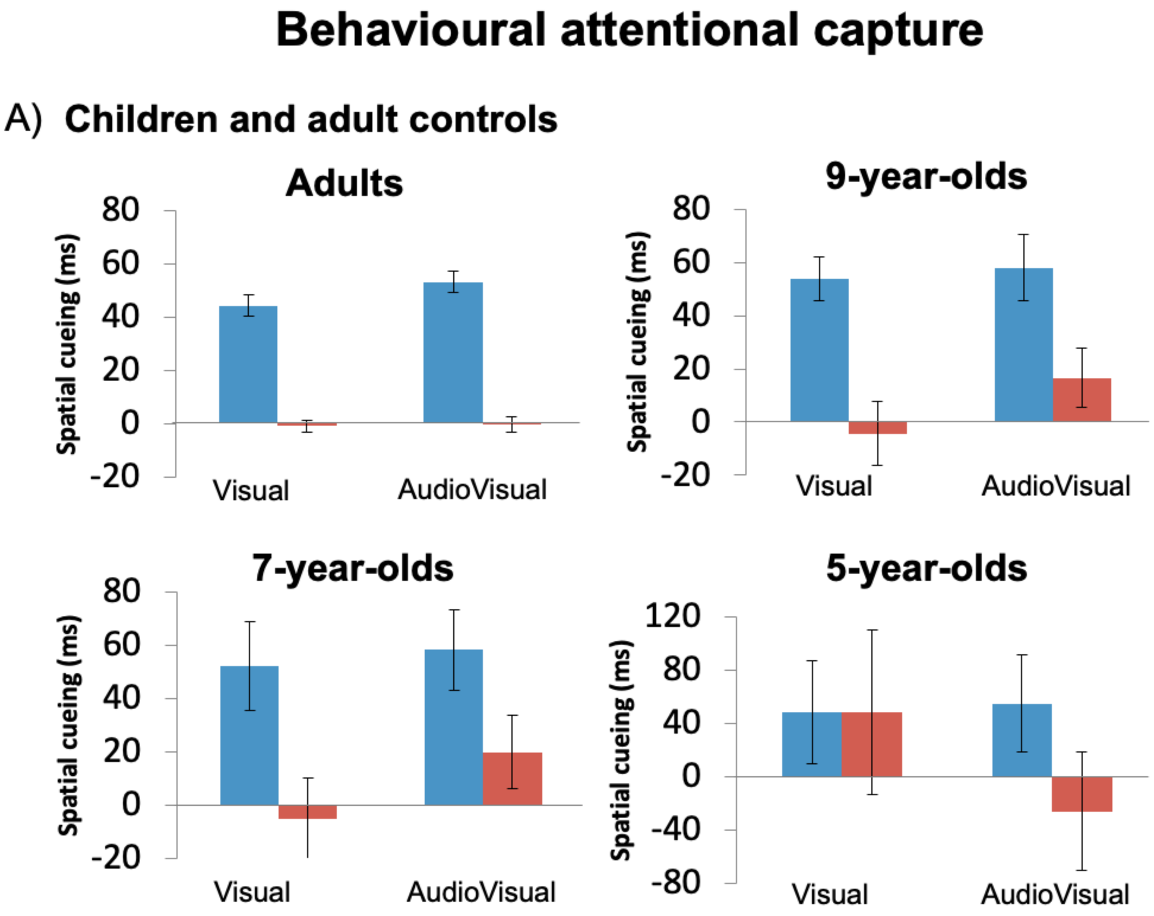


Figure 5. Mean reaction times shown for each of the 4 age groups on trials where Cue-Target Location was the same versus different, shown separately for trials TCC and NCC as well as V and AV trials. Line graphs

show the mean RTs, bar graphs show error rates (in percentages), and error bars represent the standard error of the mean.

1.1.3. Error rates

Since error data were not normally distributed, we conducted a 1-way Kruskal–Wallis *H* test to test for differences between groups, and 3-way Friedman tests (or Durbin tests where there were no errors for a given condition) to test for differences within each age-group. Overall, error rates were highest in the youngest children (57%), and steadily reduced in 7-year-olds (23%), followed by 9-year-olds (12%), culminating in the smallest error rates in adults (6%), $\chi^2(3) = 81.4$, $p < 0.001$. In adults, error rates were modulated by Cue-Target Location $\chi^2(1) = 8.7$, $p = 0.003$, such that fewer errors were made on trials where the cue and target location was the same (5.5%) than when they were different (6.6%). Error rates were not significantly modulated by Cue Colour or Cue Modality (all *p*'s > 0.1; full results in Appendix 1). In 9-year-olds, 7-year-olds, and 5-year-olds alike, error rates were not significantly modulated by Cue-Target Location, Cue Colour or Cue Modality (all *p*'s > 0.1; full results in Appendix 1).



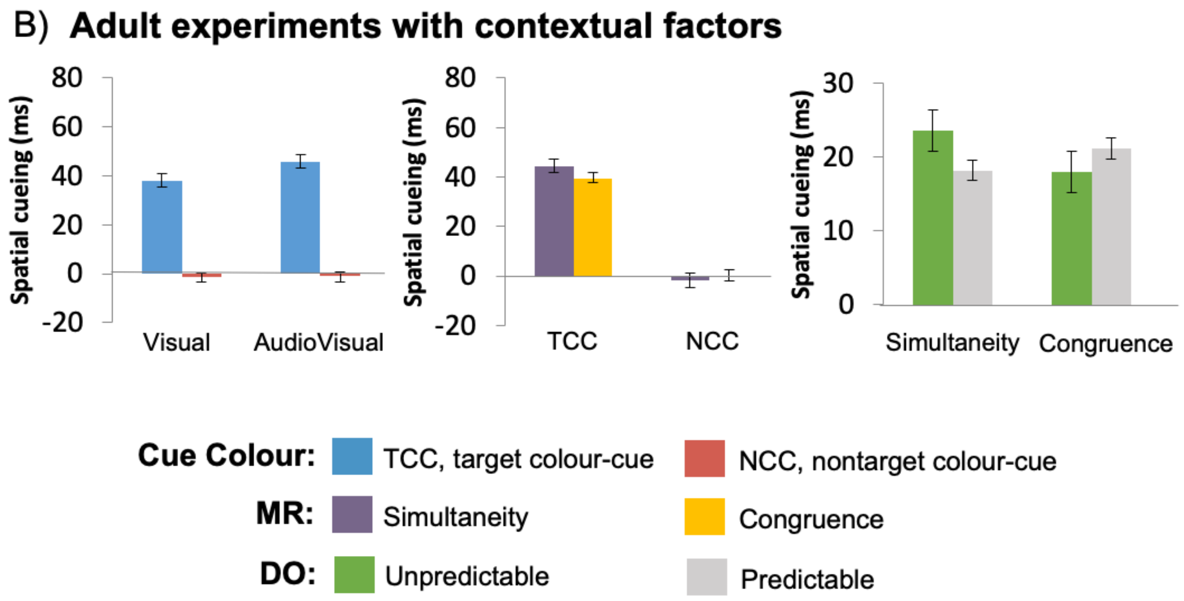


Figure 6. Cueing effects across experiments show the extent of modulation of cueing effects triggered by V and AV cues, spanning more short-term factors (MR, DO) but also more long-term factors (observers' age). Bars coloured according to the figure legend in the image represent behavioural attentional capture indexed by mean RT spatial cueing effects. A) Adults, 9-year-olds, and 7-year-olds all showed presence of top-down visual attentional control, exemplified by TAC. Specifically, all 3 age groups showed reliable attentional capture effects for target colour-cues, but not for nontarget colour-cues. In contrast, only in adults, attentional capture showed MSE. B) *Left panel*: mean capture effects as modulated by Cue Colour and Modality. Across all 4 adult experiments, target colour-cues, but not nontarget colour-cues triggered reliable attentional capture effects. *Middle panel:* mean capture effects as modulated by MR. Larger behavioural attentional capture of target colour-cues was observed when the distractors were Simultaneous than when they were Congruent. Additionally, regardless of Multisensory Relationship, attentional capture was larger for target colour-cues than for nontarget colour-cues. *Right panel*: mean capture effects as modulated by DO. For Simultaneous distractors, attentional capture was larger in contexts where Distractor Onset was Unpredictable than in contexts where it was Predictable. No such effect was observed for semantically Congruent distractors. Error bars represent the standard error of the mean.

1.2. N2pc analyses

1.2.1. Normative analysis

1.2.1.1. Adults. First, to link the present results with the existing literature, we performed canonical N2pc analyses on child and adult control ERP data. In adults, the presence of reliable overall N2pc's across the canonical electrodes and canonical time-window was supported by a statistically significant main effect of Contralaterality, $F_{(1, 38)} = 17.8$, $p < 0.001$, $\eta_p^2 = 0.3$, where the mean contralateral amplitude, over the PO7 equivalent (-0.4µV), was larger than the ipsilateral amplitude, over the PO8 equivalent (0.1µV). This result suggested the presence of a reliable N2pc. Consequently, the contra-ipsilateral difference had a mean overall amplitude of -0.5µV. As expected, cue-elicited N2pc's differed in their magnitude depending on the cue colour, as supported by a Contralaterality x Cue Colour 2-way interaction, $F_{(1, 38)} = 17$, $p < 0.001$, $\eta_p^2 = 0.3$. This interaction was driven by a reliable N2pc for target colour-cues (-0.69µV, $t_{(38)} = 5.6$, $p < 0.001$; Figure 7A, top and bottom left panels) but not for nontarget colour-cues (-0.25µV, $t_{(38)} = 2$, $p = 0.2$; Figure 7A, top and bottom right panels). This result demonstrated presence of TAC in adult N2pc's. However, there was no evidence for a reliable difference in mean N2pc amplitudes across V and AV cues, with no Contralaterality x Cue Modality 2-way interaction ($F < 1$), and therefore, no evidence for MSE.

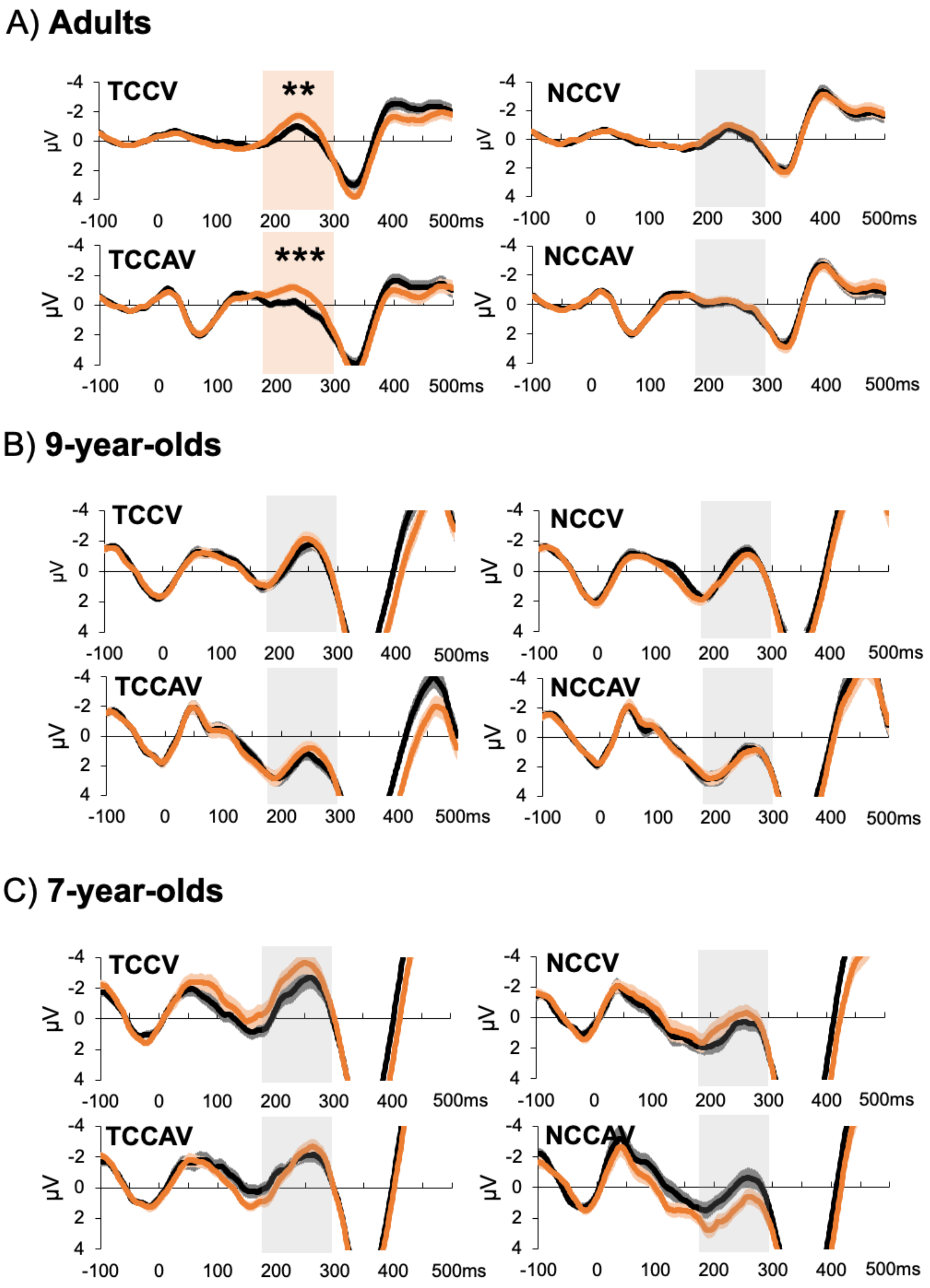
Interestingly, the N2pc amplitudes elicited by TCC and NCC cues were modulated by whether they were presented alone or with sounds, as shown by a 3-way interaction between Contralaterality, Cue Colour, and Cue Modality, $F_{(1,\ 38)} = 8$, $p = 0.007$, $\eta_p^2 = 0.2$. We first analysed this interaction as a function of Cue Modality. First, for AV cues, mean N2pc amplitudes elicited by TCCAV were larger (-0.8µV, $t_{(38)} = 3.3$, $p < 0.001$) than mean amplitudes for NCCAV cues (-0.2µV; $t_{(38)} = 0.7$, $p = 0.2$), $t = 5$, $p < 0.001$. In contrast, for V cues, there was no statistically significant difference in mean N2pc amplitudes elicited by NCCV cues (-0.3µV; $t_{(38)} = 1.5$, $p = 0.04$) and TCCV cues (-0.6µV; $t_{(38)} = 3.2$, $p < 0.001$), $t = 1.8$, $p = 0.2$. When we analysed the 3-way interaction as a function of Cue Colour, for both TCC and NCC distractors, differences in mean N2pc amplitude between AV and V were at the level of a nonsignificant trend, $t_{(38)} = 1.8$, $p = 0.06$, and $t_{(38)} = 1.4$, $p = 0.07$, respectively. Other effects did not reach statistical significance (All F's < 1), except the main effects of Cue Colour, $F_{(1,\ 38)} = 8.4$, $p = 0.006$, $\eta_p^2 = 0.2$ (driven by larger ERP amplitudes for TCC -0.3µV, than for NCC -0.03µV, and Cue Modality, $F_{(1,\ 38)} = 7.1$, $p = 0.011$, $\eta_p^2 = 0.2$ (driven by larger ERP amplitudes for V, -0.3µV, than for AV, 0.06µV; full results in Appendix 2). Thus, although MSE was not observed in N2pc's, adult's overall ERP data was jointly modulated by top-down visual and bottom-up multisensory attentional control. This effect seemed to be driven by reliable difference between TCC and NCC distractors on trials where distractors were AV but not V.

1.2.1.2. Children. In order to verify the extent to which adult-like N2pc's were present in the younger age groups, for each child age group, the 2 x 2 x 2 repeated-measures ANOVAs were conducted on mean amplitude values recorded at electrodes and over the time-window where the N2pc is typically investigated in the adults. However, in none of the child age groups was there a significant main effect of Contralaterality (9-year-olds: $F_{(1,\ 25)} = 0.4$, $p = 0.6$; 7-year-olds: $F_{(1,\ 37)} = 0.04$, $p = 0.8$; 5-year-olds: $F_{(1,\ 27)} = 0.2$, $p = 0.6$; Figure 7, panels B to D), and therefore, no N2pc. Other main effects and interactions also failed to reach significance (F's < 1), except for the main effect of Cue Modality. In 9-year-olds, the main effect of Cue Modality, $F_{(1,\ 25)} = 60.5$, $p < 0.001$, $\eta_p^2 = 0.7$, was driven by more positive ERP amplitudes for AV distractors (1.9µV) than for V distractors (-0.3µV) . Likewise, in 7-year-olds, the main effect of Cue Modality, $F_{(1,\ 37)} = 35$, $p < 0.001$, $\eta_p^2 = 0.5$, was driven by more positive ERP amplitudes for AV distractors (0.9µV) than for V distractors (-1.6µV). Meanwhile, in 5-year-olds, the main effect of Cue Modality had the level of a nonsignificant trend, $F_{(1,\ 27)} = 3.6$, $p = 0.07$, $\eta_p^2 = 0.1$, although, even here, numerically, ERP amplitudes were more positive for AV distractors (2.2µV) than for V distractors (0.3µV) . These results collectively show that, although children's ERPs did not exhibit classic N2pc's, the ERPs themselves were nonetheless modulated by the (audio)visual nature of the cues.

To rule out the possibility that a lack of N2pc's in children was merely due to literature-based parameters (electrodes, time-window) being suboptimal, we carried out an additional analysis. In this analysis, the N2pc time-window and electrode sites were selected from the adult data in a more data-driven fashion, i.e., by using EN measures to identify time-periods of stable brain source activity and choosing electrodes where N2pc differences showed on average maximal negative values. The patterns of results across age groups were largely the same. Adults showed reliable TAC, but not MSE, and Cue Colour and Cue Modality jointly modulated N2pcs. None of the child groups had reliable N2pcs, but the main effects of Cue Modality persisted. In fact, the only difference from the previous set of results was that, here, the main effect of Cue Modality was significant for in 5-year-olds, $F_{(1, 27)} = 9.4$, $p = 0.05$, $\eta_p^2 = 0.3$, and was, like in the older age groups, driven by more positive ERP amplitudes AV distractors (1.6μV) than for V distractors (-0.2μV). For brevity, we present this set of results in full in Appendix 2. This analysis has helped ascertain that children's lack of an adult-like N2pc was not due to literature-based analyses parameters being inappropriate. Rather, it may have been due to a genuine lack of a difference between the contralateral and ipsilateral voltage amplitudes. What remained unclear was, whether normative comparisons between children's and adults' N2pc's failed to capture children's N2pc, simply because they occur at different sites and/or latencies. This was addressed in the following, Descriptive analysis.

1.2.2. Descriptive analysis

As part of descriptive analyses, the N2pc was analysed only in children, with criteria derived from data-based analyses for each child age group separately (i.e., DISS to identify reliable time-window and local maximum for the N2pc difference ERP for TCC). However, despite the child age-group oriented approach, the main effect of Contralaterality was not significant for any of the groups: 9-year-olds ($F_{(1, 25)} = 2.6$, $p = 0.1$), 7-year-olds ($F_{(1, 37)} = 1.1$, $p = 0.3$) or 5-year-olds ($F_{(1, 27)} = 0.2$, $p = 0.7$; Figure 8, panels A to C, respectively), akin to the results obtained with a normative approach. These results have thus ascertained that the lack of N2pc's across child groups was not due to an inappropriate analysis approach but was instead a genuine effect.



Normative contralateral–Ipsilateral difference waveforms

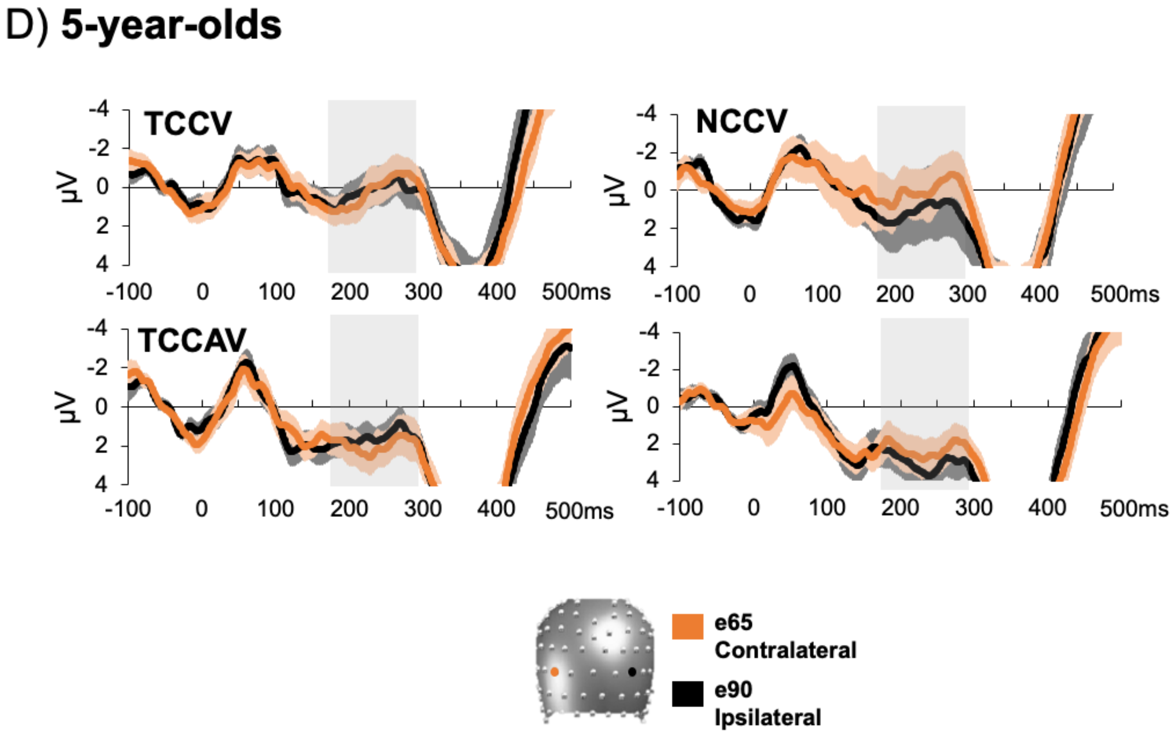


Figure 7. Contra- and ipsilateral waveforms recorded (plotted in orange and black) over the canonical PO7/8 electrode equivalents and the canonical 180-280ms post-cue time-window (in grey), shown separately for each of the 4 age groups and for each of the 4 cue conditions. The head model at the bottom of the figure shows the locations and veridical names of the canonical contra- and ipsilateral electrode channels. The canonical N2pc time-window is highlighted in grey where the contra-ipsi difference was not statistically significant, and in orange where the difference was statistically significant. Further, significant differences between contra-ipsi mean amplitudes were marked as follows: * for p < 0.05, ** for p < 0.01, and *** for p < 0.001. As shown in the figure, only the adult TCC distractors elicited statistically significant contra-ipsi differences.

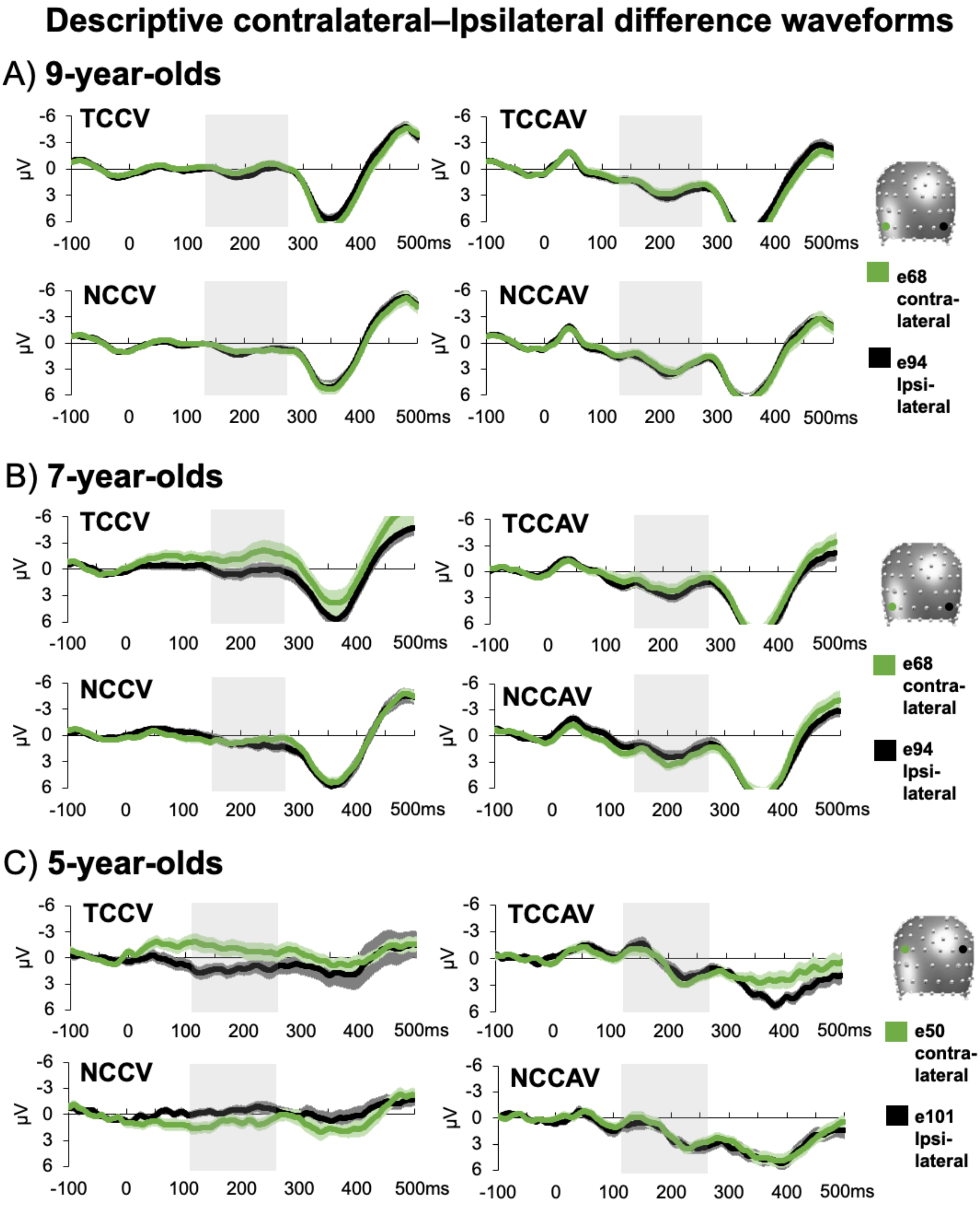


Figure 8. Contra- and ipsilateral waveforms (plotted in green and black) recorded over the age group-specific and data-based electrode pair (specified rightmost for each panel) and N2pc time-window (again in grey), shown separately respectively for each of the 4 age groups and for each of the 4 cue conditions. As with the 'normative' approach, none of the contra-ipsi N2pc differences were statistically significant in any of the age groups or conditions. Head models to the right of each age-group's set of difference waveforms show the general contra- and ipsilateral electrode sites and their exact names.

1.3. Electrical neuroimaging analyses

1.3.1. Normative analysis

1.3.1.1. GFP across age groups. Separate 2 x 2 repeated-measures ANOVAs were conducted on the average GFP values within the 180-300ms time-window, per condition. This procedure allowed us to investigate whether modulations of cue-elicited lateralised ERPs by both top-down visual and bottom-up multisensory processes and across all age groups could be detected using EN analyses. Here, we tested for modulations of these ERPs resulting from response strength differences within statistically indistinguishable brain networks, within each age group separately. The 4 ANOVAs revealed no significant main effects or interactions in GFP in adults, 9-year-olds, 7-year-olds, or 5-year-olds (All *F*'s < 1; see Figure 9), demonstrating no evidence for a strength-based modulation of cue-elicited lateralised ERPs in any of the age-groups.

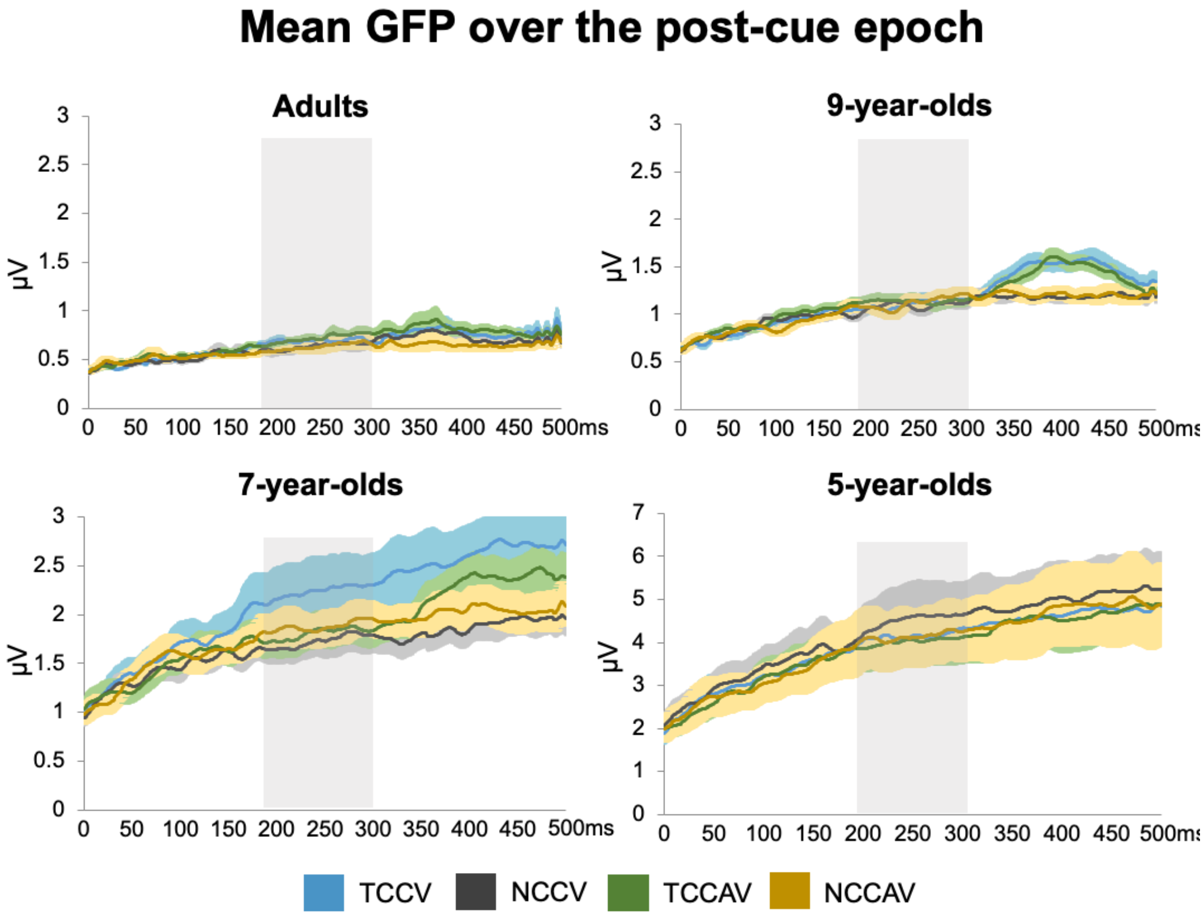


Figure 9. Overall GFP for each of the 4 cue conditions (represented according to the figure legend) per age-group, plotted across the entire post-cue time-window. Thick lines represent mean GFP's while the surrounding lighter coloured fields represent the standard error of the mean. For reference, the boundaries of the canonical N2pc time-window are highlighted in grey. As visible from overlapping means and error areas, there was no significant main effects and interactions in any of the tested age groups.

1.3.1.2. ERP topography in adults. Next, we performed the topographic segmentation of the adult control data over the post-cue time-period. This procedure was performed in order to investigate if Cue Colour- and Cue Modality-induced modulations of cue-elicited lateralised

ERPs were driven by differences in scalp topography, and therefore, by differences in underlying brain generators. The segmentation revealed 9 clusters over the post-cue time-period that explained 82.8% of the GEV in the group-averaged adult difference ERPs. We remind the reader that topographical analyses (unless otherwise stated) were conducted on difference ERPs, which accounts for the lower rates of GEV. Next, a fitting procedure on the adult single-subject data revealed 4 template maps that characterised the N2pc over the 180-300ms post-cue time-period. We next performed a 2 x 2 x 4 ANOVA on the mean durations of the 4 maps identified in the adult data. This analysis revealed a main effect of Map, $F_{(3,\ 114)} = 18.3$, $p < 0.001$, $\eta_p^2 = 0.3$, where Map4 predominated (i.e. had the longest duration of all maps) the N2pc time-window across conditions (Figure 10, middle left panel). This demonstrated that adults had stable patterns of lateralised ERP activity. Hereafter, we did not follow up the main effect of Map with post-hoc tests, as it was not informative as to the presence of TAC or MSE in topography.

There was a 2-way interaction between Map and Cue Colour, $F_{(2.4,\ 89.1)} = 12$, $p < 0.001$, $\eta_p^2 = 0.2$. In an analysis of this interaction by Cue Colour, post-hoc *t*-tests revealed that the overall most dominant map within the tested N2pc-like time-window, Map4, was present longer in response to TCC distractors (67ms) than to NCC distractors (40ms), $t_{(38)} = 5.2$, $p < 0.001$. Meanwhile, Map2 was present for a longer portion of the N2pc time-window in response to NCC distractors (34ms) than for TCC distractors (13ms), $t_{(38)} = 3.9$, $p = 0.004$. Other map durations did not differ significantly between TCC and NCC cues (all *p*'s > 0.1; full results in Table A.1, Appendix 3). Hereafter, map duration differences that are not presented in the Results chapter were not statistically significant (*p*'s > 0.1) but can be found in the Appendix. Thus, it appeared that the Map x Cue Colour interaction was driven by modulations of Map2 and Map4 durations for different cue colours. We then analysed the results as a function of Map in order to understand network-based processes within each condition. Here, no map durations differed for NCC distractors (all *p*'s > 0.1). Meanwhile for TCC cues, Map4 (67ms) was significantly longer than all other maps – Map1 (15ms), $t_{(38)} = 7.7$, Map2 (13ms), $t_{(38)} = 8$, and Map3 (25ms), $t_{(38)} = 6.3$, all *p*'s < 0.001. These results suggest that Map4 drove the processing of TCC distractors, while no particular map was more implicated than others in the processing of NCC distractors. Finally, the map modulations by Cue Colour demonstrated here support the presence of TAC in adult ERP topography.

In contrast to canonical N2pc analysis results, the relative duration of cue-elicited topographic maps within the N2pc-like time-window interacted with Cue Modality, as evidenced by a 2-way interaction, $F_{(3,\ 114)} = 3.2$, $p = 0.027$, $\eta_p^2 = 0.1$. When analysing the interaction by Cue Modality, Map2 was found to characterise a longer part of the N2pc time-window when cues were purely visual (V, 30ms) than when cues were accompanied by a sound (AV, 17ms) at the level of a nonsignificant trend, $t = 2.8$, $p = 0.08$; full results in Appendix 3). Next, we analysed the results along the factor of Map. For AV cues, Map4 (53ms) was significantly longer than all other maps – Map1 (25ms), $t_{(38)} = 4.3$, Map2 (17ms), $t_{(38)} = 5.6$, Map3 (26ms), $t_{(38)} = 4.2$, all *p*'s < 0.001. For V cues, similarly, Map4 (54ms) was significantly longer than all other maps – Map1 (18ms), $t_{(38)} = 5.7$, Map2 (30ms), $t_{(38)} = 3.7$, Map3 (19ms), $t_{(38)} = 5.5$, all p's < 0.001 (full results in Table A.2, Appendix 3). Thus, Map2 may be implicated in topographic modulations of lateralised ERPs by Cue Modality, whereas Map4 was the main map driving the processing of both AV and V cues. These results suggest that adult ERP topographic maps show overall sensitivity to MSE.

Finally, there was also a 3-way Map x Cue Colour x Cue Modality interaction, $F_{(3,\,114)} = 5.4$, $p = 0.002$, $\eta_p^2 = 0.1$. When followed up as a function of Cue Colour, for NCC distractors, Map2 duration for V cues was larger (50ms) than for AV cues (18ms), $t_{(38)} = 4.7$, $p < 0.001$. Yet, for TCC distractors, all map durations were comparable between V and AV cues (all p's > 0.1). Next, when following up as a function of Cue Modality, for AV cues, Map4 duration for TCC distractors was longer (67ms) than for NCC distractors (40ms), $t_{(38)} = 3.8$, $p = 0.004$. Likewise, for V cues, Map4 duration was longer for TCC (67ms) than NCC (39ms) distractors, $t_{(38)} = 3.6$, $p = 0.003$. However, Map2 was also longer for NCC (50ms) than TCC distractors (10ms), for V cues $t_{(38)} = 5.4$, $p < 0.001$. Thus, maps that are sensitive to TAC and MSE appear to interact, suggesting that top-down visual attentional control and bottom-up multisensory attentional control may share neural generators.

1.3.1.3. ERP Topography in Children. To explore if and when the above adult-derived topographical patterns were present in children, we submitted each child age-groups' data within the 180-300ms time-window to a fitting procedure, where child topographical data were labelled according to the adult template maps with which they best correlated spatially. We then, as in adults, analysed the durations of the fitted maps using a 2 x 2 x 4 repeated-measures ANOVA.

For 9-year-olds, the ANOVA revealed a main effect of Map, $F_{(3,\,75)} = 9.2$, $p < 0.001$, $\eta_p^2 = 0.3$, and, like in adults, Map4 predominately characterised ERPs during the N2pc time-window (Figure 10 middle right panel). Map presence was modulated only by Cue Modality, as evidenced by a 2-way interaction between Map and Cue Modality, $F_{(3,\,75)} = 3.4$, $p = 0.04$, $\eta_p^2 = 0.1$. To follow up, we split the interaction by Cue Modality, and found that Map3 was longer for AV (27ms) than V cues (11ms), $t_{(25)} = 2.6$, $p = 0.02$, while Map4 was longer for V (55ms) than AV cues (39ms), $t_{(25)} = 2.5$, $p = 0.02$ (full results in Table A.3, Appendix 3). However, the map that was sensitive to the (audio)visual nature of the cues in adults, Map2, was comparably present for V cues (31ms), and AV cues (27ms), $t_{(25)} = 0.7$, $p = 1$. When we followed up the 2-way interaction as a function of Map, there were no significant differences between map durations for AV cues (all p's > 0.1; Table A.3, Appendix 3). For V cues, however, Map4 (55ms) was revealed to be longer than all other maps – Map1 (24ms), $t_{(25)} = 4$, Map2 (32ms), $t_{(25)} = 3.7$, Map3 (11ms), $t_{(25)} = 5.8$, all p's < 0.001 (full results in Table A.3, Appendix 3). In a marked contrast to adults, 9-year-olds did not show the other 2-way interaction of interest, Map x Cue Colour ($F_{(3,\,75)} = 1.3$, $p = 0.3$). Other interactions failed to reach statistical significance (all F's < 2, p's > 0.1). Taken together, 9-year-olds seemed to show *adult*-like MSE (a Map x Cue Modality 2-way interaction), even though they did not show a modulation of the adult MSE-sensitive map. It is possible that adult-like MSE is nascent in 9-year-olds. Nonetheless, 9-year-olds' overall topographic pattern was like that of adults, with a predominance of Map4 across conditions.

In 7-year-olds, there was also a main effect of Map, $F_{(2.3,\ 85.5)} = 9.7$, $p < 0.001$, $\eta_p^2 = 0.2$, and the map with the longest duration over the N2pc time-window was Map4, akin to the other two older age groups (Figure 10 bottom left panel). Unlike in older age groups, however, no other main effects or interactions reached statistical significance (all *F*'s < 3, *p's* > 0.1). This included the 2-way interactions of interest, Map x Cue Colour ($F_{(3,\ 111)} = 0.7$, $p = 0.6$) and Map x Cue Modality ($F_{(2.4,\ 87.3)} = 1.3$, $p = 0.3$). We can therefore conclude that 7-year-olds' topography did not show adult-like TAC or MSE, although their overall topographic pattern could be considered adult-like.

Finally, 5-year-olds also showed a main effect of Map, $F_{(3,\ 81)} = 6.3$, $p < 0.001$, $\eta_p^2 = 0.2$, but here, there was no clear map dominance pattern (Figure 10 bottom right panel). No other main effects or interactions reached statistical significance (All *F*'s < 1), including the two 2-way interactions of interest, Map x Cue Colour ($F_{(2.1,\ 57)} = 0.8$, $p = 0.4$) and Map x Cue Modality ($F_{(2.3,\ 61.6)} = 0.7$, $p = 0.5$). With this, 5-year-olds seemed not to show adult-like TAC, MSE, or overall pattern of map presence.

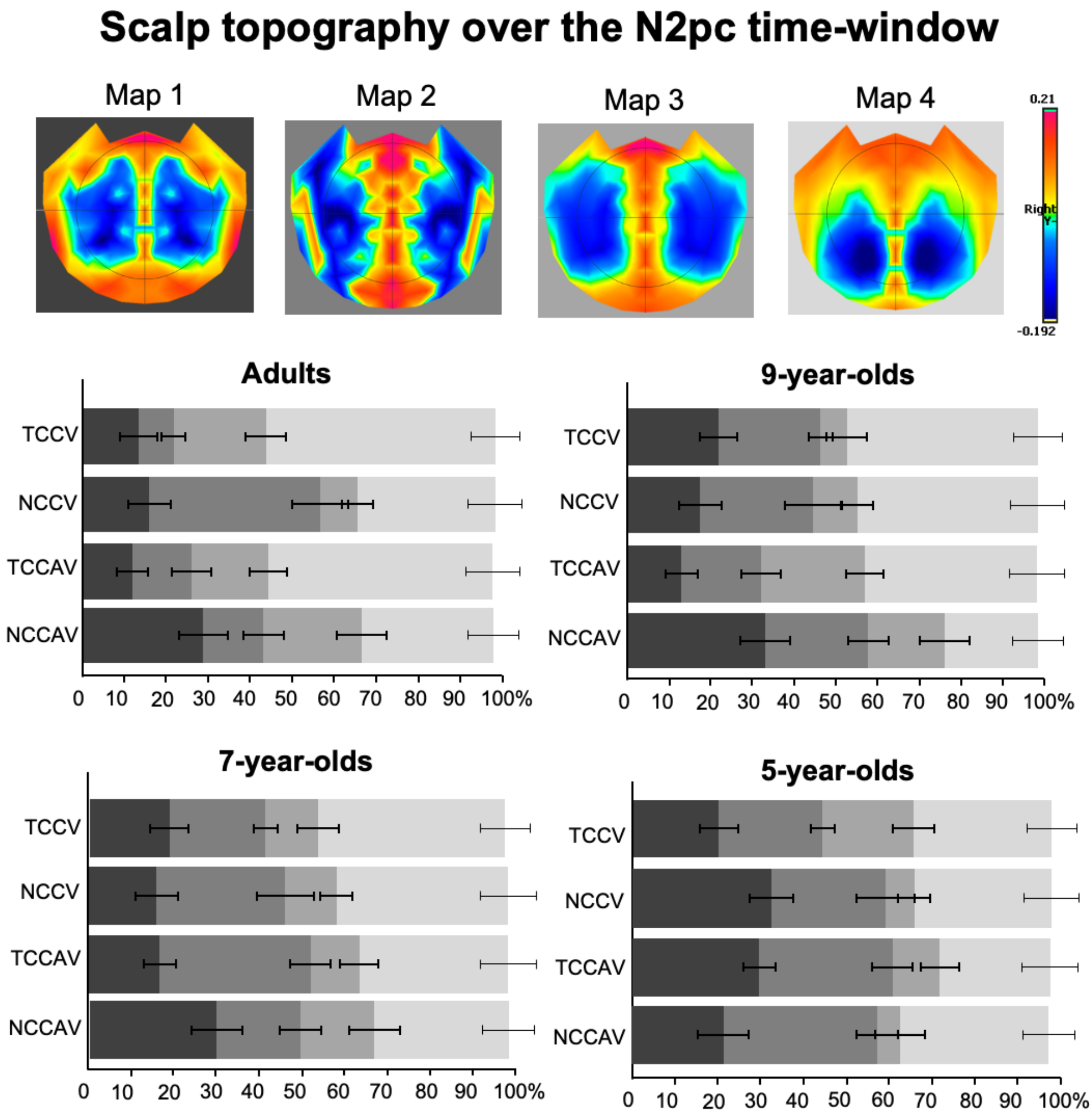


Figure 10. Segmentation of the adult difference ERP data and fitting of adult and child difference ERP data onto the segmentation results. The four template maps resulting from the segmentation of the adult data are shown in the first row. Below is each map's duration in percentages over the canonical N2pc time window (180-300ms post-cue), per condition, for each age group. Bars are coloured according to their map's backgrounds in the top row, and error bars denote the standard error of the mean. Map 4 is the most dominant in adults, 9-year-old children, and 7-year-old children, while 5-year-old children do not have a clear map dominance pattern. Only in adults is Map 4 duration modulated by Cue Colour, that is target-matching.

1.3.2. Descriptive analysis

What the normative analysis did not clarify was whether children's topographies were sensitive to cues' matching of target colour and the (audio)visual nature of cues in ways that could perhaps not be considered adult-like. For this reason, in the descriptive analysis, we carried out electrical neuroimaging analyses on the ERP data from child groups independently of the analyses parameters identified in the adults' ERP results.

1.3.2.1 GFP across age groups. In order to investigate whether response strength differences governed top-down and bottom-up modulations of cue-elicited lateralised ERPs in each of the child age groups, separate 2 x 2 repeated-measures ANOVAs were conducted on the average GFP values. However, unlike in the normative analyses, here ANOVAs were conducted over each age group's own N2pc time-window, as defined by DISS for the TCC difference ERP. The ANOVAs revealed no significant main effects or interactions in the 9-year-olds and 5-year-olds (*p*'s > 0.1), while in 7-year-olds, the main effect of Cue Colour reached the level of a nonsignificant trend ($F_{(1,37)} = 3.07$, $p = 0.09$, $\eta_p^2 = 0.08$; see Figure 9 above). These results suggested no evidence for a strength-based modulation of cue-elicited lateralised ERPs in children (full results in Appendix 3).

1.3.2.2. ERP Topography in 9-year-olds. Next, to investigate whether network-based differences governed top-down and bottom-up modulations of cue-elicited lateralised ERPs in each of the child age groups, we performed separate segmentations of each age group's data over the post-cue time-period. Further, the fitting procedure was conducted for each age group separately, within each age group's own N2pc time-window. It is to be noted that the fitting time-windows that were based on segmentation results differed slightly from N2pc time-windows that were based on the DISS parameter, inasmuch as DISS and TAAHC are calculated differently. Thus, in the fitting, we included template maps that, in their length, appeared to characterise cue-elicited N2pc's.

In 9-year-olds, a segmentation revealed 14 clusters that explained 91.5% of GEV in the group-averaged difference ERPs. Over the 144-290ms post-cue time-window, there were 9 template maps to which we 'fitted' the 9-year-olds' single-subject ERP data back onto. A 2 x 2 x 9 repeated-measures ANOVA on the mean map durations revealed a main effect of Map, $F_{(8, 200)} = 2.7$, $p = 0.009$, $\eta_p^2 = 0.1$, confirming that 9-year-olds exhibited stable patterns of lateralised N2pc-like ERP activity. To help differentiate topographic maps uncovered by descriptive analyses between age groups, and from maps uncovered by normative analyses, here, map numbers were given a prefix to indicate the age-group they belonged to, for example, Map91 for 9-year-olds, Map71 for 7-year-olds, Map51 for 5-year-olds. Thus, here, Maps 93, 95, and 98 were found to be present the longest over the N2pc time-window across conditions.

In contrast to the normative analyses, now in 9-year-olds, the presence of the identified lateralised topographic maps over the N2pc time-window varied depending on the colour of the cue, as evidenced by a 2-way Map x Cue Colour interaction, $F_{(8, 200)} = 3.4$, $p = 0.001$, $\eta_p^2 = 0.1$. Following up the 2-way interaction by Cue Colour revealed that Map96 was present longer over the N2pc time-window in response to TCC (28ms) than for NCC distractors (8ms), $t_{(25)} = 3.7$, $p = 0.005$. Conversely, Map94 was present shorter in response to TCC (7ms) than to NCC distractors (20ms), $t_{(25)} = 3.4$, $p = 0.008$, and Map99 was also present shorter for TCC (9ms) than NCC distractors (16ms), $t_{(25)} = 3$, $p = 0.04$. With this, the Map x Cue Colour interaction seemed to be driven by modulations in the durations of Map94, Map96, and Map99 (Figure 11A, left panel). Following up the 2-way interaction by

Map revealed multiple maps being preferentially active for TCC distractors, and for NCC distractors (shown in Table A4, Appendix 3). This demonstrated that 9-year-olds do show TAC, but perhaps not one of an adult-like quality, which appears to be driven by modulations in Maps 94 (positive, i.e. longer for TCC than NCC), and 96, and 99 (negative). Further, the processing of NCC distractors and TCC distractors is driven by distinct sets of neural generators.

Durations of the lateralised maps also depended on the presence of a sound, as demonstrated by a 2-way Map x Cue Modality interaction, $F_{(8,\ 200)} = 2.4$, $p = 0.02$, $\eta_p^2 = 0.1$. Following up the interaction by Cue Modality revealed that Map93 was present longer for AV (29ms) than for V cues (13ms), $t_{(25)} = 3.7$, $p = 0.007$, while Map92 was present shorter for AV (5ms) than V cues (17ms), $t_{(25)} = 3.1$, $p = 0.03$. This suggested that the Map x Cue Modality interaction was driven by modulations of durations of Map92, which was more implicated in the processing of visual cues, and Map93, which was more implicated in the processing of audiovisual cues (Figure 11A, right panel). Following up the interaction by Cue Modality revealed differences in map presence in response to AV distractors, but not V distractors and the results are shown in Table A.5 (Appendix 3). This suggested that 9-year-olds may also show MSE, which is likely driven by modulations of Map93 and 92. Further, while the processing of AV distractors is driven by a distinct set of maps the processing of V cues relies on all maps.

The durations of the lateralised maps over the N2pc time-window were also jointly modulated by the colour of the cue and presence of sound, as evidenced by a 3-way Map, Cue Colour, and Cue Modality interaction, $F_{(8,\ 200)} = 2.2$, $p = 0.048$, $\eta_p^2 = 0.1$. We first followed up this interaction by Cue Colour. For TCC cues, map durations between V and AV were comparable (all p's > 0.1), while for NCC cues, the presence of Maps 92, 93, 94, and 99 differed. That is, Map93 was present longer for AV (38ms) than V cues (11ms), $t_{(25)} = 4.2$, $p = 0.005$, and Map94 was present longer for AV (30ms) than V cues (11ms), $t_{(25)} = 3.3$, $p = 0.03$. Meanwhile, Map92 was present shorter for AV (4ms) than V cues (23ms), $t_{(25)} = 3.5$, $p = 0.005$, and Map99 was present shorter for AV (8ms) than for V cues (26ms), $t_{(25)} = 3.1$, $p = 0.04$. Next, we followed up the interaction by Cue Modality. Here, for AV cues, only Map94 was present longer for NCC (30ms) than for TCC distractors (6ms), $t_{(25)} = 5.0$, $p < 0.001$. For V cues, Map91 was present longer for TCC (24ms) than for NCC distractors (3ms), $t_{(25)} = 3.7$, $p = 0.01$, while Map99 was present shorter for TCC (5ms) than for NCC distractors (26ms), $t_{(25)} = 3.1$, $p = 0.007$ (full results in Appendix 2). With this, not only did 9-year-olds show reliable TAC and MSE, but also an interaction of these two factors, as did adults.

1.3.2.2. ERP Topography in 7-year-olds. In 7-year-olds, 11 clusters explained 88.3% of GEV in the group-averaged difference ERPs. Five template maps characterised the time-period of 151-275ms post-cue. A 2 x 2 x 5 repeated-measures ANOVA on the results of the fitting revealed a main effect of Map, $F_{(3.2,\ 117.6)} = 9.8$, $p < 0.001$, $\eta_p^2 = 0.2$, confirming that stable patterns of lateralised N2pc-like ERP activity can also be found in 7-year-olds. Maps 71 and 72 characterised the largest portions of N2pc time-window overall.

Like in 9-year-olds, in 7-year-olds map duration within the N2pc time-window varied depending on the colour of the cue, as evidenced by a 2-way Map x Cue Colour interaction, $F_{(2.9\ 107)} = 2.8$, $p = 0.04$, $\eta_p^2 = 0.1$ (Figure 11B, left panel). Following up the interaction by Cue Colour revealed that only Map75 was present longer for TCC (21ms) than NCC distractors (5ms), $t = 3.7$, $p = 0.002$. Meanwhile, following up by Map revealed significant differences between map durations for both TCC and NCC distractors (reported in Table A.7, Appendix 3). These results demonstrate that 7-year-olds, like 9-year-olds before them, showed TAC, though again perhaps not adult-like topographic maps, and that this effect was driven by modulations in Map75. The processing of TCC and NCC distractors was each orchestrated by distinct sets of neural generators.

Again, as in 9-year-olds, in 7-year-olds, there were also patterns of ERP activity elicited by visual cues that were sensitive to accompaniment of a sound. This was statistically demonstrated by a 2-way Map x Cue Modality interaction, $F_{(3.1,\ 114.3)} = 8$, $p < 0.001$, $\eta_p^2 = 0.2$ (Figure 11B, left panel). Following up the interaction by Cue Modality revealed modulations of Maps 71, 72, 73, and 74. Namely, Map72 was present longer for AV (44ms) than for V cues (26ms), $t_{(37)} = 3.5$, $p = 0.002$, and Map74 was present longer for AV (37ms) than for V cues (21ms), $t_{(37)} = 3.2$, $p = 0.01$. Conversely, Map71 was present shorter for AV (26ms) than V cues (43ms), $t_{(37)} = 3.5$, $p = 0.004$, and Map73 was present shorter for AV cues (6ms) than V cues (16ms), $t_{(37)} = 2.8$, $p = 0.006$. Following up the interaction by Map revealed, differences in map presence for both AV and V distractors (Table A.8, Appendix 3). It appeared that 7-year-olds, like 9-year-olds before them, had reliable MSE, which was driven by Map75 modulations, while the processing of AV and V cues was orchestrated by the involvement of distinct sets of neural generators.

Finally, like in 9-year-olds and adults before them, 7-year-olds' lateralised template map presence was modulated jointly by both colour of the cue and presence of sound, as demonstrated statistically by a 3-way Map x Cue Colour x Cue Modality interaction, $F_{(3,\ 111.1)} = 3.2$, $p = 0.03$, $\eta_p^2 = 0.1$. We first followed-up this interaction as a function of Cue Colour. Here, for NCC cues, Map72 was present longer for AV (56ms) than V cues (25ms), $t_{(37)} = 4.1$, $p = 0.005$, while Map71 and Map73 were both present shorter for AV cues than V cues (Map71: 27ms vs. 50ms, $t_{(37)} = 3.1$, $p = 0.004$; Map73: 8ms vs. 21ms, $t_{(37)} = 2.5$, $p = 0.03$). For TCC cues, on the other hand, only Map74 was present longer for AV (48ms) than for V cues (18ms), $t_{(37)} = 4$, $p = 0.001$. We next followed-up the 3-way interaction as a function of Cue Modality. Here, for AV cues, only Map72 was present shorter for TCC (25ms) than NCC distractors (56ms), $t_{(37)} = 2.9$, $p = 0.003$. On the other hand, for V cues, it was Map75 that was present longer for TCC (30ms, $t_{(37)} = 4$, $p = 0.002$) than NCC (13ms, $t_{(37)} = 1.9$, $p = 0.06$), $t_{(37)} = 3.2$, $p = 0.005$. Clearly, even in 7-year-olds, top-down visual attentional control and bottom-up multisensory attentional control jointly modulated N2pc difference ERP topography, as maps that were in 2-way interactions associated with either TAC or MSE appeared to be modulated by both TAC and MSE.

1.3.2.3. ERP Topography in 5-year-olds. In the youngest age group, the 5-year-olds, 11 clusters explained 84.9% of GEV in the group-averaged difference ERPs. There were 8 template maps that characterised the time-period of 110-302ms post-cue, and that were involved in the fitting. As in the older child groups, a 2 x 2 x 8 repeated-measures ANOVA on the fitting results revealed a significant main effect of Map, $F_{(4.7,\ 127.2)} = 4$, $p = 0.003$, $\eta_p^2 = 0.1$, which revealed presence of stable lateralised N2pc-like ERP patterns in children as young as 5. Map54 characterised the longest portion of the N2pc time-window.

In contrast to the behavioural and canonical N2pc results, lateralised template maps were now revealed to be modulated by the colour of the cue, as evidenced by a 2-way Map x Cue Colour interaction, $F_{(7,\ 189)} = 4.2$, $p < 0.001$, $\eta_p^2 = 0.1$. Following up the interaction by Cue Colour revealed modulations in Map53, Map54, and Map55 presence (Figure 11C). Map53 was present longer for TCC (47ms) than NCC distractors (13ms), $t_{(27)} = 4.3$, $p = 0.003$, while Map54 and Map55 were both less present for TCC than NCC distractors (Map54: 27ms vs. 52ms, $t_{(27)} = 3.1$, $p = 0.007$; Map55: 5ms vs. 19ms, $t_{(27)} = 2.8$, $p = 0.05$). Following up the interaction by Cue Colour, we found significant differences between map durations for both TCC and NCC distractors (Table A.10, Appendix 3), as in the older age groups. These results demonstrated that even in 5-year-olds children, there is evidence for TAC, though it may not be adult-like, which is driven by three maps (Map53, Map54, and Map55). Moreover, the processing of TCC distractors and NCC distractors is governed by distinct sets of neural generators.

Unlike in the two older child groups, however, the lateralised maps were not modulated by sound presence in 5-year-olds, with no evidence for a 2-way interaction between Map and Cue Modality, $F_{(7,\ 189)} = 0.9$, $p = 0.4$. That said, 5-year-olds did show a joint modulation of map presence by Cue Colour and Cue Modality, as evidenced by a 3-way Map x Cue Colour x Cue Modality interaction, $F_{(7,\ 189)} = 2.2$, $p = 0.04$, $\eta_p^2 = 0.1$. We first explored this interaction as a function of Cue Colour. Here, for NCC cues, there were no significant differences between V and AV (all *p*'s > 0.1), but for TCC cues, Map56 and Map58 were differentially present across V and AV cues. Map56 was present longer for AV (47ms) than V cues (13ms), $t = 2.8$, $p = 0.02$, while Map58 was present shorter for AV (2ms) than V cues (38ms), $t = 3$, $p = 0.007$. Next we explored the interaction as a function of Cue Modality. For AV cues, Map55 was present longer for TCC (28ms) than NCC distractors (4ms), $t_{(27)} = 2.6$, $p = 0.01$. Meanwhile for V cues, Map53 was present longer for TCC (52ms) than NCC distractors (6ms), $t_{(27)} = 4$, $p = 0.002$, and Map58 was also present longer for TCC (38ms) than NCC distractors (12ms), $t_{(27)} = 2.2$, $p = 0.04$. Conversely, Map54 was present shorter for TCC distractors (20ms) than for NCC distractors (55ms) $t_{(27)} = 2.9$, $p = 0.05$. These results showed that while 5-year-olds showed TAC, there was no evidence for MSE (even non-adult-like MSE), in 5-year-olds. Nonetheless, as in the older age-groups, ERP topography was jointly modulated by the brain's sensitivity to cues' target colour matching and presence/absence of sounds.

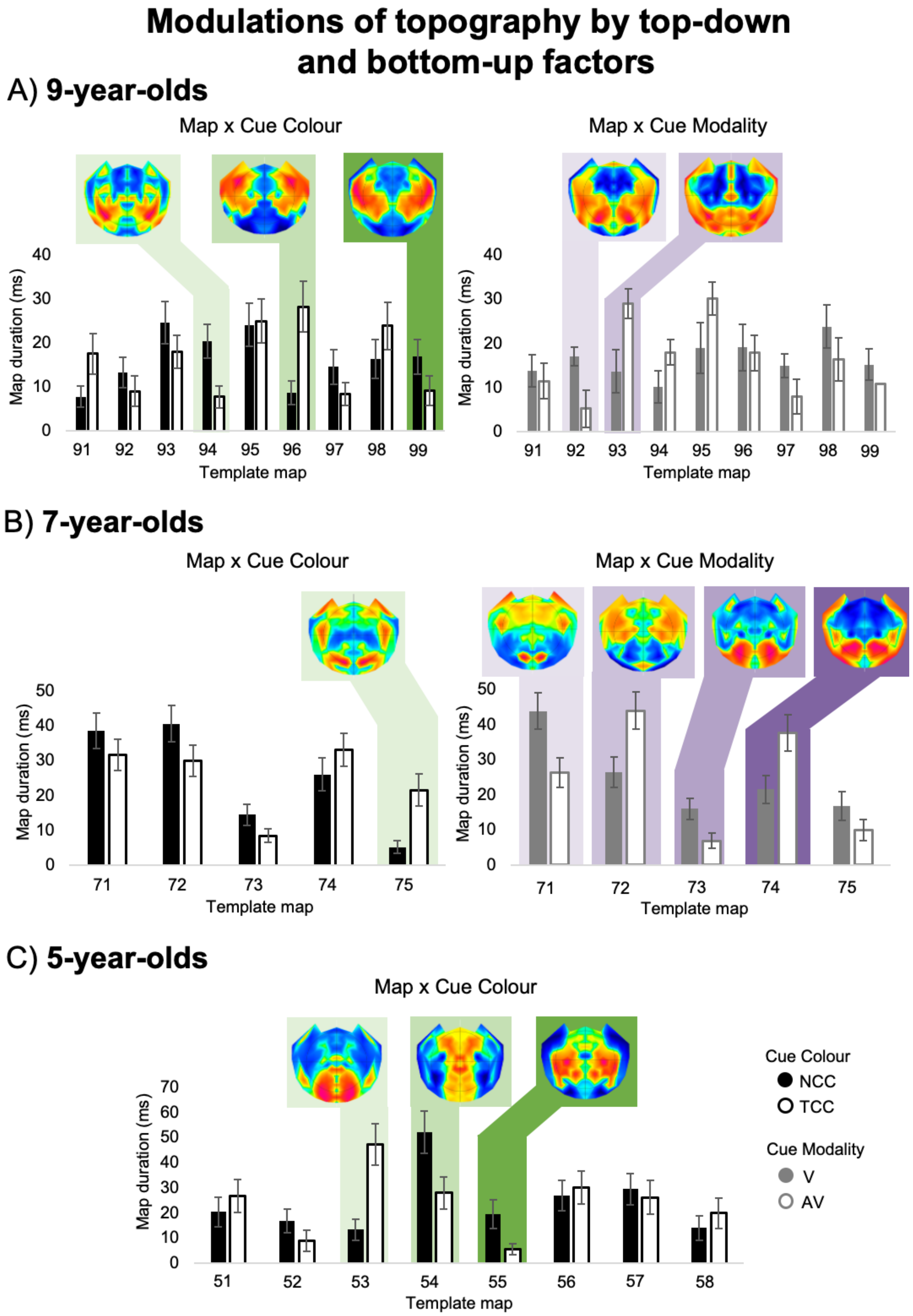


Figure 11. Template map presence modulation by Cue Colour (indicated in green) and Cue Modality (indicated in purple), for each child age-group. Template map duration in milliseconds is presented over each

group's N2pc time-window. The figure shows that for each age group, a different set of template maps was implicated, though both factors modulated map duration, except in 5-year-olds where only Cue Colour did so.

2. Relationships between children's attentional control mechanisms and educational skills

The part of the data analysis described in this section was dedicated to investigating whether children's visual attentional control skills and multisensory attentional control skills were related to their literacy and numeracy scores. Since the presence of TAC and MSE were largely confirmed in behaviour and descriptive topographic analyses, we submitted behavioural and topographic measures to a set of preliminary correlations with educational scores. Behavioural measures were indices of %TAC and %MSE. As topographic measures, we used the average durations across conditions of those maps that were modulated by Cue Colour or Cue Modality, according to Descriptive topographical analyses. To recapitulate, maps that were modulated by Cue Colour (and thus indexed TAC) were as follows: in 9-year-olds, Map94, Map96, and Map99; in 7-year-olds, Map75; and in 5-year-olds, Map53, Map54, and Map55. Maps that were modulated by Cue Modality (thus indexing MSE) were as follows: in 9-year-olds, Map92 and Map93; and in 7-year-olds Map71, Map72, Map73, and Map74. In 5-year-olds, no maps were modulated by Cue Modality. The educational scores used were the following: in 9-year-olds, Reading, Comprehension, and Mathematics; in 7-year-olds, Reading and Mathematics; and in 5-year-olds Phonological skills and Numeracy. As before, we foreshadow our findings in the overview below.

Table 2

Overview of relationships between attentional control (TAC and MSE) and educational skills (literacy and numeracy)

Correlation	**9-year-olds**	**7-year-olds**	**5-year-olds**
TAC - Literacy	✓	X	X
TAC - Numeracy	X	X	✓
MSE - Literacy	X	X*	X
MSE - Numeracy	✓	X*	X

Note. * denotes correlations that were at trend level

2.1 Behaviour – education correlations

First, correlations between educational scores and the behavioural indices of TAC and MSE were performed. However, none of these correlations were significant (all *p*'s > 0.1; see Tables A.12 – A.14, Appendix 4). This suggested that there is no sufficient statistical evidence for behaviourally-instantiated TAC and MSE being related to primary school children's literacy and numeracy scores.

2.2. Topography – education correlations

2.2.1. 9-year-olds

Educational scores were next correlated with topographical map presence for each age group. In 9-year-olds, we first considered correlations involving topographic maps that modulated with the colour of the cue. There was a significant negative correlation between Map99 and Reading ($r_{skipped}$ = -0.51, $p < 0.01$; $\rho_{skipped}$ = -0.56, $p < 0.005$), meaning that children's Reading scores were worse the longer Map99 was present over the N2pc time-window. We remind the reader that map presence characterised responses to *distractors.* Thus, intuitively speaking, we may understand these results as, the more 'Map99- top-down visual control related distraction' there was, the worse children's Reading scores were. Other correlations involving cue-colour modulated maps were not statistically significant (all *p*'s > 0.1).

For correlations involving topographic maps that modulated with sound presence, there was a significant negative correlation between Map92 and Mathematics ($r_{skipped}$ = -0.49, $p < 0.01$; $\rho_{skipped}$ = -0.45, $p < 0.05$; Figure 12), meaning that children's Mathematics scores were worse the longer Map92 characterised the N2pc time-window, or the more distraction involving Map92 and bottom-up multisensory control there was. Again, other correlations involving sound modulated maps were not statistically significant (all *p*'s > 0.1).

Taken together, these results suggested that specific patterns of distraction as a product of top-down visual attentional control (governed by Map99) and bottom-up multisensory control (governed by Map92) were related to poorer literacy and numeracy, respectively, in children around 9 years of age (in 5th grade).

2.2.2. 7-year-olds

In 7-year-olds, there were no topographic maps modulated by Cue Colour that correlated with educational scores (all *p*'s > 0.1). As for correlations involving maps that modulated with Cue Modality, the skipped Spearman correlation coefficient for the correlation between Map73 and Reading ($\rho_{skipped}$ = 0.256) was near the boundary of the $p = 0.05$ significance threshold (0.271). This suggested that the positive correlation between Map73 duration and Reading reached the level of a nonsignificant trend. Likewise, the skipped Spearman correlation coefficient for the correlation between Map71 and Mathematics ($\rho_{skipped}$ = 0.257) was also near the $p = 0.05$ significance threshold (0.271), suggesting that the positive correlation between Map71 and Mathematics was also trending. Other correlations did not reach statistical significance (all *p*'s > 0.1). Curiously, the signs of these correlations were opposite of the 9-year-olds, suggesting that 7-year-olds' literacy and numeracy may potentially benefit from certain patterns of distraction. Ultimately, however, the lack of statistical significance of these relationships precludes any strong conclusions about such relationships.

2.2.3. 5-year-olds

Finally, in 5-year-olds, topographical maps were only modulated by the colour of the cues, and not by the presence/absence of sound. Thus, the duration of the Cue Colour-modulated Map54 was significantly negatively correlated with Numeracy ($\rho_{skipped} = -0.4$, $p < 0.05$). This meant that young children's Numeracy scores were worse the longer Map54 characterised the N2pc time-window, or the more distraction involving Map54 there was. Other correlations were not significant (all p's > 0.1). This suggested that even in children as young as 5, or at school entry, lateralised brain activity patterns of distraction that is a product of top-down attentional control (governed by Map54) may be linked to poorer numeracy.

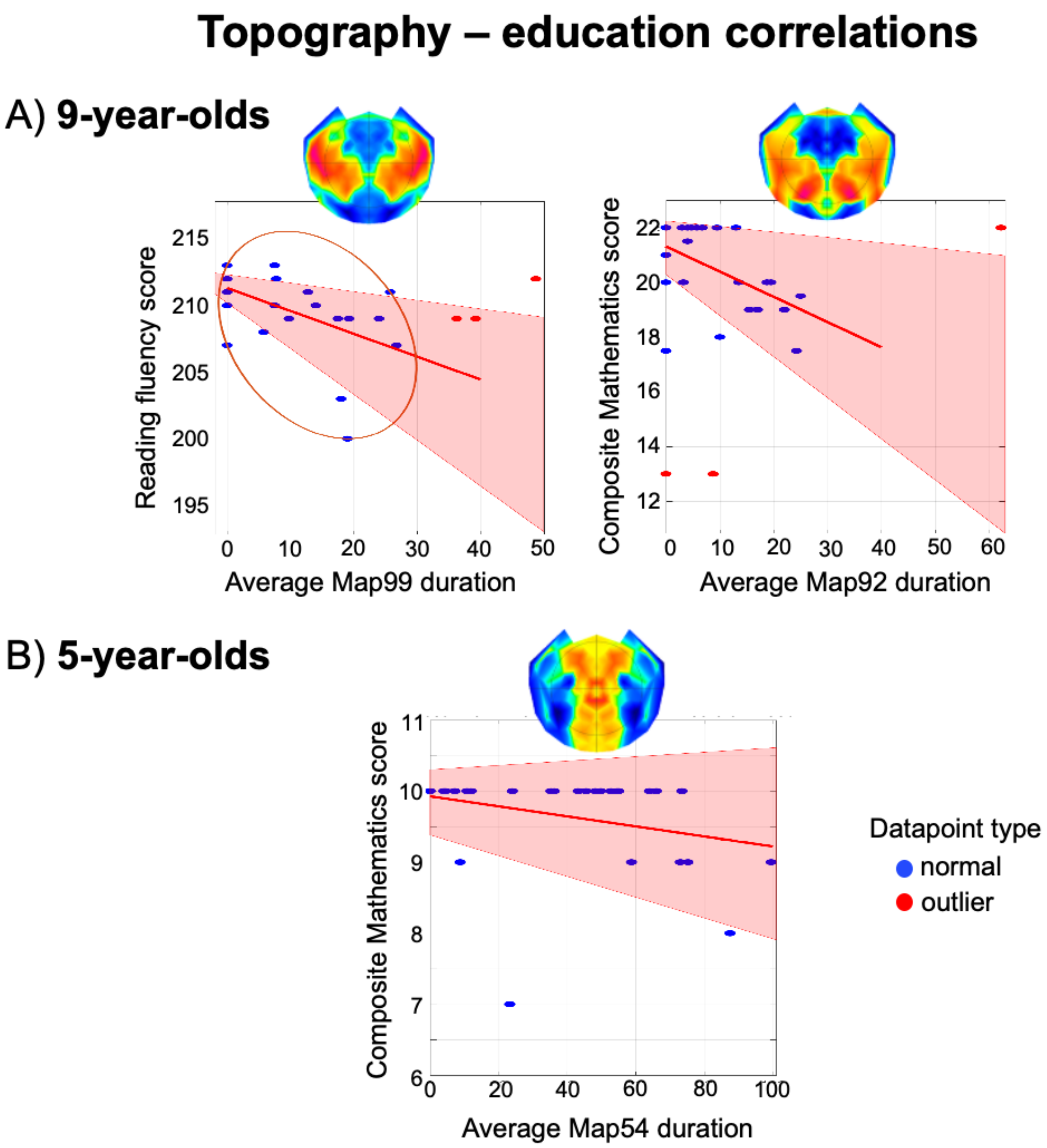


Figure 12. Results of skipped correlations between topographical map durations over each age-group's respective N2pc time-window and educational scores (literacy and numeracy), per age group. Template maps that were involved in each correlation are shown above their respective correlation plots. The average duration of each map over the age group's own N2pc time-window is plotted on the X-axis, and the score on the given educational scale is plotted on the Y axis. Ellipses are drawn around data that cluster in such shapes.

Blue dots represent datapoints that have been taken into account in the correlation ('normal' in the legend), while red dots represent outliers.

3. Adult study: Evidence for modulations of attentional control by contextual factors

The analysis described in this section was concerned with modulations of top-down visual and bottom-up multisensory attentional control mechanisms, that is TAC and MSE, by contextual factors, specifically, Multisensory Relationship (MR) and Distractor Onset (DO). We note that these modulations were only explored in adults. To avoid confusion with the adult control data reported as part of the Developmental study, we remind the reader that the data considered here are broader, spanning four adult experiments, the first of which served as the adult control data above. The results reported here are divided primarily into two parts. First, we detail the outcomes of a 'developmental analogue' analysis that used a similar design as the preceding Developmental study, including lateralised ERPs in the case of EN analyses. Next, we detail the outcomes of an exploratory set of EN analyses that were conducted using nonlateralized ERPs that represented the enhancement of visual attentional control by sound presence, somewhat like an interaction between TAC and MSE, that was referred to as Target Difference.

Across these analyses, the focus was partly on establishing the presence of TAC and MSE, but more importantly on investigating the presence and nature of any further modulations of TAC and/or MSE by MR and/or DO, or in the absence of such modulations, the direct modulation of attentional capture by contextual effects. Thus, in behavioural, N2pc, and GFP analyses that followed the Developmental study design, effects of importance were: the main effects of Cue Colour and/or Cue Modality, interactions of MR and/or DO with Cue Colour and/or Cue Modality, and the main effects of DO and/or MR (as well as a potential interaction between MR and DO). In topographical analyses that followed the Developmental study design, effects of importance were modulations of Map by Cue Colour and Cue Modality, interactions of these modulations with MR and/or DO, and modulations of Map by MR and/or DO. In exploratory EN analyses, for voltage and GFP, the effects of importance were the main effect of Target Difference, interactions of Target Difference with MR and/or DO, and the main effects of MR and/or DO. We foreshadow our results in the table below. Meanwhile for topography, the effects of importance were the modulation of Map by Target Difference, interactions of this modulation with MR and/or DO, and modulations of Map by MR and/or DO.

Table 3

Overview of adult results: presence of TAC and/or MSE, modulations of TAC and/or MSE by MR and/or DO, and direct modulations of attentional capture by MR and/or DO

Analysis	**TAC/MSE**	**MR/DO x TAC/MSE**	**MR/DO/ MR x DO**
Behaviour	✓/✓	X	✓/X/✓
N2pc	✓/X	X	X/X/X
GFP	✓/X	X	X/X/X
Topography	✓/X	X	X/✓/✓
Exploratory EN analyses			
Voltage	✓*	✓*	✓*
GFP	✓*	✓*	✓*
Topography (canonical)	X	✓*	✓*

Note. * denotes TAC and MSE effects have been collapsed into Target Difference. Topographical analyses that explored GFP-prescribed time-windows as part of Exploratory EN analyses were not included in this overview.

3.1. Behavioural analyses

3.1.1. RT results

To investigate the context-based effect of semantic associations and their temporal (un)predictability on behavioural capture effects, we carried out a 2 x 2 x 2 x 2 repeated-measures ANOVA on the RT spatial cueing data across the four adult experiments. We remind the reader that the following statistical effects describe results based on subtracted behavioural cueing effects. Thus, for example, a main effect of Cue Colour would now describe a two-way Cue Colour x Cue-Target Location interaction.

There was a significant main effect of Cue Colour, $F_{(1, 38)} = 340.4$, $p < 0.001$, $\eta_p^2 = 0.9$, where TCCs (42ms), but not NCCs (-1ms), elicited reliable cueing effects, reflecting overall presence of TAC. There was also a main effect of Cue Modality, $F_{(1, 38)} = 13.5$, $p = 0.001$, $\eta_p^2 = 0.3$, where visual attentional capture effects (18ms) were enhanced on audiovisual trials (23ms), thus confirming overall presence of MSE. There was also a 2-way Cue Colour x Cue Modality interaction, $F_{(1, 38)} = 6.4$, $p = 0.015$, $\eta_p^2 = 0.2$. This interaction was likely a false positive, potentially due to a fourfold increase in trial number compared to the adult control data, as the interaction was not statistically significant in either experiment individually (all F's < 3, all p's > 0.1; full results in Appendix 5). Those overall results confirmed the presence of behavioural TAC and MSE in adults.

In terms of contextual factors, although there was no significant main effect of MR ($F_{(1, 38)} = 1.9$, $p = 0.18$), there was a 2-way interaction between MR and Cue Colour, $F_{(1, 38)} = 4.5$, $p = 0.041$, $\eta_p^2 = 0.1$ (Figure 6B, middle panel). A follow-up by Cue Colour revealed that NCC distractors showed no evidence of a modulation by MR (Simultaneity vs. Congruence: -2ms vs. -0.2ms, $t_{(38)} = 1$, $p = 0.43$), but behavioural capture effects elicited by TCC distractors were significantly larger under simultaneity (45ms) than under congruence (40ms), $t_{(38)}$ = 1.9, p = 0.027. Conversely, when exploring the data as a function of MR, TCC distractors were found to elicit larger behavioural capture effects than NCC distractors, both under Simultaneity (TCCs vs. NCCs: 45ms vs. -2ms, $t_{(38)}$ = 32.5, p < 0.001) and under Congruence (TCCs vs. NCCs: 40ms vs. -0.2ms, $t_{(38)}$ = 25.6, p < 0.001). Thus, the MR x Cue Colour interaction was driven by the larger capture effects for TCC distractors under simultaneity than semantic congruence. In contrast, Cue Modality was not modulated by MR (F < 1). These results suggest that while behavioural TAC was present regardless of whether cues were imbued with semantic meaning or not, behavioural capture by goal-relevant cues was larger in the absence of a semantic relationship.

Similarly to main effect of MR, there was no main effect of DO ($F_{(1, 38)}$ = 0.3, p = 0.6) and Cue Colour was not modulated by DO ($F_{(1, 38)}$ = 2, p = 0.16), but Cue Modality was, at the level of a nonsignificant trend ($F_{(1, 38)}$ = 3.6, p = 0.07, η_p^2 = 0.1). With this, there was no evidence that behavioural TAC or MSE were modulated by DO.

The two context-based factors interacted in their modulation of behavioural capture effects, as evidenced by a 2-way interaction between MR and DO, $F_{(1, 38)}$ = 8.3, p = 0.007, η_p^2 = 0.2 (Fig. 2B, right panel). Though this interaction did not provide evidence for contextual modulation of TAC and MSE specifically, we nonetheless explored it, as its support for contextual modulation of general attentional capture was potentially informative. Thus, we first conducted a follow-up as a function of MR. These post-hoc tests revealed that, for simultaneous distractors, behavioural capture effects were larger when the onset of the distractors was unpredictable (24ms) compared to predictable (19ms), $t_{(38)}$ = 2.8, p = 0.03 (Figure 6B, right panel). In contrast, for semantically congruent distractors, there was no evidence for difference in capture effects as a function of the predictability of distractor onset (Unpredictable vs. Predictable: 18ms vs. 21ms, $t_{(38)}$ = 1.7, p = 0.1). We then followed up this interaction as a function of DO. Here, for unpredictable distractors, behavioural capture effects were larger for simultaneous distractors (24ms) than for congruent distractors (18ms), $t_{(38)}$ = 2.7, p = 0.04. In contrast, for predictable distractors, behavioural capture effects were not significantly different between simultaneous distractors (19ms) and congruent distractors (21ms), $t_{(38)}$ = 1, p = 0.3. No other interactions were reliable (all F's < 3, p's > 0.1). What these results demonstrated was that contextual factors (MR and DO) influence spatial cueing directly, such that modulations by DO are visible in the absence of a semantic relationship between the visual and auditory characteristics of the cues, and modulations by MR are visible when distractor onset cannot be predicted.

3.1.2. Error rates

Error data were, as in the Developmental Study, not normally distributed, and thus a 1-way Kruskal–Wallis H test was conducted between experiments, and Friedman tests (or Durbin tests where relevant) were conducted for each experiment separately (full results are available in Appendix 5). Overall, error rates differed significantly between experiments, $\chi^2(3)$ = 34.7, p < 0.001. Error rates were highest in Experiment 2 (6.1%), followed by

Experiment 1 (5.8%), both of which involved a purely simultaneous presentation of the visual and auditory attributes of multisensory distractors, i.e., the Simultaneity condition of MR. Next were Experiment 3 (2.6%) and Experiment 4 (2.5%), where the auditory and visual attributes were semantically congruent. Across experiments, Durbin tests revealed that error rates were modulated by Cue-Target Location, but not by Cue Colour or Cue Modality (*p*'s > 0.1). Thus, in Experiment 1, $\chi^2(1) = 6.9$, $p = 0.009$, fewer errors were made on trials where the cue and target location were the same (5.3%) than when they were different (6.3%). In Experiment 2, $\chi^2(1) = 13.9$, $p < 0.001$, again, fewer errors were made on trials where the cue and target location were the same (5.4%) than when they were different (6.8%). In Experiment 3, $\chi^2(1) = 10.4$, $p < 0.001$, as well, fewer errors were made when the cue and target location were the same (2.3%) than when they were different (3%). Finally, in Experiment 4, $\chi^2(1) = 8.3$, $p = 0.004$, fewer errors were made when the cue and target location were the same (2.3%) than when they were different (2.9%).

3.2. N2pc analyses

First, a canonical analysis of mean amplitudes of the N2pc difference between PO7/8 electrode equivalents was conducted over the 180-300ms post-cue time-window. This 2 x 2 x 2 x 2 repeated-measures ANOVA revealed a main effect of Cue Colour, $F_{(1,\ 38)} = 22$, $p < 0.001$, $\eta_p^2 = 0.4$, where the contra-ipsi difference for TCCs (-0.6μV) had a stronger negative mean amplitude than the contra-ipsi difference for NCCs (-0.1μV; Figure 13). However, and despite the presence of overall behavioural MSE effects, mean N2pcs found for visual trials (0.4μV) were not reliably different on audiovisual trials (0.3μV), with no evidence for a main effect of Cue Modality, $F_{(1,\ 38)} = 0.7$, $p = 0.4$, (Figure 13, leftward and rightward panels, respectively). Other main effects and interactions failed to reach statistical significance (all *F*'s < 3, *p*'s > 0.1; full results in Appendix 6). As in previous Developmental analyses, there was only evidence for TAC but not for MSE in N2pc. Further, these results showed no evidence for any contextual modulations of lateralised ERPs directly, or of the TAC observed in N2pc.

Next, in order to ascertain whether the lack of contextual effects above was due to canonical N2pc analyses being suboptimal for capturing such effects, the cluster-based electrode analyses was performed. Here, as in the canonical analysis above, a 2 x 2 x 2 x 2 repeated-measures ANOVA revealed a main effect of Cue Colour, $F_{(1,\ 38)} = 5.5$, $p = 0.03$, $\eta_p^2 = 0.1$, which was, again, driven by a stronger mean amplitude of contra-ipsi difference for TCCs (-0.08μV) than for NCCs (-0.02μV). There was, again, no significant main effect of Cue Modality, and no other main effects or interactions were significant, including the main effects of MR or DO (*F*'s < 3, *p*'s > 0.08) or any interactions between these two factors and any other factors (all *F*'s < 1; full results in Appendix 6). These results support the presence of TAC in N2pcs, albeit the difference now was more positive for TCCs than NCCs. and the lack of evidence for either MSE or contextual modulations of attentional control mechanisms in lateralised ERPs directly, or of the TAC observed in N2pc. Since this pattern of results replicated across the canonical and cluster-based approach, it is less likely that the results are a product of inappropriate analysis parameters, but rather a genuine effect.

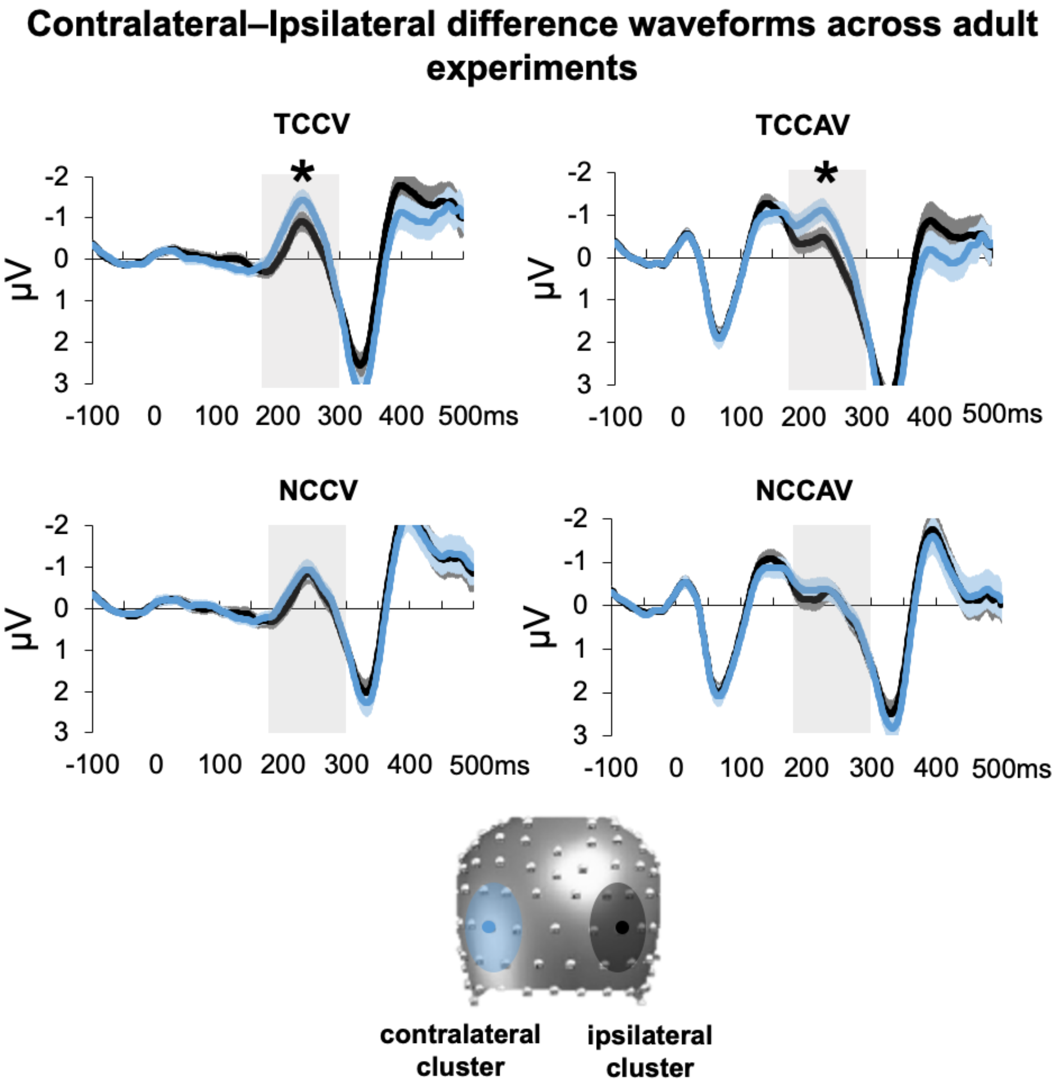


Figure 13. Overall contra- and ipsilateral ERP waveforms representing a mean amplitude over electrode clusters (plotted on the head model at the bottom of the figure in blue and black), separately for each of the 4experimental conditions (Cue Colour x Cue Modality), averaged across all 4 adult experiments. The N2pc time-window of 180-300ms is highlighted in grey, and significant contra-ipsi differences are marked with an asterisk (p < 0.05). As in the Developmental study, only the TCC distractors elicited statistically significant contra-ipsi differences.

3.3. Electrical neuroimaging analyses

3.3.1. Developmental analogue analysis – contextual factors modulating lateralised ERP mechanisms over the canonical N2pc time-window

3.3.1.1. GFP. Analogously with the Developmental study design, we investigated whether response strength differences governed the modulations of cue-elicited lateralised ERPs by contextual factors in adults, by conducting a 2 x 2 x 2 x 2 repeated-measures ANOVA on average GFP values over the canonical N2pc time-window. The ANOVA revealed a main effect of Cue Colour, $F_{(1, 38)} = 10.2$, $p = 0.003$, $\eta_p^2 = 0.2$, such that GFP was larger for TCC cues (0.6µV) than for NCC cues (0.5µV). However, main effect of Cue Modality was not significant, $F_{(1, 38)} = 0.1$, $p = 0.8$. No other main effects of interactions reached statistical significance (all *F*'s < 1; full results in Appendix 7).

3.3.1.2. ERP Topography. Next, to investigate whether network-based differences governed modulations of cue-elicited lateralised ERPs by contextual factors, a segmentation was conducted over the *entire* post-cue time-period. The segmentation revealed that across the 4 experiments, 13 clusters explained 75.4% of GEV in the group-averaged difference ERPs. Over the canonical N2pc time-window, there were 3 template maps. To differentiate the maps obtained as part of this analysis from maps obtained from the adult control data as part of the Developmental study, we added a prefix 'A' for 'Adult study' before each map's respective number.

The 2 x 2 x 2 x 2 x 3 repeated-measures ANOVA on map presence over the N2pc time-window revealed a main effect of Map, $F_{(1.6, 61.4)} = 54.7$, $p < 0.001$, $\eta_p^2 = 0.6$ where MapA3 predominated the time-window. Map presence was modulated by the colour of the cue, as evidenced by a 2-way Map x Cue Colour interaction, $F_{(1.5, 58.4)} = 5.4$, $p = 0.02$, $\eta_p^2 = 0.1$. Following up the interaction by Cue Colour revealed that MapA2 was present longer for TCC (25ms) than NCC distractors (14ms), $t = 3$, $p = 0.01$, and MapA1 was present shorter for TCC (40ms) than NCC distractors (52ms), $t = 3.1$, $p = 0.01$. When the data were analysed as a function of Map, MapA2 was found to last shorter than other maps for both TCC and NCC distractors. Specifically, for TCC distractors, MapA2 (25ms) was shorter than MapA1 (41ms), $t_{(38)} = 3.3$, $p = 0.008$, and than MapA3 (56ms), $t = 3.2$, $p < 0.001$. Similarly, for NCC distractors, MapA2 (14ms) was also shorter than MapA1 (52ms), $t_{(38)} = 5$, $p < 0.001$, and than MapA3 (56ms), $t_{(38)} = 8.7$, $p < 0.001$. In contrast with the Developmental results, here, map presence was not modulated by the presence of sound, as demonstrated by a nonsignificant main effect of Cue Modality, $F_{(1.7, 63.9)} = 0.7$, $p = 0.5$. These results supported the existence of TAC in adults, driven by modulations of MapA1 which was more implicated in the processing of NCC distractors, and by modulations of MapA2 which was more implicated in the processing of NCC distractors. However, there was no evidence for MSE in ERP topography.

Durations of lateralised maps across the 4 experiments were also modulated by contextual factors. MR did not modulate map presence, as there was no evidence for a 2-way Map x MR interaction ($F_{(1.5, 55)} < 0.01$, $p = 1$). However, DO did modulate Map, $F_{(1.8, 67.7)} = 5.9$, $p = 0.006$, $\eta_p^2 = 0.1$. A follow-up as a function of DO revealed that MapA2 was present longer for Unpredictable cues (22ms) than for Predictable cues (17ms), $t_{(38)} = 2.1$, $p = 0.01$, while MapA3 was present longer for Predictable cues (60ms) than for Unpredictable cues (52ms), $t_{(38)} = 3.4$, $p = 0.006$. A follow-up as a function of Map revealed that MapA2 was shorter than the other two maps both for Predictable and Unpredictable cues. Specifically, for Unpredictable cues, MapA2 (22ms) was shorter than MapA1 (48ms), $t_{(38)} = 6.3$, $p < 0.001$, and than MapA3 (52ms), $t = 7.4$, $p < 0.001$. Meanwhile for Predictable cues, MapA2 (17ms) was also shorter than MapA1 (45ms), $t_{(38)} = 6.8$, $p < 0.001$, and than MapA3 (60ms), $t_{(38)} = 10.4$, $p < 0.001$. These results demonstrated that DO influenced attentional capture directly, such that MapA2 was more implicated in the processing of Unpredictable cues, and MapA3 was more implicated in the processing of Predictable cues. Meanwhile, the mechanism that characterised both the processing of Predictable and Unpredictable cues was the preferential involvement of MapA2.

Next, MR and DO jointly modulated map presence, as evidenced by the 3-way interaction between MR, DO, and Map, $F_{(1.3,\ 49)} = 5.4$, $p = 0.02$, $\eta_p^2 = 0.1$. We first followed up this interaction a function of MR. Here, under Simultaneity, MapA1 was present longer for Unpredictable (53ms) than for Predictable cues (42ms), $t_{(38)} = 2.4$, $p = 0.007$, and MapA3 was present longer for Predictable (63ms) than for Unpredictable cues (49ms), $t_{(38)} = 3.5$, $p = 0.009$. Meanwhile, under Congruence, it was MapA2 that was present longer for Unpredictable (24ms) than for Predictable cues (14ms), $t_{(38)} = 2.6$, $p = 0.001$. We then analysed this interaction as a function of DO. Here, for Unpredictable cues, MapA1 was present longer under Simultaneity (53ms) than Congruence (39ms), $t_{(38)} = 2.4$, $p = 0.02$. For Predictable cues, on the other hand, MapA1 was present longer under Congruence (50ms) than Simultaneity (42ms), $t_{(38)} = 2.5$, $p = 0.03$ (Full results are available in Table A.20, Appendix 7). These results demonstrated that the two contextual factors interacted to influence attentional capture in ERP topography and did so independently of TAC or MSE.

No other main effects (F's < 1) or interactions reached statistical significance (all F's < 1, p's > 0.1, except MR x Cue Modality x Map, $F_{(1.7,\ 64)} = 1.3$, $p = 0.3$, and MR x DO x Cue Modality x Map, $F_{(1.7,\ 64)} = 2$, $p = 0.2$). However, the 4-way interaction of MR x DO x Cue Colour x Map reached the level of a nonsignificant trend ($F_{(1.5,\ 55.8)} = 3$, $p = 0.06$, $\eta_p^2 = 0.1$). Thus, there was no evidence for the two contextual factors modulating the TAC or the MSE. In fact, this could be concluded from all of the analyses up until this point. What the current EEG analyses could not investigate, however, was whether modulations of TAC and MSE by contextual factors transpired through nonlateralized effects and may thus have only partially been captured by the present, lateralised analyses. This possibility was addressed in the following, exploratory, set of analyses that investigated nonlateralized ERPs.

3.3.2. Exploratory adult analysis - contextual factors modulating lateralised and non-lateralised ERP mechanisms

In the exploratory analysis described here, we probed whether our contextual factors of interest modulated nonlateralized difference ERPs which indexed the enhancement of visual attentional control by sound presence. We remind the reader that unlike in previous analyses, these difference ERPs reflected the difference between TCCAV and NCCAV conditions (D_{AV} condition of the factor Target Difference), and between TCCV and NCCV conditions (D_V condition of the factor Target Difference).

3.3.2.1. Whole-montage voltage-based analyses. For this analysis, we first conducted a 2 x 2 x 2 repeated-measures ANOVA on voltage amplitudes in the difference ERP data, millisecond-by-millisecond, over the entire post-cue period. The ANOVA revealed a main effect of Target Difference, at 53 – 99ms and 141 – 179ms, where voltages were larger for D_{AV} (TCCAV – NCCAV difference) than for D_V (TCCV – NCCV difference) at both time-periods (all *p*'s < 0.05). In terms of the contextual factors, there was also a significant main effect of MR at 140 – 162ms, such that voltage amplitudes were higher under Congruence than under Simultaneity (all *p*'s < 0.05). There was no significant main effect of DO, as the data did not meet the temporal criterion of $p < 0.05$ at any timepoint. Further, Target Difference was modulated by the semantic relationship between the visual characteristics of the cue and its accompanying sound, as evidenced by a 2-way interaction between Target Difference and MR, at the following timepoints: 65 – 103ms, 143 – 171ms, and 194 – 221ms (all *p*'s < 0.05). The interaction was followed up as a function of MR. For semantically congruent distractors, significantly larger ERP amplitudes were observed for D_{AV} than for D_V at 48 – 97ms, 137 – 182ms, and 191 – 231ms (all *p*'s < 0.05; Figure 15C). There were no significant differences between the levels of Target Difference observed for Simultaneity. Other interactions failed to meet either the spatial or temporal criteria for significance, or both. These results suggest that target distinctiveness across V and AV cues, modulations of this target distinctiveness by MR, and a direct influence of MR on attentional capture are all observable in nonlateralized voltage data. We note, however, that voltage analyses were included more to provide a sense of the ERP components at the latency of our observed effects, and to link the present results with the existing literature. We focus a larger part of our descriptions of the results on the analysis of the GFP and topographic differences elicited by V and AV cues as a function of contextual factors.

3.3.2.2. GFP. A 2 x 2 x 2 repeated-measures ANOVA was conducted on GFP values over the entire post-cue period in a millisecond-by-millisecond fashion. This ANOVA showed significant main effects of Target Difference at 19 – 213ms, 221 – 255ms, and 275 – 290ms, where GFP was larger for D_{AV} than D_V across time-periods (all *p*'s < 0.05). There was also a significant main effect of MR at the following timeframes: 23 – 180ms, 188 – 234ms, 242 – 261ms, where GFP was larger for Simultaneity than for Congruence across time-periods (all *p*'s < 0.05). The main effect of DO was also significant, at the following timeframes: 13 – 34ms, 97 – 118ms, 304 – 335ms, where GFP was larger for Unpredictable than Predictable cues for all but the middle time-period, where Predictable cues had a larger GFP than Unpredictable cues (all *p*'s < 0.05). We would like to note that GFP modulations by all three factors spanned the canonical N2pc time-window. These results showed that target distinctiveness across V and AV cues was present in GFP, as were direct effects of both contextual factors.

The target distinctiveness across V and AV cues was further modulated by both contextual factors – MR and DV. First, we detail the 2-way Target Difference x MR interaction, which spanned a large part of the post-cue time period (23 – 255ms). We followed up the interaction by MR, as the interest was to investigate how contextual factors modulate Target Difference. For semantically congruent distractors, significantly larger GFP amplitudes were observed for D_{AV} than for D_V over 11 – 255ms ($p < 0.05$). In contrast, for simultaneous distractors, no significant differences between the levels of Target Difference were observed. Further, the Target Difference x DO interaction was significant at 88 – 127, and we followed it up as a function of DO. For both Unpredictable and Predictable distractors, significantly larger GFP amplitudes were observed for D_{AV} than for $D_{V,}$ but at different latencies (Unpredictable: 8 – 102ms and 118 – 210ms, Predictable: 10 – 211ms and 226 – 252ms; all *p's* < 0.05). These results demonstrated that the target distinctiveness across V and AV cues observed in GFP was modulated by both contextual factors such that D_{AV} exhibited larger GFP than D_V for semantically congruent cues, and regardless of distractor onset predictability.

Notably, also the MR and DO interacted independently of the target distinctiveness, and did so at 168 – 193ms, and 212 – 251ms. We first followed up the interaction by MR. Here, for simultaneous distractors, larger GFP amplitudes were observed for Predictable than Unpredictable distractors over 140-300ms ($p < 0.05$)., Now for congruent distractors, GFP was comparable between the levels of DO. We next followed up the interaction by DO. Here, there were no differences between the levels of MR for Unpredictable distractors, whereas for Predictable distractors, larger GFP amplitudes were observed for simultaneous than congruent distractors over 10-228ms ($p < 0.05$). These results support the notion that contextual factors MR and DO influence attentional capture directly. Further, the results show a joint influence of contextual factors, where it appears that the influence of DO is observable only in the absence of semantic congruence, but also that the influence of MR is observable only when stimulus onset is predictable.

Finally, MR, DO, and Target Difference all interacted jointly, and did do at 102 – 124ms and 234 – 249ms. Following the behavioural results that attentional capture was modulated by DO under Simultaneity but not Congruence, for a post-hoc analysis of the present 3-way interaction, we analysed the data as a function of MR. First, a post-hoc 2 x 2 ANOVA on the Simultaneity data revealed that there were significant main effects of DO at 46 – 118ms, 168 – 252ms, and 302 – 350ms, where GFP was larger for Predictable than Unpredictable stimuli across time-periods (all *p*'s < 0.05). There was also a main effect of Target Difference at 165 – 182ms, where GFP was larger for D_{AV} than for D_V ($p < 0.05$). Finally, there was a significant interaction between DO and Target Difference at 89 – 130ms. Upon following up the interaction, it was revealed that when cue onset was predictable, GFP amplitudes were larger for D_{AV} than D_V, with this enlargement transpiring across 74 – 154ms and 168 – 186ms (*p's* < 0.05; Figure 14A, top panel). No significant differences between the levels of Target Difference were observed for unpredictable onsets (Figure 14B, top panel). A separate post-hoc 2 x 2 ANOVA for the Congruence data demonstrated only a significant main effect of Target Difference throughout most of the post-cue period, i.e., 13 – 258ms, where D_{AV} evoked a significantly larger GFP amplitude than D_V ($p < 0.05$; Figure 14A). No other main effects or interactions were observed.

The results of the 3-way interaction provided nuance to the GFP results by shedding light on the nature of the modulation of contextual factors on the enhancement of visual attentional control by sound presence. Namely, these results suggest that in the absence of semantic relationship between the visual and auditory features of the cues, the predictability of cue onset modulated Target Difference. Meanwhile, when the visual and auditory features of the cues are semantically congruent, this semantic effect seemed to obscure if not eradicate any effects of onset predictability, directly modulating Target Difference.

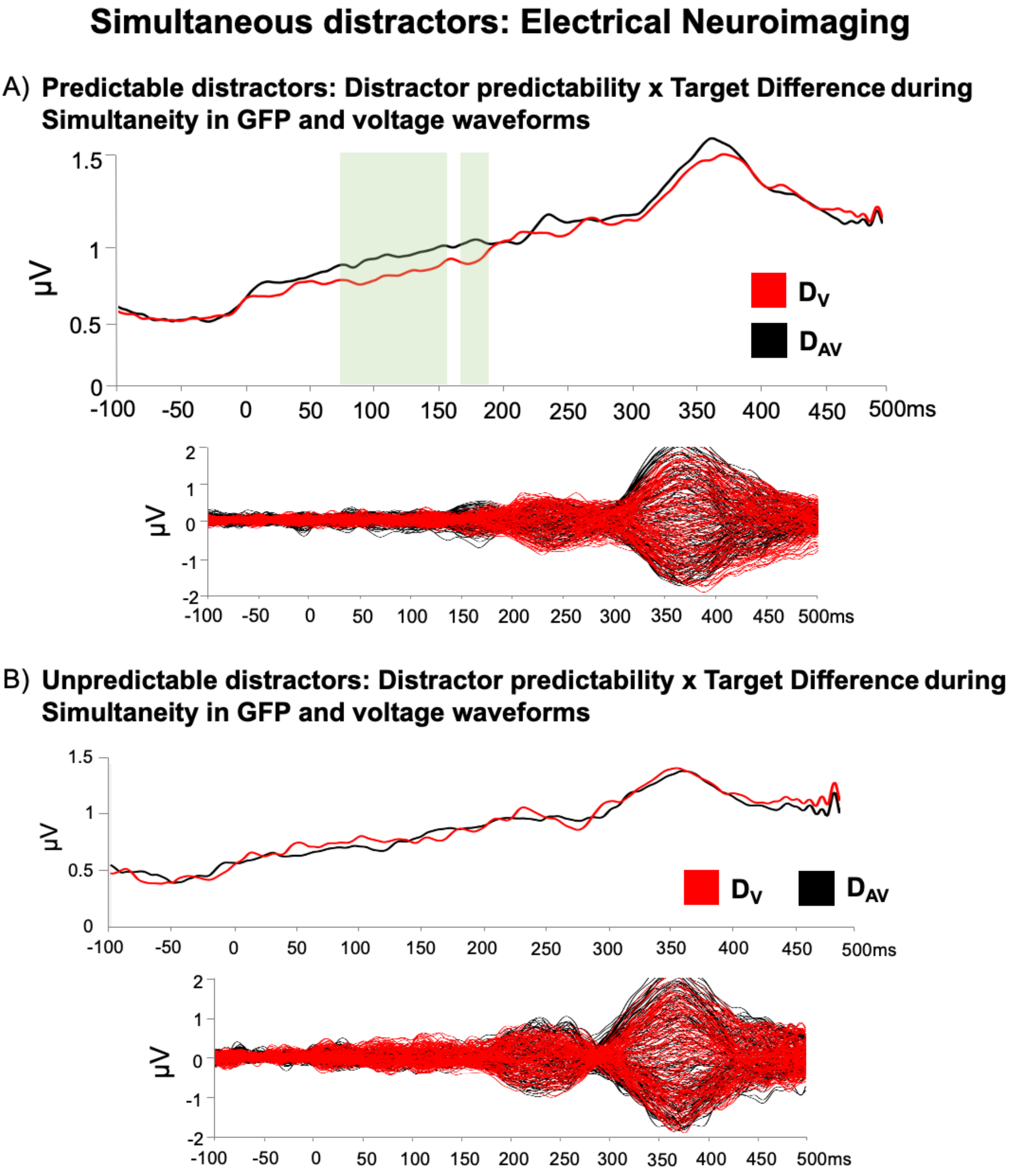


Figure 14. GFP and voltage differences between the levels of Target Difference (denoted in red and black, per the legend) for simultaneous distractors, split into Predictable and Unpredictable distractors. The figure depicts a post-hoc exploration of the MR x DO x Target Difference interaction, specifically for Simultaneous

distractors, split by the two levels of DO (Predictable and Unpredictable). A) For Predictable distractors, D_{TAV} evoked significantly larger ERP amplitudes than D_{TV} in the GFP, while no such increases were observed in the voltage data. The time-periods during which there were significant differences are highlighted in light green. B) For Unpredictable distractors, there were no differences across the levels of Target Difference in the GFP or voltage data.

3.3.2.3. ERP Topography in the canonical N2pc time-window. As part of exploratory topographic analyses, the segmentation of the post-cue period across the 4 experiments revealed 8 clusters which explained 79.4% of the GEV in the group-averaged ERPs. In order to provide a bridge between exploratory adult topographical analyses and the majority of topographical analyses in the present thesis that focused on the canonical N2pc time-window, the data were first fitted over the canonical N2pc time-window (180-300ms). Over this time-window, 4 template maps were found. To differentiate, again, the maps obtained here from those obtained in all of the previous topographical analyses, we will add a prefix 'AA' in front of every map's number. A 2 x 2 x 2 x 4 repeated-measures ANOVA on map presence revealed a significant main effect of Map, $F_{(2.4,\ 90.5)} = 19.7$, $p < 0.001$, $\eta_p^2 = 0.34$, where MapAA4 was present the longest. There was no evidence that Map presence over the N2pc time-window was modulated by the relationship between the visual characteristics of the distractors and their accompanying sounds (MR x Map 2-way interaction, $F_{(2.1,\ 78.2)} = 1.4$, $p = 0.3$), or by the predictability of distractor onset (DO x Map 2-way interaction, $F_{(2.9,\ 109.2)} = 1.2$, $p = 0.3$), or by target distinctiveness across V and AV cues (Target Difference x Map 2-way interaction, $F_{(2.1,\ 80)} = 2.3$, $p = 0.1$). This result appeared to suggest no evidence for target distinctiveness across V and AV cues, or direct effects of contextual factors on attentional capture.

However, MR and DO jointly modulated map presence over the N2pc time-window, as evidenced by a 3-way interaction between Map, MR, and DO, $F_{(2.3,\ 87.5)} = 3.1$, $p = 0.04$, $\eta_p^2 = 0.08$. A follow-up of this interaction by MR revealed that, under Simultaneity, only MapAA4 was longer for Unpredictable (54ms) than Predictable cues (37ms), $t_{(38)} = 3.4$, $p = 0.005$, while under Congruence, all map duration differences were comparable (all *p's* > 0.1). Next, a follow-up by DO revealed that, for Unpredictable cues, only MapAA3 was shorter for simultaneous (31ms) than congruent distractors (45ms), $t_{(38)} = 2.7$, $p = 0.03$, while for Predictable cues, all map duration differences were comparable (all *p's* > 0.1; full results in Table A.21, Appendix 8). The three-way interaction between Target Difference, MR, and DO was also significant, $F_{(2.3,\ 87.5)} = 110.8$, $p < 0.001$, $\eta_p^2 = 0.75$. However, post-hoc tests on this interaction showed no significant differences, regardless of whether the data were split by Target Difference, MR, or DO (all *F*'s < 0.01, *p*'s = 1), likely due to the nonsignificant main effects of the factors involved in the interaction (all *F*'s < 0.01, *p*'s = 1). It thus appeared that there was evidence for direct effects of contextual factors on attentional capture after all, where the two contextual factors acted in concert to influence ERP-topography mechanism governing attentional capture .

Importantly, the 3-way interaction between Target Difference, Map, and MR was significant, $F_{(2.4,\ 89.2)} = 4.85$, $p = 0.007$, $\eta_p^2 = 0.113$. A follow-up by MR revealed that map presence did not differ between the levels of Target Difference for simultaneous distractors (all *p's* > 0.1). However, for congruent distractors, MapAA4 was longer for D_{AV} (56ms) than D_V (36ms), $t_{(38)} = 3.9$, $p = 0.007$, and MapAA3 was shorter for D_{AV} (50ms) than D_V (34ms), $t_{(38)} = 3$, $p = 0.02$. Next, a follow-up by Target Difference revealed that for the D_{AV} condition, MapAA1 was longer for simultaneous (16ms) than congruent distractors (10ms), $t_{(38)} = 1.4$, $p = 0.04$, and conversely, MapAA4 was shorter for simultaneous (45ms) than congruent distractors (56ms), $t_{(38)} = 2.4$, $p = 0.02$. Meanwhile for the D_V condition, only MapAA3 was shorter for simultaneous (35ms) than congruent distractors (50ms), $t_{(38)} = 3.2$, $p = 0.01$. These results demonstrated that MR modulated target distinctiveness across V and AV cues in topography, such that for Congruent distractors, MapAA4 was more implicated in proceeding D_{AV} and MapAA3 was more implicated in processing $D_{V,}$ while all maps were equally involved for processing D_{AV} and D_{AV} for Simultaneous distractors. Further, the mechanism that governed the processing of D_{AV} was MapAA1 for simultaneous distractors, and MapAA4 for congruent distractors, while the processing of D_V was governed by MapAA3.

No other significant main effects or interactions were detected (all *F*'s < 1), including the three-way interaction between DO, Target Difference, and Map ($F_{(2.7,\ 101.3)} = 0.2$, $p = 0.9$) or the four-way interaction between MR, DO, Target Difference, and Map ($F_{(2.4,\ 90)} = 0.3$, $p = 0.8$; full results in Appendix 8). While MR modulated the target distinctiveness across V and AV cues in topography, there was no evidence for such modulations by DO in topography, despite evidence for such in GFP. This suggests that while a network-based mechanism may be orchestrating the modulation of attentional control by MR, a strength-based mechanism may be underlying the modulation of attentional control by DO.

3.3.2.3. ERP Topography in non-N2pc time-windows identified GFP. Post-hoc analyses on the 3-way interaction of MR, DO, and Target Difference in GFP revealed an interesting pattern of results. It appeared that under Congruence, there was a main effect of Target Difference throughout most of the post-cue period, arranged into three successive 'peaks' at 13-106ms, 107-184ms, and 185-275ms (similar pattern in voltage as well, see Figure 15, panels A and C). However, under Simultaneity, this effect of Target Difference was additionally modulated by DO in two time-windows (74 – 154ms and 168 – 186ms). Thus, the GFP results seemed to suggest that DO modulates Target Difference when the visual and auditory features of the cues are merely simultaneously presented. But, when these features are semantically congruent, the modulation of DO is no longer visible, and semantic congruence seems to 'takes over' and modulates Target Difference directly. We were curious as to whether topographical analyses could substantiate these conclusions, while also investigating whether differences in underlying brain generators drove the above effects. Thus, we conducted topographical analyses in the above five time-windows.

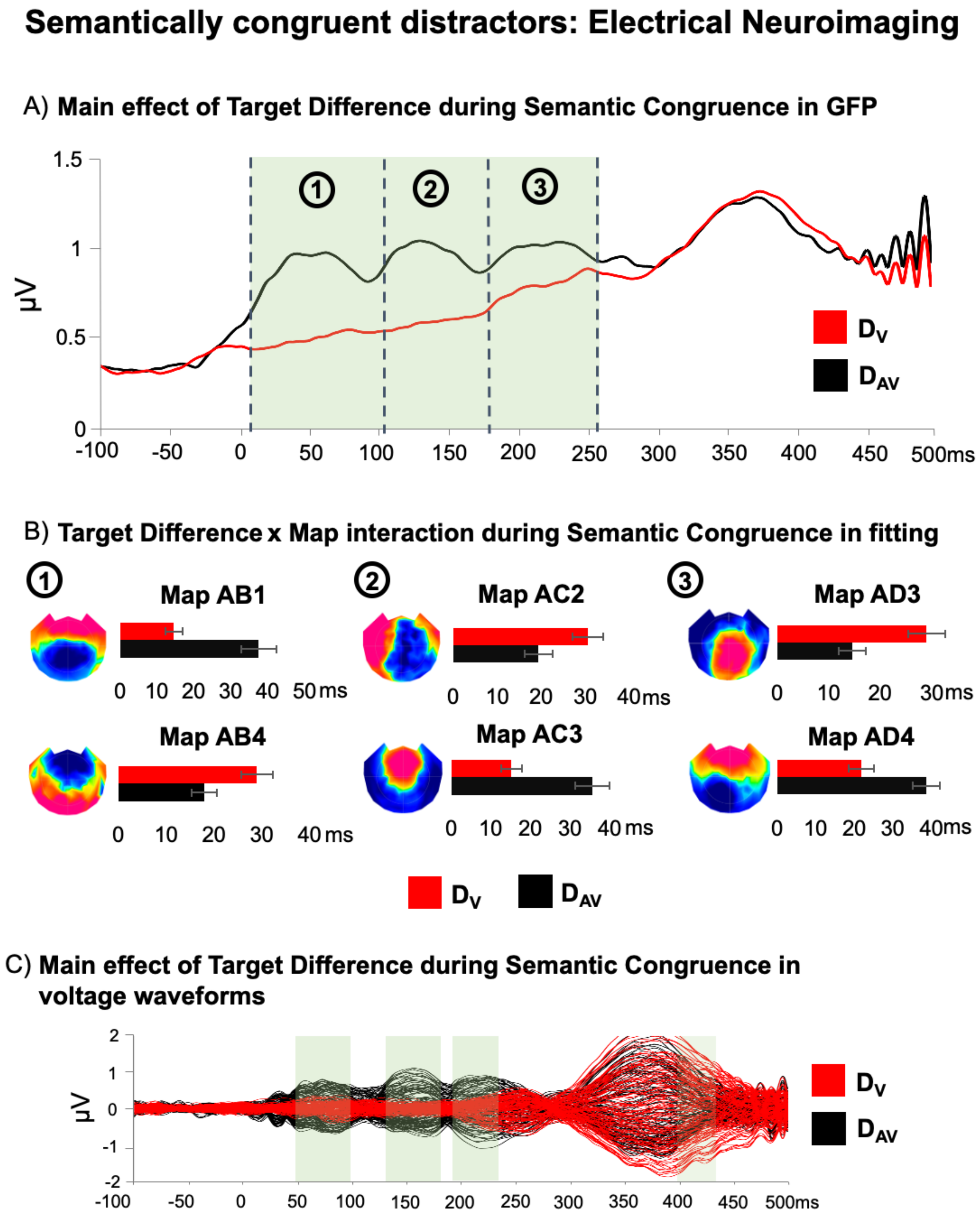
For the sake of brevity, and because of the distinct interests that guided these analyses, we will only report results, including post-hoc follow-up analysis results, that pertained to these interests. Specifically, for the periods in which there was a main effect of

Target Difference under Congruence (13-106ms, 107-184ms, and 185-275ms), the result of interest was Target Difference x Map x MR. Here, post-hoc analyses were conducted as a function of MR only, in order to investigate whether modulations by Target Difference differed between the levels of MR in topography as they did in GFP. For the periods in which DO modulated Target Difference under Simultaneity (74 – 154ms and 168 – 186ms), the result of interest was Target Difference x Map x MR x DO. Again, post-hoc analyses were conducted as a function of MR only, in order to explore whether DO modulations of Target Difference differed between the levels of MR in topography as they did in GFP. However, full results are available in Appendix 8.

To foreshadow our findings, the first set of results demonstrates that across each of the first three time-windows (13-106ms, 107-184ms, and 185-275ms), topographical map presence differences by the levels of Target Difference were only observable under Congruence. This supports the conclusion from the GFP results, that semantic congruence directly modulates Target Difference. Moreover, these results also showed that the modulation of Target Difference under congruence was orchestrated by different sets of networks for each time period, but in each, one map was preferentially involved in processing D_{AV}, and another in processing D_V. A segmentation over the entire post-cue period was conducted, revealing 8 clusters which explained 79.4% of the GEV. Next, fitting was conducted over the time-periods of interest. In the first time-period (13-106ms), 6 template maps were found. A 2 x 2 x 2 x 6 repeated-measures ANOVA revealed a significant 3-way interaction between Target Difference, Map, and MR, $F_{(3.2,\ 122)} = 5.6$, $p = 0.001$, $\eta_p^2 = 0.1$. For Simultaneity, all map duration differences between D_{AV} and D_V were comparable (all *p's* > 0.1). Meanwhile, under Congruence, MapAB1 was present longer for D_{AV} (38ms) compared to D_V (15ms), $t_{(38)} = 6$, $p < 0.001$ (Figure 15B left panel), and MapAB4 was shorter for D_{AV} (18ms) compared to D_V (29ms), $t_{(38)} = 2.9$, $p = 0.01$ (Figure 15B left panel). The second time-period (107-184ms) was characterised by 4 maps. A 2 x 2 x 2 x 4 repeated-measures ANOVA revealed a 3-way interaction between Target Difference, Map, and MR, $F_{(2.4,\ 90)} = 3.6$, $p = 0.03$, $\eta_p^2 = 0.1$. For Simultaneity, all map duration differences between D_{AV} and D_V were comparable (all *p's* > 0.1). Under Congruence, however, MapAC2 was shorter for D_{AV} (19ms) than D_V (31ms), $t = 2.7$, $p = 0.01$ (Figure 15B middle panel), and MapAC3 was longer for D_{AV} (36ms) than D_V (15ms), $t = 4.9$, $p < 0.001$ (Figure 15B middle panel). The third time-period (185-275ms) was also characterised by 4 maps. As in the first two time-periods, a 2 x 2 x 2 x 4 repeated-measures ANOVA detected a significant 3-way interaction between Target Difference, Map, and MR, $F_{(2.4,\ 90.9)} = 7.8$, $p < 0.001$, $\eta_p^2 = 0.2$. For Simultaneity, all map duration differences were comparable (all *p's* > 0.1). For Congruence, MapAD4 was longer for D_{AV} (39ms) than D_V (22ms), $t = 4.8$, $p < 0.001$ (Figure 15B right panel), and MapAD3 was shorter for D_{AV} (15ms) than D_V (29ms), $t = 4.1$, $p = 0.006$ (Figure 15B right panel).

Foreshadowing our results again, it appeared that DO modulations of Target Difference were driven by a purely strength-based mechanism, as evidenced by GFP, as there was no evidence for the topographical modulations of interest. In the fourth, 74-

154ms time-period, 7 template maps were found. However, the 2 x 2 x 2 x 7 repeated-measures ANOVA did not reveal evidence for a 4-way interaction of Target Difference x Map x MR x DO (F < 1). In the fifth, and last time-window (168-186ms) where there were 5 template maps, a 2 x 2 x 2 x 5 repeated-measures ANOVA showed a 4-way interaction of Target Difference x Map x MR x DO, $F_{(4,\ 152)} = 2.5$, $p = 0.04$, $\eta_p^2 = 0.1$. This interaction was followed up by splitting the data as a function of MR and conducting two post-hoc ANOVAs. First, a post-hoc 2 x 2 x 5 repeated-measures ANOVA on the Simultaneity data revealed a main effect of Map, $F_{(4,\ 152)} = 3.1$, $p = 0.02$, $\eta_p^2 = 0.1$, but no other significant main effects or interactions (all F's < 1), including the interaction of interest, Target Difference x Map x DO ($F = 1.7$, $p = 0.2$). A separate post-hoc 2 x 2 x 5 repeated-measures ANOVA on the Congruence data again revealed a main effect of Map, $F_{(3.2,\ 120)} = 8.6$, $p < 0.001$, $\eta_p^2 = 0.2$, as well as a significant two-way interaction between Target Difference and Map, $F_{(3.1,\ 118.3)} = 3$, $p = 0.03$, $\eta_p^2 = 0.7$ (full results in Table A.33, Appendix 8). There were no other significant main effects or interactions (all F's < 1), including the interaction of interest, Target Difference x Map x DO ($F = 0.9$, $p = 0.5$). In the latter two analyses, there was not enough evidence to support that DO modulations of Target Difference would be observable under Simultaneity in topography, as they were in GFP. This is because, in the first time-window, the 4-way analysis was not significant, and in the second time-window, there was no evidence for a Target Difference x Map x DO interaction under Simultaneity, or under Congruence, for that matter.



Semantically congruent distractors: Electrical Neuroimaging

A) Main effect of Target Difference during Semantic Congruence in GFP

B) Target Difference x Map interaction during Semantic Congruence in fitting

C) Main effect of Target Difference during Semantic Congruence in voltage waveforms

Figure 15. Differences in GFP, topography, and voltage waveforms between the levels of Target Difference (denoted in red and black, per the legend) for Congruent distractors. This figure illustrates the post-hoc exploration of the Target Difference x MR interaction, specifically for Congruent distractors. A) In GFP, there were three time-periods (marked with 1, 2, and 3) over which D_{AV} evoked larger ERP amplitudes than D_V (highlighted in light green). B) The differences in scalp topography between the levels of Target Difference during the above time-points are shown. Bars denote durations of each map, presented to their left, in milliseconds. C) Voltage results echo the GFP results, showing that ERP amplitudes are significantly larger for D_{AV} than for D_V across the highlighted timepoints.

Chapter 4: Discussion

Real-world settings, including learning environments like school classrooms, are cluttered with competing information, and necessitate effective control over selective attention in order to focus on relevant inputs and ignore unimportant inputs. Most of what is known about the brain and cognitive mechanisms of attentional control comes from laboratory-based paradigms that have considered individual sensory modalities in isolation. However, real-world environments provide constant inputs to multiple senses at a time, which are structured along various dimensions, including space, time, and semantic relationships. It remains unclear how such contextual factors interact with each other and the observer's goals in their guidance of attentional control over multisensory objects. Further, while there has been modest research on how adults and children differ in attentional control mechanisms engaged by purely visual (and less so, auditory) information, less is known about developmental differences in multisensory attentional control. Finally, it is not clear at all how developing visual and multisensory attentional control skills, derived more from research in adults, are related to children's learning and educational outcomes.

Over a series of studies, we aimed to provide much-needed insights into the development of neuro-cognitive mechanisms of attentional control engaged by multisensory objects in a bottom-up fashion, vis-à-vis the slightly better researched developing top-down control towards visual objects, and how such mechanisms are further influenced by contextual factors. We employed the highly process-specific Folk et al. (1992) spatial cueing paradigm and combined it with a dEEG measurement in order to derive traditional behavioural measures of attentional selection (RT spatial cueing effects) and their traditional EEG/ERP counterpart, the N2pc component. Further, multivariate electrical neuroimaging analyses were applied in order to provide insights into the neurophysiological mechanisms of visual and multisensory audiovisual attentional control in children and adults. In so doing, we clarified how children's multisensory attentional control mechanisms operate at different levels of schooling experience, and when, over the course of this experience, do attentional control processes begin to take on an adult-like form. We demonstrated some preliminary links between literacy and numeracy skills and developing attentional control over visual and multisensory objects. We also shed light on how fully developed, adult visual attentional capture is modulated by top-down factors such as colour task set, semantic meaning, predictability of stimulus onset, as well as the multisensory nature of the environment as a bottom-up factor - simultaneously, as they occur in real-world settings.

In the following sections, we recapitulate our study results and situate them in the broader research context, discuss the implications of our methodology for further research efforts and provide suggestions for future research directions while mentioning related ongoing work. We begin by discussing what the present research has found in terms of adults' visual and multisensory attentional control in real-world contexts, and how it extends existing hypotheses and theories. We next discuss our developmental results, beginning with 9- and 7-year-olds' visual and multisensory attentional control, followed by the same processes in 5-year-olds, and relate them to the existing knowledge on developing attentional control and multisensory processes. Next we discuss the potential implications of our findings for education. Finally, we touch on the suitability of our methodological approach for investigating attentional control in real-world contexts.

1. Real-world attentional control in adults

1.1. Task-set contingent attentional capture (TAC)

Our results add a strong line of support to the established view of top-down goal-relevance having priority over bottom-up stimulus salience in visual attentional control (e.g., Bacon & Egeth, 1994; Desimone & Duncan, 1995). Across nearly all of the analyses reported in the current thesis, reliable TAC was observed in adults. In behaviour, cues that matched the targets by colour elicited large behavioural attentional capture, while cues that did not match the targets by colour did not elicit behavioural attentional capture, replicating Matusz and Eimer (2011, Experiment 2). This result was observed both in the adult control sample as part of the Developmental study, and the full Adult study dataset. Further, ERPs, whether they were analysed fully canonically or using more data-driven parameters, replicated the well-established TAC effect in N2pc. That is, mean N2pc amplitudes were larger for target-matching than for non-matching distractors, replicating patterns observed elsewhere in the visual attention literature (e.g., Eimer et al., 2009, Eimer & Kiss, 2008, 2010; Kiss et al., 2008a; 2008b). Only in the adult control data was there no TAC observed in GFP, whereas in the full Adult study data, GFP was larger for target-matching than for non-matching cues over the canonical N2pc-time-window. Finally, throughout the adult data, topographical map modulations supporting the presence of TAC were observed. In adult controls, the map that dominated all of the experimental conditions was sensitive to top-down visual control, such that it was engaged for a longer period of the N2pc time-window for target matching than nonmatching cues. Notably, in the full Adult study data, there were maps that were more implicated in the processing of target matching cues and other maps that were more implicated in the processing of target nonmatching cues.

Our EN findings suggest that the enhancement of attentional capture of cues that matched the target colour, and the inhibition of cues that did not match the target colour, likely drove the TAC effect throughout the adult data. In behaviour, apart from the large capture effects for target-matching visual distractors, null or even negative capture effects were observed for nonmatching distractors. ERP topography results supported that both mechanisms were occurring simultaneously to drive TAC, instead of a mere enhancement of target-matching cues. First, in the adult controls, there were two stable patterns of EEG activity (topographical maps) that were sensitive to the cues' target-colour matching. The first map, which predominated the N2pc time-window overall, was preferentially involved in the processing of target-matching cues, while the other map was preferentially involved in the processing of nonmatching cues. In the Adult study dataset as well, there were two distinct topographical maps, where one was more involved in processing target-matching cues, and the other, nonmatching cues. The consistent finding of separable sets of spatially-selective sets of brain generators that were involved in processing target-matching and nonmatching cues, coupled with the behavioural manifestation of this activity, where target-matching cues were 'enhanced' while nonmatching cues were 'suppressed' demonstrates that alongside facilitatory processing of candidate targets there was also suppression of fully irrelevant cues. Recently, growing research interest has been afforded to inhibitory processes in visual attentional control, and many new neurocognitive models of distraction inhibition have been put forward in order to explain TAC (e.g., Gaspelin & Luck, 2019, Geng et al., 2019; van Moorselaar & Slagter, 2019, reviewed in Noonan et al. 2018). Of course, this work has not nullified the importance of target facilitation, and a possible mechanism for the latter may lie in enhanced phase coupling between frontoparietal and visual areas observable just before the N2pc (Kuo et al., 2016). Much of this work has examined facilitatory and inhibitory processes separately, and with the use of complex methods or paradigms. Though notably, in the context of the N2pc specifically, Hickey et al. (2008, 2009) decomposed the N2pc into two components – the Distractor positivity, and the Target negativity, where the former indexed distractor suppression and the latter indexed target enhancement. However, even here, such effects were established laboriously over multiple experiments. Our EN findings enrich this large literature, first, by showing that the use of EN can detect both facilitatory and inhibitory processing in the context of TAC at the same time, without the use of complex, multi-experimental setups. Over and above detecting these processes, our EN measures can demonstrate their underlying mechanism, which is the recruitment of two distinct networks of brain generators.

The EN results presented here show that the mechanisms of TAC were network-based, where different spatially-selective networks of brain generators were active for goal-relevant versus irrelevant information. In another study that combined EN with a classical N2pc measurement, Matusz et al. (2019b) also found that GFP modulations were followed by topographical modulations. With this, the evidence presented here speaks directly against the traditional gain-control mechanism of the N2pc, and of top-down visual attentional control. The latter mechanism would have been evidenced by TAC-modulated differences in GFP with no concurrent modulations in topography, which was not the case in any of our adult data. Another curious observation was that, in the adult control data at least, the topographic map that was shown to contribute to the processing of target-matching cues also predominated the N2pc time-window overall, across all experimental conditions. The pervasiveness of this 'target-matching map' could have reflected the maintenance of the attentional template containing the goal-relevant stimulus features. This stands to reason, as in a paradigm with such high top-down task demands as ours, constant maintenance of the attentional template was necessary for successful performance. Taken together, or results suggest that the classic behavioural (and N2pc) TAC effect is a product of two top-down processes generated by different sets of spatially-selective brain generators: one process is the maintenance of the attentional template in working memory, and the selection of information which matches the template, and the other process is the inhibition of fully irrelevant information that does not match the template.

1.2. TAC and the influence of contextual factors

Our results demonstrated that TAC was a robust effect which persisted despite the addition of more top-down control factors; however, it may operate independently from such factors. TAC was observed throughout behaviour, N2pc modulations, GFP, and topography, in the Adult study, which included other sources of top-down control such as the semantic relationship between the visual and auditory aspects of the cues and the predictability of cue onset. However, these contextual factors overwhelmingly modulated measures of attentional selection (behavioural attentional capture, ERP amplitudes, GFP, and topographical map presence) directly, without modulating TAC. In behaviour only did semantic meaning modulate TAC. Here, while TAC was present regardless of whether cues were imbued with semantic meaning or not, behavioural capture by goal-relevant cues was larger in the absence of a semantic relationship. This seemed to suggest that the existence of semantic relationships somehow decreased the ability of target-matching information to capture attention. However, there was no support for such or any sort of contextual modulation of goal-based top-down control from N2pc or EN measures. What this could rather suggest is that goal-relevance and contextual factors of top-down control are independent in their top-down control of attention.

The semantic meaning of distractors, and the predictability of their onsets jointly modulated spatial attention in a complex interplay. In behaviour, modulations by distractor onset were visible only the absence of a semantic relationship between the visual and auditory characteristics of the cues. Specifically, behavioural attentional capture was larger for unpredictable distractors than predictable distractors, when the visual and auditory distractor features were purely simultaneous. In topography, in such purely simultaneous conditions, one map was preferentially active for predictable distractors, and another for unpredictable distractors. These results suggested that, is that one set of spatially-selective brain generators enhanced the processing of unpredictable beep-flash distractors, while another set of generators inhibited the processing of predictable beep-flash distractors, in the service of guiding spatial attention. In turn, modulations by semantic meaning were visible only when distractor onset could not be predicted. Here, for unpredictable distractors, attentional capture was larger when distractor features were purely simultaneous than when they were semantically congruent. In topography, when distractor onset was unpredictable, there was one map that was preferentially active for simultaneous distractors over semantically congruent distractors. Based on this result, it is likely that the driver of top-down guidance over spatial attention by contextual factors was the enhancement of unpredictable beep-flash distractors by a network of spatially-selective brain generators. Our findings of enhanced processing of unpredictable stimuli, are in line with the idea that predictability decreases neural responsiveness, and by extension, behavioural performance (see e.g., Auksztulewicz & Friston, 2016). There is a large literature on the facilitatory effects on behavioural responses of temporally predictable stimuli (e.g., Ellis & Jones, 2010; Niemi & Näätänen, 1981; Ten Oever et al., 2014), but the debate surrounding the salience of predictable or unpredictable information is far from resolved (e.g., Itti & Baldi, 2006; versus Barascud et al., 2016; for reviews and possible unifying theories, see e.g., Esber & Haselgrove, 2011; Pearce & Mackintosh, 2010). With the above result, our findings provide a line of support to the growing evidence (see Southwell et al., 2017) that temporally predictable information does not preferentially capture attention. However, we note that this conclusion pertains exclusively to situations where information (here, colour cues) were not laden with semantic meaning. Since such non-semantic beep-flash stimuli are still often the norm in laboratory-based research, future research of this sort should take note, in order to preclude that effects of relevance are 'washed out' by temporal predictability effects.

The conclusion that goal-relevance on one hand, and semantic meaning and temporal predictability on the other hand, are independent mechanisms only holds in purely visual settings. In our exploratory adult EN analyses, TAC and MSE were included into a single factor which represented the enhancement of visual attentional control by sound presence. In contrast with the results reviewed above, both semantic meaning and temporal predictability modulated this factor across GFP and topography, spanning most of the post-cue period and including the N2pc time-window. We detail these modulations in more depth in Section 1.4 below, in the context of MSE. It has been suggested that studying attention in visual settings alone is not sufficient to understand how attentional control functions in the real-world (Matusz & Eimer 2011, 2013; adult work in Matusz et al., 2015, 2019a). Together with this body of work, our findings suggest that considering only the contextual modulation of visual attentional control may provide misleading conclusions as to the interplay of top-down mechanisms in real-world contexts.

1.3. Multisensory enhancement of attentional capture (MSE)

Our results jointly demonstrate that multisensory processes are able to influence visual attentional selection in a bottom-up fashion. This was first borne out by our behavioural results, where, regardless of whether cues matched the target colour or not, attentional capture was enhanced with the addition of a meaningless, spatially uninformative, co-occurring sound, replicating Matusz and Eimer (2011). Given the strong top-down attentional demands of the experimental task, the presence of behavioural MSE supported the idea put forward by Matusz and Eimer that multisensory enhancements of visual attentional capture can occur involuntarily and independently of task demands. Though there was no concurrent MSE in N2pc to support this claim, corroborating evidence came from sensitive EN topographical analyses. In the adult control data specifically, one stable pattern of spatially-selective EEG activity (template map), was found to be sensitive to the (audio)visual nature of the cues. Thus, our results appeared to support that, in settings that incorporate multisensory stimuli (like real-world settings do), bottom-up multisensory control of attention may have priority over top-down attentional control.

Interestingly, however, the topographical results suggested that the behavioural enhancement of visual attentional capture by sound presence was driven by a top-down inhibition of visual stimulus characteristics in the presence of a sound rather than a bottom-up enhancement. Namely, the topographical map that was shown to be sensitive to MSE (specifically Map2, see Figure 10) was more involved in the processing of visual cues than audiovisual cues. In other words, it appeared that the enhancement of visual attentional capture by the presence of a sound was driven by the *reduced* involvement of a given, visually-specific, set of brain generators. Alternatively, the effect could have driven by the relatively stronger involvement of the other three maps, at the expense of the more visually-involved map. However, this interpretation was discarded, as the presence of other maps was not significantly different between visual and audiovisual cues. That the above visually-involved map reflected inhibitory processing was supported by the results of the 3-way interaction in the normative adult topographical analysis. Here, not only was the map in question (Map2) more active for visual cues overall, but also, for visual cues that did not match the target colour. Behavioural, and N2pc results, as well as literature, support that the processing of target-nonmatching cues is inhibited under such strong task demands as in the current paradigm. Thus, the preferential engagement of this map for target-nonmatching cues indirectly supports its role in indexing inhibitory processing. If bottom-up multisensory enhancement of behavioural attentional control is indeed driven by a brain network that reflects top-down inhibition of visual stimulus features, that suggests a close link between top-down and bottom-up mechanisms in real-world stimulus processing. Specifically, it may suggest that the purportedly bottom-up control over multisensory stimuli may hinge on top-down inhibition of visual attentional control – at least in contexts where the task demands are purely visual. Perhaps, thus, it was the purely visual attentional template that was being momentarily inhibited, in favour of processing a unified audiovisual stimulus. More broadly, if MSE requires the inhibition of top-down control, would the lack of such inhibition, or an increase in top-down control, obscure even behavioural MSE effects?

Behavioural MSE in adults is a robust, replicable effect, as we have observed it despite changes to the original paradigm and experimental setup, and despite the fact that MSE is less forthcoming in traditional EEG/ERP measures of mean amplitude differences. Originally found in Matusz and Eimer (2011, Experiment 2), we have replicated behavioural MSE in an adaptation of their paradigm which was optimised for children, with a reduced number of elements and a game-like narrative. Behavioural MSE survived these modifications both in the adult control data, and in the larger Adult study dataset. The latter pooled data from four experiments, each with additional modifications as to the semantic meaning and temporal onset of the multisensory stimuli. However, in EEG measures, MSE may not be as consistently present. As we have mentioned, there was no MSE in N2pc. As we detail below in Section 1.5, this may have resulted from the N2pc not being ideally suited to detect audiovisual effects, or even bottom-up effects in general. However, where the normative analyses in the adult control data found MSE-sensitive topographical patterns, there was no such, or any other, modulation of topography by MSE in the full Adult study dataset. This was surprising, as the adult dataset included four times as many trials as the adult control data, and such a sheer increase in statistical power should have only amplified MSE in a measure as sensitive as topography. However, the experimental manipulations across the Adult study also engendered more factors of top-down control, including control by semantic meaning and by distractor onset alongside goal-relevance. As suggested above, this increased engagement of top-down mechanisms could have obscured MSE effects. This suggests that bottom-up enhancement of attentional capture by multisensory interactions may have priority over top-down visual attentional control by goal-relevance, but not over other top-down control factors that are determined by the context.

1.4. MSE and the influence of contextual factors

Throughout the behavioural and EEG results, we found no evidence that bottom-up multisensory control of attention was directly modulated by contextual factors. That MSE was not modulated by the semantic relationship between the visual and auditory features of the cues was especially surprising in light of evidence that contextual properties modulate multisensory processing (low-level stimulus regularities, e.g., Sarmiento et al., 2016; Retsa et al., 2019; others, more generally: van Atteveldt et al., 2014). As for the modulation of MSE by distractor onset, there was only a nonsignificant trend in behaviour. One possible explanation for such a pattern of results is that MSE only transpires in certain conditions. Since MSE was observed in the adult control data, these conditions may mean that the visual and auditory features of stimuli should be devoid of meaning and linked purely by their temporal co-occurrence, and the onset of such stimuli should not be predicted. This, however, paints a rather restricted picture of an effect that should presumably be ubiquitous in real-world multisensory environments. An alternative explanation could be that the lateralised brain measures we used here did not capture the entirety of the MSE effect in the brain. Indeed, although the visual features of the cues were presented in lateralised spatial locations, to ensure the detection of a lateralised marker of visual attentional control – the N2pc. Because the N2pc is a lateralised spatially selective ERP, its underlying brain generators were also assumed to be lateralised and spatially selective. However, this assumption may have been reductive for the brain generators underlying the enhancement of such visual attentional control by the presence of a spatially diffuse sound.

The above idea was tested in exploratory nonlateralised EN analyses, which, in brief, helped clarify the interacting influences of contextual factors on the enhancement of TAC by sound presence. Before we discuss these influences, it is important to remember that, for nonlateralized analyses, the effect of sound processing had to be subtracted out. Practically, this meant that all analyses were conducted on difference ERPs that captured the enhancement of visual attentional control by sound presence. This measure can be thought of as the product of an interaction of Cue Colour and Cue Modality – the enhancement that is afforded by matching the target by colour when cues are visual, versus the enhancement that is afforded by target colour matching when cues are audiovisual. For brevity, we will refer to this effect according to its factor name, Target Difference.

Target Difference was larger for audiovisual than visual-only enhancement when the visual and auditory features of the cues shared semantic meaning. However, when the visual and auditory features were purely simultaneous without shared meaning, Target Difference was instead modulated by the predictability of cue onset. Here, Target Difference was, again, larger for audiovisual than visual cues, but only when cue onset was predictable. This result supports that MSE only seems to occur in a specific set of conditions. This intricate pattern of results was observed across most of the post-cue time-window and was present in GFP and, for the most part, topography. Specifically, for the modulation of Target Difference under semantic congruence, in every time-period of interest, there was one topographic map that was preferentially involved in audiovisual enhancement and another map that was preferentially involved in visual-only enhancement. This meant that, under semantic congruence, the different globally-distributed brain generators were recruited for audiovisual versus visual-only enhancement of target processing. Meanwhile, the modulation of Target Difference by distractor onset under simultaneity was not reflected in changes in topographical map presence, but rather exclusively GFP. This means that, under multisensory simultaneity, and when stimulus onsets were predictable, a single globally-distributed brain generator was activated more strongly for audiovisual versus visual-only enhancement of target processing. Taken together, these results thus speak to a hierarchy of top-down control processes in real-wold settings where semantic meaning has the most priority, followed by onset predictability, in influencing the enhancement of visual attentional control by sound presence. Thus, when possible, semantic meaning will be employed to reduce attentional capture by irrelevant events.

1.5. Implications for N2pc as a marker of attentional control in real-world settings

The N2pc's status as a well-established marker of top-down visual attentional control in adult populations has been confirmed time and again in the present work. However, its suitability for indexing bottom-up non-visual processes or top-down processes that are not strictly goal-based has been challenged. Throughout the present series of studies, the classic TAC effect in adult N2pc's was persistently visible in larger mean amplitudes for target-matching than for non-matching distractors, despite changes to electrode sites, numbers, and time-window latencies. However, across these data, the N2pc failed to capture the MSE effect, as well as the effects of any contextual factors, despite such effects being detected in behaviour. Such a lack of effects held even in cases where electrode sites and time-windows for analysis were selected in a data-driven fashion, or when electrode sites were expanded to a larger cluster of electrodes. Given that the only other study of N2pc's to task-irrelevant multisensory stimuli (Van der Burg et al., 2011) presented only weak evidence for N2pc enhancements by audiovisual integration, we can conclude that the N2pc may simply not be optimised to detect bottom-up capture of attention by objects that are not purely visual. It is possible that the N2pc may not be particularly well-suited to index bottom-up control at all, in light of no evidence for an N2pc in response to salient visual distractors (Eimer et al., 2009). As such, the N2pc may be limited as a means of investigating attentional control in real-world contexts, where distracting information is not exclusively visual, and is certainly embedded in a host of contextual factors.

2. The development of attentional control in real-world-like contexts

2.1. Primary school children (7-year-olds and 9-year-olds)

2.1.1. Task-set contingent attentional capture (TAC)

Behaviourally, children as young as 6-7 (3rd grade), and children aged 8-9 (5th grade), showed adult-like magnitude of both facilitatory visual attentional control, as shown by large and reliable spatial cueing by target matching cues, and inhibitory visual attentional control, as shown by null cueing effects for target nonmatching cues. This effect held even after correcting for children's overall cognitive slowing. These results suggest that children may reach an adult-like state of visual, feature-specific attentional control the likes of TAC already at the age of 6-7. Typical development of this form of visual control may plateau around this time. Converging evidence has come from a study where participants searched large arrays of horizontal green fish for a target vertical green fish, the magnitude of attentional capture by a nontarget colour singleton fish was comparable between adults and 6-year-olds, although developmental slowing effects were not accounted for (Oh-Uchi et al. 2010). However, the sort of additional singleton paradigm that was used here could only speak to 6-year-olds attentional capture by salient stimuli, but not goal-driven control of attention, i.e., TAC. Our study, by contrast, has readily demonstrated TAC in the same age group, with the use of our adapted Folk et al. paradigm. More similarly to our paradigm, Greenaway and Plaisted (2005) conducted a replication of Folk and colleagues' original study in 11-year-olds and found that attentional capture by target matching cues was reliable. However, their participants were older, and our study found similar effects as much as 5 years younger. Finally, the study of Gaspelin et al. (2015) which was also based on Folk et al.'s paradigm found no observable capture by target matching cues in in 4-year-olds. However, since other older child groups were not included, this study could not indicate any developmental patterns of TAC over childhood that would lead up to adult TAC. By contrast, our study included three age-groups, which helped reveal when TAC emerged, and how it persisted into adulthood. With this, the current research seems to have presented the earliest behavioural evidence for goal-driven visual attentional control (at around age 6), at least within the context of research of adult attentional control, as well as (cross-sectional) evidence that this effect continues years later.

All of the above studies, including our own, investigated colour-based attentional control (or capture), but the study of Greenaway & Plaisted (2005) also involved onset-based control and suggested differences in the two processes. Across the discussed studies, the magnitude of attentional capture was five times weaker for nonmatching colour distractors than matching colour distractors, but in the study of Greenaway and Plaisted (2005), capture by a task-irrelevant onset distractor (in a colour search task) was half the size of capture by target-matching colour distractors. These results suggest that abrupt onsets, as another stimulus category postulated as particularly salient, similarly to the multisensory stimuli in our studies, may at least somewhat override top-down visual attentional control. However, since an adult control group was not included in the study of Greenaway and Plaisted (2005), it is not certain if the same distracting propensity reported in 11-year-olds persisted in adulthood.

In terms of the EEG results, there were no N2pc's detected in any of the child groups, regardless of whether literature-based, adult-data-driven, or child-data-driven parameters were used for its analysis, and despite the clear behavioural TAC effects in both 7-year-olds and 9-year-olds. For most of the normative and descriptive approaches to children's N2pc, the contralateral and ipsilateral voltage amplitudes overlapped completely. However, normative EN analyses showed that the template map that dominated the N2pc time-window and drove visual attentional control in adults was also the most dominant map across the traditional N2pc time-window in primary school children. The presence of this map was not modulated by target-colour-matching in the child groups. However, that the brain network recruitment of those child groups that showed adult-like visual attentional control in behaviour, patterned with adult network recruitment that was modulated by target-colour-matching, at least indirectly supports that the child groups in question can deploy their top-down attention in a way that could be considered adult-like.

Further, descriptive analyses, where the lateralised ERP topography of each child group was analysed independently of adults, revealed that each group's N2pc time-window was characterised by its own, distinct, set of topographical map configurations. Taking these child-data-driven maps into account helped clarify the mechanisms of both visual and multisensory attentional control in children. Where normative analyses could only show that a TAC-sensitive adult map was present, and dominant, over children's N2pc time-window, descriptive analyses revealed that in 9-year-olds, there were three maps that were sensitive to TAC, and in 7-year-olds, there was one such TAC-sensitive map. More precisely, in 9-year-olds, one map was preferentially involved in the processing of target colour matching than nonmatching cues, while two maps were more involved in the processing of target nonmatching than matching cues. In 7-year-olds, the TAC-sensitive map was more implicated in the processing of target matching than nonmatching cues. Because of the lack of comparability with adult topography, we could not be certain whether the latter map recruitment could be considered adult-like. Likewise, because only cross-sectional comparisons were used at present, we could not investigate developmental change in map patterns or recruitment, i.e., how such map patterns would become adult-like. Nonetheless, these analyses provided important evidence for a network-based mechanism that may have orchestrated behaviourally observed TAC. In 7-year-olds, increased behavioural capture by target matching over nonmatching cues may have been driven by the preferential recruitment of a TAC-sensitive map. Meanwhile in 9-year-olds, behavioural TAC may have been driven by a combination of the recruitment of three TAC-sensitive maps. However, in 9-year-olds particularly, it is unclear if behavioural TAC was driven by increased inhibition of nonmatching cues by maps that were more involved in processing such cues, or by stronger top-down control lead by a stronger activation of the map that was more involved in processing target matching cues. Indeed, the relationship between topographic map modulations and distractor processing is not clear cut. What is clear, however, is that differences in networks of brain generators, and not differences in response strength, are the mechanism that guides TAC in children. Taken together, our results behavioural and EN topographical results suggest that adult-like visual attentional control may already be present in children aged 6-7.

2.1.1. Multisensory enhancement of attentional capture (MSE)

In contrast with visually elicited attentional control effects, neither in 9-year-olds nor in 7-year-olds were there enhancements of behavioural attentional capture for audiovisual cues over visual cues. Thus, there was no evidence for MSE in behaviour. This result was somewhat surprising, given the protracted development of frontoparietal areas that would render children both weaker at top-down attentional control skills and more susceptible to distraction (e.g., Bunge et al., 2002; Casey et al., 2005; Konrad et al., 2005; Hwang et al., 2011). Another reason for the unexpectedness of such a result was that multisensory stimuli are purported to be especially salient compared to unisensory stimuli given that MSI can arise early on during information processing, in primary cortices, perhaps even before the influence of top-down control factors (see Introduction, Section 3., de Meo et al., 2015). As discussed above in relation to adults' MSE, the lack of behavioural MSE in school-aged children is not likely to stem from the high attentional demands of the paradigm. How, then, to explain our results? First, the null MSE results are consistent with other studies on the development of multisensory processing. Since the oldest children in the current study were aged 8-9, it is possible that no MSE was detected due to MSI purportedly maturing only after this age (e.g., Gori et al., 2008; 2012; Barutchu et al. 2009). This could mean that also more naturalistic functions like attentional control are not sensitive to MSI before this age. However, it is important to note that the current research did not study MSI per se, but rather crossmodal interactions between vision and audition, and there is evidence that such interactions are present from early ages even already at the age of 5 (e.g. Bahrick, 2001, Broadbent et al., 2018a). Therefore, it does not seem that undeveloped MSI was the root of our results. It is also possible that our developmental sample sizes were not sufficient to detect a reliable MSE under strong unisensory top-down attentional control. Indeed, even in adult controls, which was the largest group with the smallest variability in the Developmental study, the effect of MSE was numerically smaller than in Matusz & Eimer (2011, Experiment 2). However, it could have also been the case that the variability of MSE was too high in children, as children may have generally higher variability in cognitive responses than adults. Such variability also nullified multisensory interference effects in the highly demanding task set in Matusz et al. (2015). Alternatively, behavioural analyses may not have been sensitive enough to detect MSE in children. The null effect of behavioural MSE in children becomes less surprising if we consider that MSE was a much smaller effect than TAC even in the original adult cohort where the effect was first noted (Matusz & Eimer, 2011, Experiment 2), and in the present adult control cohort. Had our analyses stopped at behaviour, we could have concluded that multisensory-versus-unisensory nature of distracting information has no bearing on children's control of attention. However, our EN results demonstrated that children's brains were indeed responsive to this contrast, but that more sensitive measures were required in order to detect them.

EN analyses of MSE in primary school children demonstrated that children as young as 6 were sensitive to multisensory distraction, even if this did not manifest in behaviour. As the descriptive EN analyses showed, 9-year-olds had two MSE-sensitive maps, where one was preferentially recruited for visual cues and the other for audiovisual cues. Importantly, MSE-sensitive topographical maps were present even in 7-year-olds, and again, one map was preferentially recruited for visual cues and another for audiovisual cues, though these maps were not the same as in 9-year-olds. These results demonstrate that multisensory processes, even when task-irrelevant, can permeate children's goal-directed behaviour. Complementarily, normative EN analyses have suggested that 9-year-olds' MSE could be considered at an adult like level, as topographical maps that were identified in the adult lateralised EEG over the N2pc time-window were, in 9-year-olds, statistically modulated by the (audio)visual nature of the distractors. This suggested that distraction by multisensory objects activated spatially selective brain mechanisms characterising attentional capture and its control in adults, in children aged 8-9. In this way, the normative EN approach helped uncover that adult-like attentional control by multisensory objects may begin to form after four years of schooling experience (age 8). While no such pattern was observed in 7-year-olds, the evidence from descriptive analyses clearly shows that this group is sensitive to MSE, but perhaps not in an adult-like way yet. Taken together, our results demonstrate that primary school children aged 6 onwards are sensitive to MSE at the level of brain mechanisms but not behaviour. This finding is important insomuch as studies that used only behaviour measures have suggested the age at which optimal MSI (Gori et al., 2008, 2012), and even interference by multisensory objects (Matusz et al., 2015; 2019a) to be later. Our findings thus demonstrate that distraction by multisensory objects may emerge around age 6-7 and begin to resemble adult patterns around age 8-9. In a sense, these findings show that both groups of children were adult-like in that they could not help but become distracted by audiovisual distractors more than visual distractors (at least according to EN measures). With this, it seems that the propensity to be distracted by goal-irrelevant, yet salient, multisensory objects is present already since age 6, and that 6-year-olds may not be protected from multisensory distraction, as the research on interference has suggested. Finally, our results demonstrate that the use of EEG (and especially EN) measures which focus on specific brain mechanisms, and avoid confounding influences by immature motor responses, can reveal insights into the development of MSE, and the age at which it begins to take on an adult-like form.

Some questions remain. First, why were the MSE effects observed in EN not observed in behaviour? One potential answer lies in the slow development of children's motor responses, which are captured in reaction times but not EN measures. It is well documented (Kail, 1991; Kail & Ferrer, 2007) and seen in our own results, that reaction times increase from early childhood to adulthood. Reasons for this effect could be speeding of the time it takes to process stimuli, but also of the latencies between stimulus processing, retrieval of the attentional template from working memory, and executing a response based on the retrieved information. As we have seen and discussed above, MSE effects are subtle even in adults, and so in children that have longer latencies between stimulus processing and motor execution, these effects may not transpire at all. Second, is the result of such an early distraction by multisensory object the product of an integration of the auditory and visual aspects of the cues, or merely their interaction by, for example, their simultaneous presentation. Our current study design could not address this issue given that it only investigated audiovisual interactions. An auditory-only condition would need to be incorporated alongside our present visual-only and audiovisual condition in order to clarify if integration was truly taking place.

Interestingly, in primary school children, networks that responded to sound presence were also sensitive to target-colour matching, as shown by 3-way interactions. This suggests a greater interdependence of top-down and bottom-up control mechanisms, in line with the general idea that stimuli in real-world settings are structured by manifold interrelated organisation systems (Sarmiento et al., 2016; Soto-Faraco et al., 2019). There was a curious pattern of results, were template maps modulated by sound presence were present for a longer portion of the N2pc time-window when cues did not match the target by colour (except one map in 5th graders). In a similar way to the adult N2pc 3-way interaction result, this finding could suggest that the presence of TAC obscures any effects of MSE. Since MSE is presumed to be a bottom-up influence on attentional control, the priority of TAC over MSE would be in line with the established hierarchy of top-down over bottom-up control processes. Of course, replication of this effect in children would be necessary before drawing conclusions. A possible way to resolve this issue would be to investigate whether TAC and MSE effects persist in child and adult populations, when the two experimental manipulations are separate. If yes, we could be sure of at least a partial independence of these two sources of control, but if MSE disappears, for example, that could be evidence for a hierarchical structure of control factors, in multisensory like in visual contexts.

2.2. Young children at school entry (5-year-olds)

2.2.1. Task-set contingent attentional capture (TAC)

In the youngest group of 5-year-olds, behavioural results did not show reliable TAC. This result contrasts with the only other study on TAC in young children, of Gaspelin and colleagues (2015), whose data seem to point to the presence of TAC in this age group. In their study, both their RT and contingent capture ratio scores showed that children had ‘less’ top-down visual attention control than adults. However, both of these behavioural scores were larger than zero in young children and in adults, suggesting that even young children exhibited a degree of TAC, even if it was smaller than that of adults. Differences in results between their study and ours could be attributed to the subtle differences in participant age and study design, despite our use of a similar paradigm and similar data cleaning procedures. The youngest participants in our study were older (mean age: 5 years) compared to their child participants (mean age: 4.2 years), and responded faster overall, compared to their participants, as revealed by overall mean RT’s: 1309ms vs. 1727ms, respectively. Arguably, such differences should have provided evidence for TAC in our sample. However, our experimental procedure may have been more difficult, given the additional EEG recording that might have increased the overall testing time and participant discomfort. Coupled with the relatively fast paced experimental task which included fully irrelevant sound stimuli, it is possible that null TAC effects stemmed from increased difficulty/fatigue in our youngest participants. This explanation is supported by differences in error rates, were children made many more errors in our study (57%) than in Gaspelin et al.’s study (4.6%). Nevertheless, and exactly despite such potential difficulties, we managed to provide novel evidence with respect to visual attentional control in such young children. First, we demonstrated that they utilised the colour-change distractors quite reliably to orient their spatial attention, leading to substantial attentional capture effects. These effects were found despite the large variability in this age group’s RTs, which in turn may have prevented a reliable group-wide TAC from emerging. Since there were no differences by the factor of Age after correcting for overall cognitive slowing, we can conclude that spatial cueing in the youngest children was comparable to those of older children and adults. Indeed, spatial cueing capabilities may develop very early in life. A collection of studies using *Posner’s* spatial cueing paradigm have shown that even 3-month-olds can orient attention faster to cued versus uncued locations (e.g., Amso & Johnson (2008); Johnson & Tucker, 1996; Markant & Amso, 2016). However, *Folk et al.’s* spatial cueing paradigm that was used in our research engendered particularly strong demands for visual top-down control, as targets were embedded in cluttered arrays filled with equiluminant unique stimuli. Our findings therefore underscore that visuo-spatial attentional capture in cluttered, real-world like contexts, develops relatively early and before substantial schooling experience.

Crucially, EN analyses revealed that in 5-year-olds already there is nascent top-down (visual) control. Namely, descriptive EN analyses revealed that 5-year-olds’ recruitment of spatially selective patterns of EEG activity was modulated by target colour matching, and similar findings were seen in older children and adults. Specifically, two maps were preferentially recruited for target nonmatching cues, and one was recruited for target-matching cues. These results are novel insomuch as prior research, such as that of Gaspelin and colleagues, has yet to explore the neuro-cognitive mechanisms behind behavioural patterns of young children’s top-down visual control. That separable sets of brain networks are preferentially active in response to potentially goal-relevant and irrelevant information even earlier than the 5-to-7-year shift is the first finding of its kind. Indeed, most studies examining control processes during the 5-to-7-year shift have only included behavioural measures (e.g., Burrage et al., 2008; Roebers et al., 2011, with the exception of Brod et al., 2017). As our research has demonstrated, even with a rigorous process-specific paradigm, behaviour alone may not present the full picture. On the other hand, most of the neuroimaging literature on EF has not compared control over goal-relevant and irrelevant information in the same design. Perhaps this was due to the historical separation of distractor inhibition and retrieval of task goals from working memory into separate constructs in the EF framework (Bavelier & Green, 2019, Figure 1). Thus, our current findings enrich this framework by demonstrating that while the same globally distributed sets of brain networks are active during the processing of distractors, some of these networks are more involved in processing potentially goal-relevant distractors, while others for processing fully irrelevant distractors.

2.2.1. Multisensory enhancement of attentional capture (MSE)

With regards to MSE, as in older children, there was no enhancement of capture by the addition of a sound in behaviour or in N2pc. In EN measures as well, there was no observed modulation of template map duration over the N2pc time-window by the multisensory-versus-visual nature of distractors.

If anything, the addition of sound to visual distractors seemed to have a disruptive effect on ERPs overall, as shown by visually suppressed contralateral ERP responses. Most of the time, the contra- and ipsilateral voltages were overlapping, as in the older children, suggesting no presence of lateralised, spatially-selective brain responses in any of the child age groups. But in some distractor conditions in 5-year-olds, the contralateral voltage seemed more positive than the ipsilateral one, akin to a distractor positivity (Pd; Hickey, Di Lollo & McDonald, 2009; Sawaki et al. 2010). It has been suggested that attentional resources can be separably allocated to vision and audition (e.g., Duncan, Martens, & Ward, 1997; Welch & Warren, 1980), though more recent evidence for this account has been mixed (e.g., Parks et al., 2011; Jacoby et al., 2012). However, if this account held true, it could be that, although young children's visual capacities were fully occupied by the primarily visual nature of the task, remaining resources in audition processed the accompanying sounds. This could have, in turn, changed performance for the visual aspect of the task. If this were the case for our study, we would have expected slower RTs to audiovisual distractors over visual distractors, and more errors on audiovisual over visual trials. However, there were no differences in error rates, and RTs were, in fact, faster in response to audiovisual cues than to visual cues, but only at the level of a nonsignificant trend. However, as we have argued before, behavioural measures may not be sensitive enough to capture differences in (audio)visual distractor processing in children. It is therefore unclear how the youngest participants processed the addition of sound to visual distractors, but the addition of an auditory-only condition could help disambiguate that in future work.

2.3. Implications for N2pc as a marker of developing real-world attentional control

Across the present studies, no TAC or MSE were observed in children's N2pc's, however, this may not be sufficient evidence to claim the N2pc is not a good marker of attentional selection in non-adult populations. It was surprising that no effects of TAC or MSE were detected in the N2pc's of children of varying ages, especially since older groups showed reliable TAC in behaviour. However, there are many possible explanations for this result. First, such a lack of effects could have been due to children's N2pc's potentially originating at different sites and latencies than those of adults, or than those prescribed by the adult-based literature. Indeed, in the visual literature, delayed but significant N2pc's have been reported already in 9-year-olds (Couperus & Quirk, 2015; Shimi et al., 2015; Sun et al. 2017). However, this idea was discarded, as no effects were found regardless of electrode site or latency choice – even when they were derived from children's own data. Secondly, and in relation to latency choice, it is likely that the context of our paradigm did not create optimal conditions to test if the N2pc may have appeared later in children. As the targets in our task appeared after 200ms of cue onset, we had little leeway in allowing child data to determine the optimal latency for investigation. Thus, it is probable that the strong target-related perceptual (and later) components effectively overwrote any distractor N2pcs that might have occurred later than approximately 180-300ms. Finally, in all of the above studies, N2pc's were elicited by targets, whereas in our studies, they were elicited by distractors. If anything, in previous research, visual distractors were found to elicit an adult-like Pd in 9-15-year-olds (Sun et al. 2017). Thus, even if after the above points, we conclude that the N2pc is not optimal for detecting distractor processing in children, we cannot extend this conclusion to real-world attentional control in general. In fact, there is evidence that N2pc is a robust biomarker of attentional selection that is sensitive to healthy development, aging, as well as mental disorders. Apart from the above evidence in children, target-elicited N2pcs are similarly delayed and attenuated in healthy older adults compared to young adults (Pagano, Fait, Monti, Brignani, & Mazza, 2015; Wiegand et al., 2013), corroborating reduced efficiency in attentional selection during typical aging. The N2pc is larger in adults with stronger top-down control capacities and children with higher working memory capacity (Wiegand et al. 2017; Shimi et al. 2015), while being attenuated and/or delayed in children and adults with ADHD (Cross-Villasana et al., 2015; Wang et al., 2016) and individuals with high schizotypy (Fuggetta, Bennett, & Duke, 2015; Verleger, Talamo, Simmer, Smigasiewicz, & Lencer, 2013). Crucially, however, all of the above studies have focused on the visual domain.

3. Implications of our research for education

3.1. The influence of schooling experience on developing TAC and MSE

Our findings so far have suggested that even children with less than a year of schooling experience show a brain-network-level sensitivity to the goal-relevance of visual stimuli. Meanwhile children with two additional years of schooling experience show at least partly overlapping sets of adult-like attentional control mechanisms, with TAC in behaviour and the general predominance of adult-like TAC-sensitive brain generators over the N2pc time-window. In the case of MSE, topographical measures revealed sensitivity to the (audio) visual nature of stimuli already at 3rd grade. A potential reason behind such observations is that Swiss children, which were tested as part of the current PhD project, become acquainted with the context of formal education relatively early. For instance, per the local school system, 4-5-year-old children learn how to interact appropriately with peers and teachers and receive training in foundational skills such as phonics and numerical awareness (CIIP, 2012). That said, they only begin to sit in benches and follow instruction in a less play-oriented format at around age 6-7. However, by that age, they will have been in formal education for two years, and even one year of such an experience can augment the involvement of attentional control networks in response to the same stimuli (Brod et al., 2017). Thus, it is tempting to interpret our early topographical modulations by TAC in 5-year-olds, and by TAC and MSE in 7-year-olds as a training effect of schooling experience on children's attentional control skills. This is certainly suggested by the 5-to-7-year shift account (e.g., Brod, Bunge & Shing, 2017), and others that have argued for the idea of schooling experience as a "neurocognitive developmental institution" (Baker, Salinas & Eslinger, 2012). However, before drawing any strong conclusions about the effects of experience, we must note here the variability in the children's behavioural and EEG data, and especially in the youngest participants.

The exceptional variability in 5-year-olds could have partly been driven by differences in processing speed or motor function maturity across children in this group, as children were tested across the span of the whole school year. Such skills develop rapidly in early childhood, and thus the differences between children at the beginning and end of the first grade could have been quite large. Alternatively, the variability may have been caused by other factors such as motivation or the time of day when the data were collected. To disentangle such potential sources of variability, in a future research direction, we could compare children's topographical and behavioural results at the beginning and end of the first grade. If 5-year-olds that were tested later in the year already showed behavioural TAC or even adult-like topography, but 5-year-olds that were tested earlier did not, that could speak to the influence of motor function development. Further, the use of mathematical modelling on longitudinal data (e.g., Kievit et al., 2017), in our child cohorts could help shed light on true developmental change in TAC and MSE as a function of schooling experience. Such a design could reveal the rate of development in behaviourally- and topographically-measured TAC that one year of schooling experience can afford 5-year-olds that have been tested earlier versus later in the year. Further, in older groups, it could investigate whether one additional year of schooling could bring about changes in topographical measures. Namely, it could investigate whether 7-year-olds' topographical TAC and MSE-sensitive maps became more like those of 9-year-olds after a year of schooling, and whether 9-year-olds' maps became more like those of adults. For these purposes, we have already conducted a longitudinal follow-up one year after the present data were obtained. Even so, this design would still not be able to fully disentangle the effects of schooling experience from experience-independent maturation. For this, a broad comparison of children across countries and school systems would be necessary.

3.2. The links between children's attentional control skills and literacy and numeracy

Our preliminary correlational analyses suggested the existence of relationships between children's attentional control skills and their literacy and numeracy attainment. First, in 9-year-olds, distraction that was orchestrated by the presence of a TAC-sensitive topographical map was negatively related to reading fluency. Meanwhile, distraction that was led by an MSE-sensitive map was negatively related to a composite score of mathematical skills. In other words, the more distraction involving a set of brain generators that were sensitive to TAC or MSE there was, the worse children's reading and mathematics skills were. There was also some tentative evidence that, in 7-year-olds, the involvement of two separate MSE-sensitive maps in distraction was positively relates to literacy and numeracy, respectively. If these correlations had been significant, they could have suggested that more distraction guided by MSE sensitive brain generators was linked to *better* reading and mathematics skills. Finally, in 5-year-olds, the involvement of a TAC-sensitive map in distraction was negatively related to numeracy skills. Thus, the more TAC-sensitive distraction there was, the worse young children's numeracy skills were.

There are a few important points to be made about the above topographically-measured patterns of distraction. First, the measure that we correlated with educational scores was the overall presence of TAC- and MSE-sensitive maps over the N2pc time-window, and not the modulation of these maps per-se. We did so because, as we mentioned above in Section 2, the directionality and meaning of topographical map modulation by TAC and MSE is not straightforward in the context of distractor processing. For example, is the preferential involvement of a map in processing visual distractors over audiovisual distractors positive (ability to resist distraction by multisensory stimuli) or negative (inability to process multisensory stimuli)? Using general map presence as a measure avoids such confounds. For this reason, but to still be able to make conclusions about the links between TAC and MSE and education, we correlated the overall presence of those maps that previous statistical analyses have highlighted as modulated by TAC or MSE. Secondly, the way in which map presence was modulated was not factored into the correlation. To use the above example, that a map was preferentially involved in processing visual distractors over audiovisual distractors did not mean that visual distractor processing was related to a given educational score. Such a conclusion could only come from separate correlations of map presence for visual distractors and map presence for audiovisual distractors, with educational skills, which were not conducted at present. Finally, we remind the reader that, topographical marker choice notwithstanding, correlational analyses on the current dataset should be considered preliminary, given the low sample sizes in at least the 9-year-olds and 5-year-olds.

Despite potential caveats for interpretation, the findings discussed here are novel in that they showcase that attentional control by both visual and multisensory information, as measured by sensitive, multivariate analyses of the electrical field at the scalp, may be relevant for children's educational outcomes. It was curious, however, that in the oldest group, reading comprehension was unrelated to topographic map recruitment. Where one could expect the same template map to govern all literacy-related skills, it has been suggested that, indeed, different domain general skills may differentially support domain-specific skills. For example, a study by Arrington and colleagues (2014) found that working memory, sustained attention, and cognitive inhibition were directly related to reading comprehension, while working memory and response inhibition were related to decoding (i.e., the ability to 'translate' print into spoken language, see e.g., Perfetti et al., 1984). The main takeaway from the Arrington et al. (2014) study is that investigating individual domain-specific skills, rather than composite scores, may be a worthwhile direction in which to continue exploring the rich datasets acquired as part of the present research. That said, there were some important differences between our study and theirs. First, they used path analyses where we used correlations. In ongoing work, however, we will conduct Structural Equation Modelling (SEM), which combines path analysis and latent variable analysis, to investigate the links between behavioural and brain measures of TAC and MSE and children's literacy and numeracy skills. Further, this study included children that appeared to be older were likely older than children in our cohort (grades 6-12 in Houston area, Texas – no indication of age).

Another key difference lies in the spread of the data. In the Arrington et al (2014) study, within-norm children that scored lower on general reading ability were oversampled, probably to increase the spread of scores, and thus the explanatory power of their model, in a cohort of children in regular education. By contrast, in our research, most children scored rather high on educational measures, and this lack of spread could have driven the trend-level correlations in 7-year-olds. Oversampling lower-scoring children or using a potentially more sensitive battery of educational measures was not feasible in the current research for several reasons. Firstly, our study protocol necessitated an EEG recording in an unfamiliar setting, unlike most other research in this field which relies on questionnaires. Though clearly advantageous for mechanistic understanding, this step made many local families reluctant to participate in the study (a challenge that we actively addressed through various outreach work, see Curriculum Vitae), effectively reducing the number of available children, and somewhat biasing the sample towards higher educated families and higher achieving children. Regarding the testing battery, the choice was extremely limited, since none of the testing batteries commonly used for research purposes (e.g., Comprehensive Test of Phonological Processing, the reading and mathematics subtests of the Woodcock-Johnson

Tests of Achievement, Test of Silent Word Reading Fluency, Test of Word Reading Efficiency, etc.) were available in the French language at the time the testing began (e.g., the French version of the Clinical Evaluation of Language Fundamentals was only released September 2019). What is more, such testing batteries are not standardised for the French-speaking part of Switzerland, and there are differences across the French and Swiss-French school systems. The battery used in the current research was therefore chosen by recommendation of a child neuropsychologist versed in educational testing in the local setting. A potential remedy for future research in the same environment could come from further outreach and continuing relationships with schools that facilitated the current research. Such efforts could familiarise members of the general public with the harmlessness of the EEG method, the game-like nature of our study protocols, and the applicability of our research aims, and thus help increase and improve the diversity of participant recruitment. Another possibility would be to use scores from local teacher-led school assessments of literacy and numeracy skills instead of testing batteries, in an effort to find more representative measures of the educational skills of children in French-speaking Switzerland. Finally, since behavioural measures alone were not related to educational scores, there could be merit in exploring ways to bring EEG to the classroom.

3.3. Applied value of our results

The topographical results of the current research provided evidence for sensitivity to multisensory distraction after as little as two years of schooling. Though we did not specifically test the effects of multisensory distraction by classroom design, there is an ever-growing literature on how the features of children's learning environments modulate learning (e.g., Hanely et al., 2017; Rodrigues & Pandeirada, 2018; for results in pre-schoolers' play behaviour see Stern-Ellran et al., 2016). For example, Fisher and colleagues (2014) have shown that, in veridical real-world environments, children as young as 5 learn less information in visually cluttered classrooms than they do in modestly decorated classrooms. Since our research shows that children aged 6 and above seem sensitive to distraction by audiovisual objects, such distraction could further compound the adverse effects of classroom learning incurred by visual-only distraction. Auditory noise seems to have a similarly detrimental effect in 5-8-year-olds, with such effects being especially pronounced in children with weak attentional control skills (Massonnié, Rogers, Mareschal & Kirkham 2019). Notably, the auditory classroom noise in the above study might have, at least in part, been accompanied and synchronised with distracting stimulation in other senses, such as vision or touch, or less so the chemical senses. Here, such multisensory stimuli (active peers, the shuffling of chairs, etc.) would make up much more salient distractors for goal-directed behaviour than the non-semantically-laden small beep-flashes used in the present research.

Our results, especially if replicated in a larger sample, and across both EEG and behavioural measures, would suggest that more effort needs to put into creating classrooms where the risks of multi-sensory distraction are minimised. Such implications need not apply to kindergarten and pre-school environments, since children with little to no school experience seem to be protected from multisensory distraction, as shown by my PhD work, as well as by Matusz and colleagues (2015, 2019a). In school classrooms, however, such implications may translate into reducing decoration or the involvement of new technologies in the classroom – unless if they are relevant to the current goal (the subject of instruction). Indeed, the superior salience of multisensory information may facilitate the processing of goal-relevant information, and as shown by our own results, the modulatory effect on topography by multisensory *distractors* was largely present for goal-*irr*elevant information. Thus, the involuntary and attentional-demand-independent capture of attention by multisensory stimuli could facilitate the encoding of to-be-learnt information into memory, as we know that the same occurs with attended visual objects (see Astle & Scerif, 2011).

In terms of literacy and numeracy attainment specifically, our preliminary findings may be the most relevant in showing that, depending on the age/schooling experience, children's sensitivity to different types of distraction relates differently to literacy scores and numeracy scores. How do such findings translate into practice? For one, the above implications for classroom and instructional design could be tailored given the specific age groups' patterns of results. For example, at school entry, visual distractions should be minimised, while after two years, the focus should shift to increasing multisensory stimulation, and after four years, both visual and multisensory distractors should be minimised. Moreover, if the present results were to replicate in a larger sample of schoolchildren, the presence of certain topographical patterns at given levels of schooling experience could be used for designing screening tools for potential literacy and numeracy difficulties. Thus, instead of waiting for children to fail at literacy and numeracy milestones to be diagnosed, early suspected cases of dyslexia or dyscalculia could be screened with our current study protocol for the recruitment of given template maps in response to distracting information. However, to be sure that the same template map recruitment occurs in children with learning difficulties, as in lower scoring within-norm learners, testing should be expanded to populations with learning difficulties. Further, more direct and nuanced relationships should be ascertained between educational scores and brain and behavioural responses to distractions. Indeed, that behavioural indices were not at all related to educational scores was a surprising result, given the variety of studies linking purely behavioural measures to children's educational measures (reviewed in e.g., Cragg & Gilmore, 2014). Such relationships are currently being explored as part of an ongoing project, which assumes the use of structural equation modelling to investigate the links between behavioural and EEG measures of visual and multisensory attentional control on literacy and numeracy measures, and at two timepoints (one year apart). This approach will offer a decisive advantage over correlations in that the variance shared across different measures would be included in the model, link between attentional control and educational skills would be more predictive, the efficacy of behavioural and EEG measurements at capturing attentional control could be directly compared, and measurement errors would be taken into account. Further, retesting the same participants in a year's time will not only reveal whether the relationships between attentional control and education change over time and schooling experience, but also just how much the relationship one year later depends on the initial relationship at the first timepoint (see Kievit et al., 2018).

4. The suitability of the current methodology for the study of real-world attentional control

4.1. The behavioural task

Our series of studies employing (an adapted) Folk et al. spatial cueing paradigm has confirmed its suitability for studying attentional control processes in real-worlds contexts. The spatial cueing task allows for a clear delineation of task-irrelevant (distractor-based), task-relevant (target-based), and response-based processing, unlike classical visual search paradigms where all of these processes are locked to the same stimulus array. Thus, processes related to the presence/absence of matching by a single stimulus attribute (e.g., colour) between task-irrelevant (distractor) and relevant (target) stimuli can be measured. Specifically, the paradigm allows for the measuring of the likely maximal attentional capture that can be gauged by a given stimulus in strongly controlled visual top-down task settings – in this case by a distractor containing a target-defining feature. As such, it can serve as the measure of the strength of top-down facilitatory (feature-based) attentional control. At the same time, capture effects to distractors that do not match the target by colour can serve as a measure of the relative weakness of top-down inhibitory (feature-based) control. Operationalising the complex interactions between such visual attentional control processes with multisensory processing, and where relevant, temporal predictions and semantic relationships, was made possible by ‘adding’ additional processes to the paradigm. Insofar as key parameters of natural environments, such as clutter, ‘multisensoriness’, semantic meaning, etc., can be incorporated as additional processes, the spatial cueing paradigm can provide both real-world relevance and ecological validity, as well as a high degree of experimental control.

The widespread behavioural replication of TAC and MSE effects (at least in adults and partly also in children) demonstrated that even in a ‘gamified’ child-friendly form, the spatial cueing paradigm can still measure important attentional control processes. This is an important point for any future attempts at using this paradigm as a screening or intervention tool, given the increased interest in using games in rehabilitation (e.g., of motor functions, Bruno et al., 2016, of functional vision, Linehan et al., 2014) in training specific, complex skills (e.g., surgical procedures, Rosser et al., 2007), as well as domain-general cognitive skills like attentional control (Green & Bavelier, 2012; Oei & Patterson, 2013). Further, that children aged four to ten could successfully take part in the experimental task, and provide usable data demonstrates the suitability of the task for (typically) developing populations. Here, it is worth mentioning that the task may have not been ideally suited to the youngest group, as evident from a higher number of excluded participants compared to other groups, as well as blocks and trials removed from this group’s data relative to others. The fast nature of the task, as well as the intimidating experience that is a first-ever EEG recording in a hospital setting surely affected this group the most. Even for participants that could complete the paradigm in full or in part, complaints with regards to task difficulty or length were noted, and similar issues could potentially arise in other, clinical populations where attentional resources are known to be weaker, such as in those with ADHD or autism. One way to mitigate such issues is further adaptation, such as slowing down particular stimulus arrays, and shortening the total duration of the task. That said, if distractor arrays had a longer duration, we could no longer be sure if attentional capture by distractors were involuntary, i.e., bottom-up, thus casting doubt on the type of mechanism being studied. Such a manipulation would also render the task less challenging for older groups, and demanding task conditions may be necessary for multisensory effects on attentional control to transpire (see Santangelo and Spence, 2007a,b). The *overall* duration of the task could be shortened by reducing the number of trials. However, first we would need to know the number of trials sufficient to detect effects when they are present. For such reasons, and so that the paradigm may be used across different populations, typically developing or not, an ongoing 'best practices' project was initiated. One part of this project focuses on establishing the inter-block reliability in the child-friendly multisensory spatial cueing paradigm (henceforth known as the pirate game), by computing the TAC and MSE indices that were here used as part of the correlational analyses, per experimental block, in an iterative fashion. That is, TAC and MSE indices are calculated across participants in one age group on the first block, then on the first two blocks, then the first three, etc. The aim is to detect at which experimental block participants' top-down visual and bottom-up multisensory attentional control are optimally observable, in order to derive at an ideal number of blocks for each age group.

An important limitation of the multisensory aspect of the paradigm in its current state, is the lack of an auditory-only condition. Because there was no auditory-only condition in addition to the visual-only and audiovisual conditions, the nonlinear responses that are a hallmark of MSI could not be established. The co-occurrence of the visual and auditory features in the audiovisual condition makes MSI probable, at least in adults. Indeed, most adult participants that took part in the present studies reported that if they kept their eyes on the fixation point, the colour distractors would 'pop out' more in the presence of a sound, despite the irrelevance of the stimulus to the task. This is in line with the idea that simultaneously presented colour distractors and sounds can create a novel integrated audiovisual object. However, such conclusions can only be established by a comparison of responses to both unisensory and multisensory conditions. The addition of an auditory-only condition could also help clarify multisensory processes in our child data, in that it could disambiguate whether: a) the lack of topographical modulations by multisensory attentional control in the youngest children originated from them not integrating the visual and auditory information, and b) the older groups that do show topographical modulations by multisensory attentional control do so because the auditory and visual information was integrated.

4.2. Electrophysiological methods

4.2.1. The N2pc

The evidence presented in the current thesis overwhelmingly supports that the N2pc is specialised to index top-down visual control of attention. Specifically, it is most responsive to task-relevant stimuli (targets) or purely visual distractors. As such, it seems to be applicable to research with non-neurotypical populations and cohorts other than young adults, albeit in children it may require a longer time to materialise. What can be done in situations where multisensory distractors or the influence of contextual factors on attentional control are the topic of investigation? Here, the present series of studies have shown that combining EN measures with classic ERP measures, such as the N2pc, can help both uncover the mechanisms underlying the latter, and compensate for their lack of sensitivity. Across our studies, and across children and adults, where the N2pc failed to capture MSE effects, EN identified topographic map captured them. If our developmental analyses had stopped at canonical N2pc analyses, one could infer that top-down (TAC) or bottom-up (MSE) attentional control processes were simply not elicited by task-irrelevant stimuli before adulthood. However, with the use of EN, our conclusions were free from such important omissions. Further, had we not applied EN, the driving mechanism behind the lateralised N2pc effects would have remained unclear. Where the N2pc did index the presence of TAC, EN clarified that modulations of N2pc amplitude were likely driven by different networks being recruited for target-matching distractors and for nonmatching distractors, rather than the traditional gain-control mechanism. In the study of contextual factors, however, the sort of EN analyses of lateralised voltage gradients that were used for TAC and MSE provided inconclusive results as to the interaction between contextual factors, and TAC and MSE. Though the EN methods applied in the current studies primarily served to elucidate the guiding mechanisms behind the well-researched N2pc effect, it was only when nonlateralized analyses were applied did the influence of contextual effects become clearer. From this we may deduce that enriching the N2pc with analogously lateralised EN analyses is a fitting option for studying attentional control by multisensory vis-à-vis visual stimuli, but to derive contextual influences on such effects, nonlateralized EN analyses, unconstrained by the N2pc, may be required.

4.2.2. EN

The use of signal from all of the electrodes in a montage, as well as the average reference, make EN analyses not only more easily replicable between contexts and research groups (this argument has been further substantiated in Murray et al., 2008), but also potentially more easily comparable across development. The issue of different electrode sites and time-window between adults, children, etc., that traditional ERP analyses may face, and that required a host of manipulations over the course of our studies, is completely avoided by EN. Thus, using EN may simplify comparing neuro-cognitive mechanisms between developmental stages. For example, While Gaspelin et al. (2015) reported some form of top-down visual control in 4-year-olds, even when controlling for age differences in processing speed, it cannot be stated with confidence that this control was instantiated by similar neuro-cognitive mechanisms. Such uncertainty is further substantiated by the marked differences always present in the canonically analysed N2pcs between young adults, older adults, and children, be it in onset latency, or amplitude (Pagano, Fait, Monti, Brignani, & Mazza, 2015; Wiegand et al., 2013; Shimi et al., 2015; Couperus & Quirk, 2015). In contrast, our normative analyses showed that EN could reliably identify the presence of adult-like attentional control processes, in that stable patterns of EEG activity that characterised adult EEG, also did children's EEG, from two years of schooling experience (age 6-7) onwards. Meanwhile, our descriptive analyses revealed that children as young as 4-5 with little schooling experience, demonstrate stable patterns of EEG activity that, though they may not be comparable to adult patterns, are still modulated by the goal-relevance of task-irrelevant stimuli. To our knowledge, this is the earliest age group in which spatially-selective time-defined brain mechanisms have been reported.

Though EN applications in children are still extremely rare, the results of these studies, coupled with our own hold promise for EN as a tool for investigating the neurocognitive bases of difficulties relating to literacy (and numeracy) skills. The two extant studies that have used EN in child samples (Yoder, Molfese, Murray & Key, 2013; Bakos et al., 2020), have contributed to our understanding of the brain mechanisms behind typical and struggling readers' processing of linguistic stimuli. Briefly, Yoder and colleagues compared typically developing pre-schoolers (M_{age} = 3.5 years) and age-matched children with specific language impairment on their processing of speech sounds. They used the latencies of ERPs to speech sounds in typically developing children to derive a set of topographical clusters, onto which single-subject ERPs of typically developing children and children with specific language impairment were fitted. Then, the latencies of template maps that characterised different speech sound were averaged for each participant and denoted a 'speed of speech processing' index. Comparing this index across the two groups of children, they found not only that children with specific language impairment processed speech sounds faster after a grammatical treatment programme, but also that changes in speed during treatment predicted their post-treatment learning of grammar. Separately, Bakos and colleagues (2020) were interested in clarifying the role of naming speed (as in rapid automatized naming tasks) in reading difficulties, and spelling difficulties in school-aged children (ages 9-10). The neurophysiological mechanisms of this skill are purportedly different in reading disorders as opposed to typical development, but comparable in spelling disorders as opposed to typical development. To clarify this, they compared ERP activity and whole-scalp topography between children with reading difficulties, spelling difficulties, and typically developing children. Consistently with predictions, they found that children with reading problems showed a differential brain network recruitment than did typically developing children, around 300ms, which corresponded to P2 component activation. Meanwhile, children with spelling problems had a comparable configuration of template maps to that of typically developing children. Taken together with our results that EN but not behavioural markers of attentional control correlated with educational scores, it seems

EN may be useful for investigating the neurocognitive bases of difficulties relating to literacy (and numeracy) skills.

At this stage, we must remember that ERPs have had an immeasurable impact on our understanding of the timing of attentional processes, and in so doing, the disambiguation of detection-based (e.g., P1, N1), control-based (e.g., N2pc), and preparatory (LDAP, ADAN, EDAN) processes involved in selective attention. Thus, the availability of a method like EN does not mean ERPs have become obsolete. It was the N2pc literature in the first place that informed the current series of studies of the timing of visual attentional control in adults, forming the basis of forays into the largely unknown effects of multisensory control, and influences thereof by contextual factors, and also in children over the course of primary education. Then, EN confirmed that, when activity across the whole brain is taken into account, there are important attentional control processes that occur from 150ms post-stimulus onwards within the lateralised voltage gradients – single points of which have been captured by canonical electrode-pair analyses. Similarly, in the study of Yoder and colleagues (2013), the latency of ERPs to speech stimuli were used to constrain further topographical analyses. Meanwhile, for Bakos and colleagues (2020), topographic results were interpreted in light of their concurrent P2 component activation results. With this, we would argue that the combination of traditional ERP component analysis and more advanced EN analyses is well-suited to investigating the neuro-cognitive mechanisms behind the control of selective attention in real-world-like contexts.

5. Summary of results

Taken together, the research presented as part of the current thesis revealed that a frequently studied visual top-down control mechanism, that is TAC, develops after the age of 5 (at school entry). Our results suggest that top-down visual control of attentional selection may reach levels comparable to those of adults after a couple of years of schooling experience, around age 6-7. The development of bottom-up attentional control by multisensory stimuli, though undetected in behaviour and traditionally analysed ERP signals, was clarified owing to EN. Spatially-selective brain mechanisms sensitive to the multisensory nature of distracting stimuli were uncovered in children as young as 6-7. However, such sensitivity may only begin to take on an adult-like form after four years of schooling experience, or age 8-9. These results jointly suggest that top-down visual attentional control may develop before bottom-up multisensory control of attention, but even before these processes become adult-like, children’s brains are sensitive to visually-instantiated potential goal-relevance and multisensory nature of task-irrelevant information in the environment. At each level of schooling experience, distinct brain networks orchestrate top-down visual attentional control and bottom-up multisensory attentional control. Such processes persist into adulthood, where TAC is a robust effect, observable in behaviour, traditional ERP analyses, and EN analyses, while MSE is detectable in behaviour and EN only. The influence of MSE on TAC is, in adults, further modulated by contextual factors, such as the predictability of the onset of task-irrelevant stimuli and the multisensory relationship between auditory and visual features of task-irrelevant stimuli. Specifically, onset predictability influences are only present when the auditory and visual features are merely presented at the same time, with no semantic relationship between these features. However, when the two features share semantic meaning, onset predictability influences are no longer present, and TAC for audiovisual stimuli is larger than TAC for visual stimuli. The findings of our studies jointly underline the utility of combining traditional behavioural and EEG/ERP markers of visual attentional control with advanced EEG analytical techniques for investigating the developmental trajectory of attentional control in settings that closely approximate those that we encounter in everyday life.

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Personal contributions

Over the course of the present PhD work, I had a major contribution to the organisation of recruitment of child participants at schools, which included the following: establishing and maintaining collaboration with the director general for compulsory education in the canton of Vaud, the heads of Lausanne’s school establishments, and directors and teachers of schools within these establishments. My responsibilities in this regard progressed from partial to full over the course of the thesis, as some initial personal contacts and communications had been put in place beforehand. I was also responsible for liaising with responsible persons for the Teddy Bear Hospital and Mysteres de l’UniL events, where children were recruited from. I also participated in these events as an animator, providing interactive information on my currently presented work to families and lay audiences (see Curriculum Vitae). I conducted the recruitment of children from schools and public or private events, and adult volunteers by word of mouth, including distributing study information and obtaining consent, initial screening for counterindications to participation, and scheduling. I contributed to the setup of the experimental testing spaces, including organising the acquisition of parts of the equipment, putting in place parts of the equipment, troubleshooting, and setting up guidelines for future users. Here, I also trained other research staff in the use of the equipment, specifically the EEG system. I handled data storage and management.

I conducted behavioural, EEG, and neuropsychological data collection, with the exception of a part of the child neuropsychological data that was collected by a visiting PhD student. I conducted all of the cleaning and analyses of the behavioural data, preprocessing of the EEG data and its analysis in N2pc and EN frameworks, and correlational analyses presented in the current thesis, under the guidance and supervision from my thesis director and co-director. A part of the EEG data preprocessing was conducted by a former PhD student in the research group, under my tutelage. I conducted the literature review presented in this thesis and presented some of the literature as part of a journal club that I organised and managed in the first half of my doctoral study. I have prepared parts of the child and adult results presented in the current thesis in their preliminary forms at national and international conferences (see Curriculum Vitae). I am currently preparing parts of the current results as manuscripts for publication (see Curriculum Vitae).

With regards to ongoing work that was not fully detailed in the current thesis, I was responsible for establishing a collaboration with an international expert on modelling behavioural and brain data from developmental samples. My co-supervisor, myself, and the collaborator in question were jointly responsible for building the design and data analysis pipeline for the project related to modelling the relationships between behavioural and brain measures of attentional control and education across two timepoints. Over the course of my doctoral study, I have collected the behavioural, EEG, and neuropsychological data as part of the second testing timepoint. During this time, I also underwent training on conducting structural equation modelling, and conducted part of the data processing and analyses for this project. For the ‘best practices’ project, myself and my co-supervisor are equally credited for its conceptualization. It is currently being advanced in a collaboration with a postdoctoral researcher in the research team.

Curriculum Vitae

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EDUCATION

2016–2020 **PhD in Neuroscience**

Department of Radiology, University of Lausanne (UniL)/University Hospital Center (CHUV), and Institute of Information Systems, HES-SO Valais, Switzerland

Thesis: Early Multisensory Attention as Foundation for Learning in Multicultural Switzerland
Supervision: Dr Paul (Pawel) Matusz (direct supervisor) & Prof. Micah Murray (thesis director)

- Tested 120 children's (4 to 10-year-olds) behavioural performance and EEG during a visual/multisensory selective attention task. Administered standardised tests of educational achievement (literacy and numeracy) in a longitudinal design (with 1-year-follow-up). Additionally, tested 40 young adults on a similar visual/multisensory selective attention task with behavioural and EEG measures. Analysed EEG data using traditional ERP markers of attentional selection and with multivariate 'electrical neuroimaging' analyses to obtain robust accurate measures of specific brain strength vs network-based mechanisms of developmental change.

Midterm examination: passed April 2018 (Committee: Prof. Silvia Brem, Prof. Monica Gori, Dr. Duncan Astle. Committee president: Prof. Kirsten von Plessen)
PhD examination: due June 2020

Resulting publications:

1. Matusz, P., Turoman, N., Tivadar, R., Retsa, C., and Murray, M.M. (2019) Brain and cognitive mechanisms of top-down attentional control in a multisensory world: Benefits of electrical neuroimaging. *Journal of Cognitive Neuroscience,* 31(3), 412-430.
2. Turoman, N., Merkley, R., Scerif, G., and Matusz, P. (2017) How Do Kids and Grown-Ups Get Distracted in Everyday Situations?. *Frontiers for Young Minds,* 5(8). doi: 10.3389/frym.2017.00008

In preparation:

3. Turoman, N., Tivadar, R., Retsa, C., Maillard, A., Scerif, G., and Matusz, P. The development of attentional control mechanisms in multisensory environments.
4. Turoman, N., Tivadar, R., Retsa, C., Maillard, A., Scerif, G., and Matusz, P. Uncovering the mechanisms of real-world attentional control over the course of primary education.
5. Turoman, N., Tivadar, R., Retsa, C., Murray, M. M., and Matusz, P. How do we pay attention in naturalistic settings?

2015–2016 **MSc in Psychological Research (Upper Second Class)**
Department of Experimental Psychology, University of Oxford, United Kingdom
Thesis: Symmetry and its Role in the Crossmodal Correspondence between Shape and Taste
Supervision: Prof. Charles Spence

- Tested 90 adults with an online questionnaire aimed to understand the links between visual object symmetry and taste perception

Resulting publication: Turoman, N., Velasco, C., Chen, Y.-C., Huang, P.-C., & Spence, C. (2018). Symmetry and its role in the crossmodal correspondence between shape and taste. *Attention, Perception, & Psychophysics, 80*(3), 738-751.

2012–2014 **BSc (Hons) in Psychological Studies (First Class)**
Cardiff Metropolitan University, Singapore branch

PROFESSIONAL EXPERIENCE

April 2016 **Data Processing Assistant**
Oxford University Student Union (OUSU), Oxford, UK

- Analysed and presented data gathered for the OUSU Welfare Survey Project in the form of a university-wide report, and smaller college-level reports

2015– 2016 **Research Assistant**
Oxford Cognitive Neuropsychology Centre, University of Oxford, UK
Supervision: Prof. Glyn Humphreys

- Administered perceptual tasks to chronic stroke patients and healthy adults (young and elderly) in the scope of a pilot study

2014– 2015 **Research Assistant**
Brain, Language, and Intersensory Perception (BLIP) Laboratory, Nanyang Technological University, Singapore
Supervision: Prof. Suzy Styles

- Designed stimuli, collected and analysed data, and co-wrote manuscript for a study of correspondences between the auditory properties of speech-sounds, and visual properties of letters

Resulting publication: Turoman, N., & Styles, S. J. (2017). Glyph guessing for 'oo' and 'ee': spatial frequency information in sound symbolic matching for ancient and unfamiliar scripts. Royal Society Open Science, 4(9), 170882.

AWARDS

2019 **Flux pre-conference workshop stipend.** Flux, the Society for Developmental Cognitive Neuroscience (funded by the Hope Lab and the Bezos Family Foundation; 123 CHF)

2019 **Lemanic Neuroscience Travel Award.** University of Lausanne, CH (1,085 CHF)

2016 **George Humphrey Prize for Best Research Project.** University of Oxford, UK

2014 **Meritorious Award for graduating with First Class Honours.** Cardiff Metropolitan University, UK

PEER-REVIEWED PUBLICATIONS

1. Matusz, P., **Turoman, N.,** Tivadar, R., Retsa, C., and Murray, M.M. (2019). Brain and cognitive mechanisms of top-down attentional control in a multisensory world: Benefits of electrical neuroimaging. *Journal of Cognitive Neuroscience, 31*(3), 412-430.

2. Tivadar, R.I., Rouillard, T., Chappaz, C., Knebel, J.-F., **Turoman, N.,** Anaflous, F., Roche, J., Matusz, P., and Murray, M.M. (2019). Mental Rotation of Digitally-Rendered Haptic Objects. *Frontiers in Integrative Neuroscience, 13,* 7.

3. Tivadar, R.I., Retsa, C., **Turoman, N.,** Matusz, P.-J., and Murray, M.M. (2018). Sounds enhance visual completion processes. *Neuroimage, 179,* 480-488.

4. **Turoman, N.,** Velasco, C., Chen, Y.-C., Huang, P.-C., and Spence, C. (2018). Symmetry and its role in the crossmodal correspondence between shape and taste. *Attention, Perception, & Psychophysics, 80*(3), 738-751.

5. **Turoman, N**., and Styles, S. J. (2017). Glyph guessing for 'oo' and 'ee': spatial frequency information in sound symbolic matching for ancient and unfamiliar scripts. *Royal Society Open Science*, *4*(9), 170882.

6. **Turoman N**, Merkley R, Scerif G and Matusz P (2017) How Do Kids and Grown-Ups Get Distracted in Everyday Situations?. Frontiers for Young Minds. 5(8). doi: 10.3389/frym.2017.00008

MANUSCRIPTS IN PREPARATION

1. **Turoman, N.,** Tivadar, R., Retsa, C., Maillard, A., Scerif, G., and Matusz, P. The development of attentional control mechanisms in multisensory environments.

2. **Turoman, N.,** Tivadar, R., Retsa, C., Maillard, A., Scerif, G., and Matusz, P. Uncovering the mechanisms of real-world attentional control over the course of primary education.

3. **Turoman, N.,** Tivadar, R., Retsa, C., Murray, M. M., and Matusz, P. How do we pay attention in naturalistic settings?

OUTREACH ACTIVITIES

23rd Jan, 2020 **MedGIFT writing workshop**

Collaborated on a blog post hosted on Medium.com entitled 'How to 'crack the code' of the developing brain?' https://medium.com/research-at-medgift/the-use-of-mathematical-modeling-to-understand-neurocognitive-development-and-real-world-24885c837178

23rd – 26th May, 2019

Mysteres de l'UniL, University of Lausanne, Lausanne, Switzerland

Presented interactive family-friendly workshop entitled 'Visual Problems: See the World Through Their Eyes' including a dyslexia simulation task, and a demonstration of PhD research paradigm (4 days, app. 140 children – one of the most popular exhibits at the event)

15th May, 2019

Jacobs Foundation's Blog on Learning and Development (BOLD)

Wrote invited post as part of Learning in the 21st Century series entitled 'How to bridge the gap between families and the science of learning'. https://bold.expert/how-to-bridge-the-gap-between-families-and-the-science-of-learning/

17th – 18th Nov, 2018

L'Hôpital des Nounours, CHUV, Lausanne, Switzerland

Informing participating families on research work (my own, and in the field of developmental cognitive neuroscience) and recruiting interested families for ongoing research

4th – 5th Nov, 2017

L'Hôpital des Nounours, CHUV, Lausanne, Switzerland

Informing participating families on research work (my own, and in the field of developmental cognitive neuroscience) and recruiting interested families for ongoing research

March – May, 2017

Frontiers for Young Minds: Understanding Neuroscience

Author on: **Turoman N**, Merkley R, Scerif G and Matusz P (2017) How Do Kids and Grown-Ups Get Distracted in Everyday Situations?. Frontiers for Young Minds. 5(8). doi: 10.3389/frym.2017.00008

Science mentor/reviewer on: Myers T (2017) Getting Out of the Laboratory to Make Experiments Real: Can Sports Fans Influence Muay Thai Judges?. Frontiers for Young Minds. 5(13). doi: 10.3389/frym.2017.00013

17th – 19th Nov, 2015

Food Matters Live, ExCel, London, UK

Exhibiting experimental research as part of the Food Sensorium Attraction

18th – 23rd Aug, 2015

Soundislands Festival (SI15), Nanyang Technological University and ArtScience Museum, Singapore

Presentation of scientific poster. Interactive live demonstration of previous research work

CONFERENCE PRESENTATIONS

18th Nov, 2019

1st Annual Meeting of the Swiss Society for Early Childhood Research (SSECR), Lausanne, Switzerland

Flash talk: "Educational outcomes depend both on visual and multisensory control of selective attention"

24th – 26th Oct, 2019	**Rovereto Attention Workshop, Rovereto, Italy** Presentation of scientific poster: "Educational outcomes depend both on visual and multisensory control of selective attention"
29th Aug – 1st Sept, 2019	**Flux Congress 2019, New York, NY, USA** Presentation of scientific poster: "Educational outcomes depend both on visual and multisensory control of selective attention"
3rd – 4th April, 2019	**1st Annual Meeting of the NeuroLeman Network and Doctoral Schools 2019 (NLN'19), Les Diablerets, Switzerland** Presentation of scientific poster: "Educational outcomes depend both on visual and multisensory control of selective attention"
27st – 29rd Sept, 2018	**The International Mind Brain and Education Society 2018 Conference, Los Angeles, CA, USA** Presentation of scientific poster: "Multisensory control over developing visual selective attention and its role in educational outcomes"
2st – 3rd Sept, 2018	**Lemanic Neuroscience Annual Meeting (LNAM) 2018, Les Diablerets, Switzerland** Presentation of scientific poster: "Taking attention back to school: Multisensory processes influence developing visual attention control"
30th Aug – 1st Sept, 2018	**Flux Congress 2018, Berlin, Germany** Presentation of scientific poster: "Taking attention back to school: Multisensory processes influence developing visual attention control"
1st – 2nd Sept, 2017	**Lemanic Neuroscience Annual Meeting (LNAM) 2017, Les Diablerets, Switzerland** Presentation of scientific poster: "Semantics in the multisensory brain: Insights from electrical neuroimaging"
19th – 22nd May, 2017	**International Multisensory Research Forum (IMRF) 2017, Nashville, TN, USA** Presentation of scientific poster: "Semantics in the multisensory brain: Insights from electrical neuroimaging"
28th Aug – 1st Sept, 2016	**European Conference of Visual Perception (ECVP) 2016, Barcelona, Spain** Presentation of scientific poster: "Visual symmetry influences the cross-modal correspondence between visual shape and taste"

PROFESSIONAL MEMBERSHIPS

2018 – ongoing	**The Swiss Society for Early Childhood Research (SSECR)** – junior member
2018 – ongoing	**Flux, the Society for Developmental Cognitive Neuroscience** – trainee member
2018 – 2020	**The International Mind, Brain and Education Society (IMBES)** – trainee member

AD-HOC JOURNAL REVIEWING

- Journal of Cognitive Neuroscience – assistant reviewer to Dr. Matusz
- Frontiers for Young Minds – reviewer and mentor for 14-year-old reviewer

ACADEMIC TRAINING

Aug 2019	**Pre-Conference workshop "Beyond the lab: Translating developmental neuroscience",** Flux society, Los Angeles, CA, USA
Nov 2018	**Open Science and reproducibility workshop - "Data management & Open Data"**, University of Lausanne, Lausanne, CH
Sept 2018	**Comp2Psych Workshop: Structural Equation Models,** Max Planck Institute for Human Development, Berlin, Germany
Nov 2017	**BMI Symposium: Neural Implementation of Learning Models,** EPFL, Lausanne, CH
Dec 2016	**BMI Symposium: Connectivity and Plasticity of Neural Circuits,** EPFL, Lausanne, CH

TECHNICAL SKILLS

- EEG data acquisition (BioSemi, EGI, ANT) and analysis (CarTool, NetStation)
- Experimental paradigm design and data analysis using MatLab
- Experimental paradigm design and data analysis using Pyhton
- Structural equation modelling of cross-sectional and longitudinal data using Onyx
- Data analysis using SPSS, JASP, and JAMOVI
- Design and administration of online experiments using Qualtrics
- Design of visual materials for research and outreach using Adobe CC

LANGUAGES

- English – Native proficiency
- Serbian – Native proficiency
- Hungarian – Native proficiency
- French – Full professional proficiency
- German – Elementary proficiency
- Japanese – Elementary proficiency

Appendices

Appendix 1 – Developmental study, behavioural analyses

Raw RT results

4 x 2 x 2 x 2 mixed ANOVA

- Main effect of Age, $F_{(3, 127)} = 94.7$, $p < 0.001$, $\eta_p^2 = 0.7$
- Main effect of Cue Modality, $F_{(1, 127)} = 12.9$, $p < 0.001$, $\eta_p^2 = 0.09$
- Main effect of Cue Colour, $F_{(1, 127)} = 18$, $p < 0.001$, $\eta_p^2 = 0.1$
- Main effect of Cue-Target Location, $F_{(1, 127)} = 57.6$, $p < 0.001$, $\eta_p^2 = 0.3$
- Interaction of Cue Modality x Age, $F_{(3, 127)} = 0.6$, $p = 0.6$, $\eta_p^2 = 0.01$
- Interaction of Cue Colour x Age, $F_{(1, 127)} = 1.9$, $p = 0.13$, $\eta_p^2 = 0.04$
- Interaction of Cue-Target Location x Age, $F_{(3, 127)} = 0.3$, $p = 0.9$, $\eta_p^2 = 0.01$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 127)} = 0.4$, $p = 0.5$, $\eta_p^2 = 0.003$
- Interaction of Cue Modality x Cue Colour x Age, $F_{(3, 127)} = 0.6$, $p = 0.6$, $\eta_p^2 = 0.01$
- Interaction of Cue Modality x Cue-Target Location, $F_{(1, 127)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of Cue Modality x Cue-Target Location x Age, $F_{(3, 127)} = 0.8$, $p = 0.5$, $\eta_p^2 = 0.5$
- Interaction of Cue Colour x Cue-Target Location, $F_{(1, 127)} = 24$, $p < 0.001$, $\eta_p^2 = 0.2$
- Interaction of Cue Colour x Cue-Target Location x Age, $F_{(3, 127)} = 0.05$, $p = 1$, $\eta_p^2 = 0.001$
- Interaction of Cue Modality x Cue Colour x Cue-Target Location, $F_{(1, 127)} = 0.4$, $p = 0.6$, $\eta_p^2 = 0.003$
- Interaction of Cue Modality x Cue Colour x Cue-Target Location x Age, $F_{(3, 127)} = 1$, $p = 0.4$, $\eta_p^2 = 0.02$

2 x 2 x 2 repeated-measures ANOVA - adults

- Main effect of Cue Modality, $F_{(1, 38)} = 76.08$, $p < 0.001$, $\eta_p^2 = 0.7$
- Main effect of Cue Colour, $F_{(1, 38)} = 36.9$, $p < 0.001$, $\eta_p^2 = 0.5$
- Main effect of Cue-Target Location, $F_{(1, 38)} = 110.91$, $p < 0.001$, $\eta_p^2 = 0.75$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 38)} = 0.05$, $p = 0.8$, $\eta_p^2 = 0.001$
- Interaction of Cue Modality x Cue-Target Location, $F_{(1, 38)} = 4.9$, $p = 0.03$, $\eta_p^2 = 0.1$
- Interaction of Cue Colour x Cue-Target Location, $F_{(1, 38)} = 161.5$, $p < 0.001$, $\eta_p^2 = 0.8$
- Interaction of Cue Modality x Cue Colour x Cue-Target Location, $F_{(1, 38)} = 2.7$, $p = 0.1$, $\eta_p^2 = 0.07$

2 x 2 x 2 repeated-measures ANOVA – 9-year-olds

- Main effect of Cue Modality, $F_{(1, 25)} = .3$, $p = 0.08$, $\eta_p^2 = 0.1$
- Main effect of Cue Colour, $F_{(1, 25)} = 28.4$, $p < 0.001$, $\eta_p^2 = 0.5$
- Main effect of Cue-Target Location, $F_{(1, 25)} = 68.9$, $p < 0.001$, $\eta_p^2 = 0.7$

- Interaction of Cue Modality x Cue Colour, $F_{(1, 25)} = 0.8$, $p = 0.4$, $\eta_p^2 = 0.03$
- Interaction of Cue Modality x Cue-Target Location, $F_{(1, 25)} = 1.4$, $p = 0.3$, $\eta_p^2 = 0.05$
- Interaction of Cue Colour x Cue-Target Location, $F_{(1, 25)} = 19.5$, $p < 0.001$, $\eta_p^2 = 0.4$
- Interaction of Cue Modality x Cue Colour x Cue-Target Location, $F_{(1, 25)} = 0.7$, $p = 0.4$, $\eta_p^2 = 0.03$

2 x 2 x 2 repeated-measures ANOVA - 7-year-olds

- Main effect of Cue Modality, $F_{(1, 37)} = 8.6$, $p = 0.006$, $\eta_p^2 = 0.2$
- Main effect of Cue Colour, $F_{(1, 37)} = 18.7$, $p < 0.001$, $\eta_p^2 = 0.3$
- Main effect of Cue-Target Location, $F_{(1, 37)} = 14$, $p < 0.001$, $\eta_p^2 = 0.4$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 37)} = 1.6$, $p = 0.2$, $\eta_p^2 = 0.04$
- Interaction of Cue Modality x Cue-Target Location, $F_{(1, 37)} = 2.1$, $p = 0.2$, $\eta_p^2 = 0.03$
- Interaction of Cue Colour x Cue-Target Location, $F = 6.4$, $p = 0.016$, $\eta_p^2 = 0.2$
- Interaction of Cue Modality x Cue Colour x Cue-Target Location, $F_{(1, 37)} = 0.6$, $p = 0.5$, $\eta_p^2 = 0.02$

2 x 2 x 2 repeated-measures ANOVA - 5-year-olds

- Main effect of Cue Modality, $F_{(1, 27)} = 3.5$, $p = 0.07$, $\eta_p^2 = 0.1$
- Main effect of Cue Colour, $F_{(1, 27)} = 2.6$, $p = 0.1$, $\eta_p^2 = 0.03$
- Main effect of Cue-Target Location, $F_{(1, 27)} = 14$, $p < 0.001$, $\eta_p^2 = 0.4$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 27)} = 0.07$, $p = 0.8$, $\eta_p^2 = 0.003$
- Interaction of Cue Modality x Cue-Target Location, $F_{(1, 27)} = 0.4$, $p = 0.5$, $\eta_p^2 = 0.05$
- Interaction of Cue Colour x Cue-Target Location, $F_{(1, 27)} = 1.4$, $p = 0.2$, $\eta_p^2 = 0.04$
- Interaction of Cue Modality x Cue Colour x Cue-Target Location, $F_{(1, 27)} = 0.7$, $p = 0.4$, $\eta_p^2 = 0.03$

RT results corrected for children's cognitive slowing

2 x 2 x 2 repeated-measures ANOVA – 9-year-olds

- Main effect of Cue Modality, $F_{(1, 25)} = 3.7$, $p = 0.07$, $\eta_p^2 = 0.1$
- Main effect of Cue Colour, $F_{(1, 25)} = 30.7$, $p < 0.001$, $\eta_p^2 = 0.5$
- Main effect of Cue-Target Location, $F_{(1, 25)} = 65.6$, $p < 0.001$, $\eta_p^2 = 0.7$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 25)} = 1.1$, $p = 0.3$, $\eta_p^2 = 0.04$
- Interaction of Cue Modality x Cue-Target Location, $F_{(1, 25)} = 1.4$, $p = 0.3$, $\eta_p^2 = 0.05$
- Interaction of Cue Colour x Cue-Target Location, $F_{(1, 25)} = 20.3$, $p < 0.001$, $\eta_p^2 = 0.5$
- Interaction of Cue Modality x Cue Colour x Cue-Target Location, $F_{(1, 25)} = 0.5$, $p = 0.5$, $\eta_p^2 = 0.02$

2 x 2 x 2 repeated-measures ANOVA - 7-year-olds

- Main effect of Cue Modality, $F_{(1, 37)} = 8.5$, $p = 0.006$, $\eta_p^2 = 0.2$
- Main effect of Cue Colour, $F_{(1, 37)} = 14.8$, $p < 0.001$, $\eta_p^2 = 0.3$

- Main effect of Cue-Target Location, $F_{(1, 37)} = 11$, $p < 0.001$, $\eta_p^2 = 0.2$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 37)} = 1.5$, $p = 0.2$, $\eta_p^2 = 0.04$
- Interaction of Cue Modality x Cue-Target Location, $F_{(1, 37)} = 2.1$, $p = 0.2$, $\eta_p^2 = 0.5$
- Interaction of Cue Colour x Cue-Target Location, $F_{(1, 37)} = 8$, $p = 0.008$, $\eta_p^2 = 0.2$
- Interaction of Cue Modality x Cue Colour x Cue-Target Location, $F_{(1, 37)} = 1.2$, $p = 0.3$, $\eta_p^2 = 0.03$

2 x 2 x 2 repeated-measures ANOVA - 5-year-olds

- Main effect of Cue Modality, $F_{(1, 27)} = 3.5$, $p = 0.07$, $\eta_p^2 = 0.1$
- Main effect of Cue Colour, $F_{(1, 27)} = 2.6$, $p = 0.1$, $\eta_p^2 = 0.02$
- Main effect of Cue-Target Location, $F_{(1, 27)} = 4.4$, $p = 0.045$, $\eta_p^2 = 0.1$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 27)} = 0.3$, $p = 0.6$, $\eta_p^2 = 0.01$
- Interaction of Cue Modality x Cue-Target Location, $F_{(1, 27)} = 0.03$, $p = 0.9$, $\eta_p^2 = 0.001$
- Interaction of Cue Colour x Cue-Target Location, $F_{(1, 27)} = 1$, $p = 0.3$, $\eta_p^2 = 0.03$
- Interaction of Cue Modality x Cue Colour x Cue-Target Location, $F_{(1, 27)} = 0.6$, $p = 0.4$, $\eta_p^2 = 0.02$

Error rates

1-way Kruskal–Wallis *H* test

- Main effect of Age, $\chi^2(3) = 81.4$, $p < 0.001$

3-way Durbin test – Adults

- Main effect of Cue Modality, $\chi^2(1) = 0.8$, $p = 0.4$
- Main effect of Cue Colour, $\chi^2(1) = 0.005$, $p = 0.9$
- Main effect of Cue-Target Location, $\chi^2(1) = 8.7$, $p = 0.003$

3-way Friedman test – 9-year-olds

- Main effect of Cue Modality, $\chi^2(1) = 0.1$, $p = 0.7$
- Main effect of Cue Colour, $\chi^2(1) = 0.1$, $p = 0.8$
- Main effect of Cue-Target Location, $\chi^2(1) = 0.9$, $p = 0.3$

3-way Friedman test – 7-year-olds

- Main effect of Cue Modality, $\chi^2(1) = 0.01$, $p = 0.9$
- Main effect of Cue Colour, $\chi^2(1) = 1.4$, $p = 0.2$
- Main effect of Cue-Target Location, $\chi^2(1) = 1.3$, $p = 0.3$

3-way Friedman test – 5-year-olds

- Main effect of Cue Modality, $\chi^2(1) = 0.07$, $p = 0.8$
- Main effect of Cue Colour, $\chi^2(1) = 0.01$, $p = 0.9$
- Main effect of Cue-Target Location, $\chi^2(1) = 0.4$, $p = 0.5$

Appendix 2 – Developmental study, N2pc analyses

Normative analysis – canonical

2 x 2 x 2 repeated-measures ANOVA - Adults

- Main effect of Cue Modality, $F_{(1, 38)} = 7.1$, $p = 0.011$, $\eta_p^2 = 0.2$
- Main effect of Cue Colour, $F_{(1, 38)} = 8.4$, $p = 0.006$, $\eta_p^2 = 0.2$
- Main effect of Contralaterality, $F_{(1, 38)} = 17.8$, $p < 0.001$, $\eta_p^2 = 0.3$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 38)} = 0.7$, $p = 0.4$, $\eta_p^2 = 0.02$
- Interaction of Cue Modality x Contralaterality, $F_{(1, 38)} = 0.2$, $p = 0.7$, $\eta_p^2 = 0.006$
- Interaction of Cue Colour x Contralaterality, $F_{(1, 38)} = 17$, $p < 0.001$, $\eta_p^2 = 0.3$
- Interaction of Cue Modality x Cue Colour x Contralaterality, $F_{(1, 38)} = 8$, $p = 0.007$, $\eta_p^2 = 0.2$

2 x 2 x 2 repeated-measures ANOVA – 9-year-olds

- Main effect of Cue Modality, $F_{(1, 25)} = 60.5$, $p < 0.001$, $\eta_p^2 = 0.7$
- Main effect of Cue Colour, $F_{(1, 25)} = 0.8$, $p = 0.4$, $\eta_p^2 = 0.03$
- Main effect of Contralaterality, $F_{(1, 25)} = 0.4$, $p = 0.6$, $\eta_p^2 = 0.02$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 25)} = 5.3$, $p = 0.03$, $\eta_p^2 = 0.2$
- Interaction of Cue Modality x Contralaterality, $F_{(1, 25)} = 0.06$, $p = 0.8$, $\eta_p^2 = 0.003$
- Interaction of Cue Colour x Contralaterality, $F_{(1, 25)} = 2.2$, $p = 0.2$, $\eta_p^2 = 0.08$
- Interaction of Cue Modality x Cue Colour x Contralaterality, $F_{(1, 38)} = 0.04$, $p = 0.8$, $\eta_p^2 = 0.002$

2 x 2 x 2 repeated-measures ANOVA - 7-year-olds

- Main effect of Cue Modality, $F_{(1, 37)} = 35$, $p < 0.001$, $\eta_p^2 = 0.5$
- Main effect of Cue Colour, $F_{(1, 37)} = 2$, $p = 0.2$, $\eta_p^2 = 0.05$
- Main effect of Contralaterality, $F_{(1, 37)} = 0.04$, $p = 0.8$, $\eta_p^2 = 0.001$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 37)} = 0.4$, $p = 0.5$, $\eta_p^2 = 0.01$
- Interaction of Cue Modality x Contralaterality, $F_{(1, 37)} = 3.4$, $p = 0.07$, $\eta_p^2 = 0.08$
- Interaction of Cue Colour x Contralaterality, $F_{(1, 37)} = 3.9$, $p = 0.06$, $\eta_p^2 = 0.1$
- Interaction of Cue Modality x Cue Colour x Contralaterality, $F_{(1, 37)} = 2.1$, $p = 0.2$, $\eta_p^2 = 0.05$

2 x 2 x 2 repeated-measures ANOVA - 5-year-olds

- Main effect of Cue Modality, $F_{(1, 27)} = 3.6$, $p = 0.07$, $\eta_p^2 = 0.1$
- Main effect of Cue Colour, $F_{(1, 27)} = 1.1$, $p = 0.3$, $\eta_p^2 = 0.04$
- Main effect of Contralaterality, $F_{(1, 27)} = 0.2$, $p = 0.6$, $\eta_p^2 = 0.008$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 27)} = 0.1$, $p = 0.7$, $\eta_p^2 = 0.004$
- Interaction of Cue Modality x Contralaterality, $F_{(1, 27)} = 0.1$, $p = 0.7$, $\eta_p^2 = 0.005$
- Interaction of Cue Colour x Contralaterality, $F_{(1, 27)} = 0.4$, $p = 0.5$, $\eta_p^2 = 0.02$

- Interaction of Cue Modality x Cue Colour x Contralaterality, $F_{(1, 27)} = 0.001$, $p = 1$, $\eta_p^2 < 0.001$

Normative analysis – data-driven

2 x 2 x 2 repeated-measures ANOVA - Adults

- Main effect of Cue Modality, $F_{(1, 38)} = 6.3$, $p = 0.016$, $\eta_p^2 = 0.1$
- Main effect of Cue Colour, $F_{(1, 38)} = 10.7$, $p = 0.002$, $\eta_p^2 = 0.2$
- Main effect of Contralaterality, $F_{(1, 38)} = 17.6$, $p < 0.001$, $\eta_p^2 = 0.3$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 38)} = 0.8$, $p = 0.4$, $\eta_p^2 = 0.02$
- Interaction of Cue Modality x Contralaterality, $F_{(1, 38)} = 0.1$, $p = 0.8$, $\eta_p^2 = 0.002$
- Interaction of Cue Colour x Contralaterality, $F_{(1, 38)} = 20.4$, $p < 0.001$, $\eta_p^2 = 0.4$
- Interaction of Cue Modality x Cue Colour x Contralaterality, $F_{(1, 38)} = 0.03$, $p = 0.9$, $\eta_p^2 = 0.001$

2 x 2 x 2 repeated-measures ANOVA – 9-year-olds

- Main effect of Cue Modality, $F_{(1, 25)} = 45.8$, $p < 0.001$, $\eta_p^2 = 0.7$
- Main effect of Cue Colour, $F_{(1, 25)} = 0.5$, $p = 0.5$, $\eta_p^2 = 0.02$
- Main effect of Contralaterality, $F_{(1, 25)} = 0.9$, $p = 0.4$, $\eta_p^2 = 0.03$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 25)} = 4.2$, $p = 0.05$, $\eta_p^2 = 0.1$
- Interaction of Cue Modality x Contralaterality, $F_{(1, 25)} = 1.9$, $p = 0.2$, $\eta_p^2 = 0.07$
- Interaction of Cue Colour x Contralaterality, $F_{(1, 25)} = 1$, $p = 0.3$, $\eta_p^2 = 0.04$
- Interaction of Cue Modality x Cue Colour x Contralaterality, $F_{(1, 38)} = 0.09$, $p = 0.8$, $\eta_p^2 = 0.003$

2 x 2 x 2 repeated-measures ANOVA - 7-year-olds

- Main effect of Cue Modality, $F_{(1, 37)} = 42.4$, $p < 0.001$, $\eta_p^2 = 0.5$
- Main effect of Cue Colour, $F_{(1, 37)} = 0.4$, $p = 0.6$, $\eta_p^2 = 0.01$
- Main effect of Contralaterality, $F_{(1, 37)} = 0.1$, $p = 0.7$, $\eta_p^2 = 0.003$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 37)} = 0.8$, $p = 0.4$, $\eta_p^2 = 0.02$
- Interaction of Cue Modality x Contralaterality, $F_{(1, 37)} = 2.5$, $p = 0.1$, $\eta_p^2 = 0.06$
- Interaction of Cue Colour x Contralaterality, $F_{(1, 37)} = 4$, $p = 0.06$, $\eta_p^2 = 0.1$
- Interaction of Cue Modality x Cue Colour x Contralaterality, $F_{(1, 37)} = 0.5$, $p = 0.5$, $\eta_p^2 = 0.1$

2 x 2 x 2 repeated-measures ANOVA - 5-year-olds

- Main effect of Cue Modality, $F_{(1, 27)} = 9.4$, $p = 0.05$, $\eta_p^2 = 0.3$
- Main effect of Cue Colour, $F_{(1, 27)} = 0.2$, $p = 0.7$, $\eta_p^2 = 0.008$
- Main effect of Contralaterality, $F_{(1, 27)} = 0.3$, $p = 0.6$, $\eta_p^2 = 0.01$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 27)} = 0.1$, $p = 0.7$, $\eta_p^2 = 0.005$
- Interaction of Cue Modality x Contralaterality, $F_{(1, 27)} = 1.6$, $p = 0.2$, $\eta_p^2 = 0.06$

- Interaction of Cue Colour x Contralaterality, $F_{(1, 27)} = 0.6$, $p = 0.5$, $\eta_p^2 = 0.02$
- Interaction of Cue Modality x Cue Colour x Contralaterality, $F_{(1, 27)} = 1.5$, $p = 0.2$, $\eta_p^2 = 0.05$

Descriptive analysis

2 x 2 x 2 repeated-measures ANOVA – 9-year-olds

- Main effect of Cue Modality, $F_{(1, 25)} = 37.4$, $p < 0.001$, $\eta_p^2 = 0.6$
- Main effect of Cue Colour, $F_{(1, 25)} = 2.2$, $p = 0.1$, $\eta_p^2 = 0.08$
- Main effect of Contralaterality, $F_{(1, 25)} = 2.6$, $p = 0.1$, $\eta_p^2 = 0.1$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 25)} = 1.1$, $p = 0.3$, $\eta_p^2 = 0.04$
- Interaction of Cue Modality x Contralaterality, $F_{(1, 25)} = 0.002$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of Cue Colour x Contralaterality, $F_{(1, 25)} = 0.6$, $p = 0.4$, $\eta_p^2 = 0.02$
- Interaction of Cue Modality x Cue Colour x Contralaterality, $F_{(1, 25)} = 0.02$, $p = 0.9$, $\eta_p^2 = 0.001$

2 x 2 x 2 repeated-measures ANOVA - 7-year-olds

- Main effect of Cue Modality, $F_{(1, 37)} = 10.9$, $p = 0.002$, $\eta_p^2 = 0.2$
- Main effect of Cue Colour, $F_{(1, 37)} = 3.7$, $p = 0.06$, $\eta_p^2 = 0.09$
- Main effect of Contralaterality, $F_{(1, 37)} = 1.1$, $p = 0.3$, $\eta_p^2 = 0.03$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 37)} = 1.4$, $p = 0.2$, $\eta_p^2 = 0.04$
- Interaction of Cue Modality x Contralaterality, $F_{(1, 37)} = 2.3$, $p = 0.1$, $\eta_p^2 = 0.06$
- Interaction of Cue Colour x Contralaterality, $F_{(1, 37)} = 1.2$, $p = 0.3$, $\eta_p^2 = 0.03$
- Interaction of Cue Modality x Cue Colour x Contralaterality, $F_{(1, 37)} = 0.1$, $p = 0.8$, $\eta_p^2 = 0.003$

2 x 2 x 2 repeated-measures ANOVA - 5-year-olds

- Main effect of Cue Modality, $F_{(1, 27)} = 2$, $p = 0.2$, $\eta_p^2 = 0.07$
- Main effect of Cue Colour, $F_{(1, 27)} = 4.6$, $p = 0.04$, $\eta_p^2 = 0.1$
- Main effect of Contralaterality, $F_{(1, 27)} = 0.2$, $p = 0.7$, $\eta_p^2 = 0.008$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 27)} = 0.8$, $p = 0.4$, $\eta_p^2 = 0.03$
- Interaction of Cue Modality x Contralaterality, $F_{(1, 27)} = 0.3$, $p = 0.6$, $\eta_p^2 = 0.01$
- Interaction of Cue Colour x Contralaterality, $F_{(1, 27)} = 1.5$, $p = 0.3$, $\eta_p^2 = 0.2$
- Interaction of Cue Modality x Cue Colour x Contralaterality, $F_{(1, 27)} = 0.4$, $p = 0.9$, $\eta_p^2 = 0.001$

Appendix 3 – Developmental study, EN analyses

Normative analysis – GFP

2 x 2 repeated-measures ANOVA - Adults

- Main effect of Cue Modality, $F_{(1, 38)} = 0.1$, $p = 0.7$, $\eta_p^2 = 0.003$
- Main effect of Cue Colour, $F_{(1, 38)} = 2.8$, $p = 0.1$, $\eta_p^2 = 0.07$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 38)} = 0.5$, $p = 0.5$, $\eta_p^2 = 0.01$

2 x 2 repeated-measures ANOVA – 9-year-olds

- Main effect of Cue Modality, $F_{(1, 25)} = 45.8$, $p < 0.001$, $\eta_p^2 = 0.7$
- Main effect of Cue Colour, $F_{(1, 25)} = 0.5$, $p = 0.5$, $\eta_p^2 = 0.02$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 25)} = 4.2$, $p = 0.05$, $\eta_p^2 = 0.1$

2 x 2 repeated-measures ANOVA - 7-year-olds

- Main effect of Cue Modality, $F_{(1, 37)} = 1.5$, $p = 0.2$, $\eta_p^2 = 0.04$
- Main effect of Cue Colour, $F_{(1, 37)} = 3.8$, $p = 0.06$, $\eta_p^2 = 0.1$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 37)} = 3$, $p = 0.08$, $\eta_p^2 = 0.1$

2 x 2 repeated-measures ANOVA - 5-year-olds

- Main effect of Cue Modality, $F_{(1, 27)} = 0.3$, $p = 0.6$, $\eta_p^2 = 0.01$
- Main effect of Cue Colour, $F_{(1, 27)} = 1.2$, $p = 0.3$, $\eta_p^2 = 0.04$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 27)} = 0.1$, $p = 0.7$, $\eta_p^2 = 0.005$

Normative analysis – topography

2 x 2 x 4 repeated-measures ANOVA - Adults

- Main effect of Cue Modality, $F_{(3, 114)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Cue Colour, $F_{(3, 114)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Map, $F_{(3, 114)} = 18.3$, $p < 0.001$, $\eta_p^2 = 0.3$
- Interaction of Cue Modality x Cue Colour, $F_{(3, 114)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of Cue Modality x Map, $F_{(3, 114)} = 3.2$, $p = 0.03$, $\eta_p^2 = 0.1$
- Interaction of Cue Colour x Map, $F_{(2.4, 89.1)} = 12$, $p < 0.001$, $\eta_p^2 = 0.2$
- Interaction of Cue Modality x Cue Colour x Map, $F_{(3, 114)} = 5.4$, $p = 0.002$, $\eta_p^2 = 0.1$

Table A.1

Post-hoc Inter-map duration comparisons following 2-way Map x Cue Colour interaction – Adults, Normative

Map	**Map1 TCC (15ms)**	**Map2 TCC (13ms)**	**Map3 TCC (25ms)**	**Map4 TCC (67ms)**	**Map1 NCC (28ms)**	**Map2 NCC (34ms)**	**Map3 NCC (20ms)**	**Map4 NCC (40ms)**
Map1 TCC	/							

(15ms)								
Map2 TCC (13ms)	0.3	/						
Map3 TCC (25ms)	1.5	1.8	/					
Map4 TCC (67ms)	7.7[c]	8[c]	6.3[c]	/				
Map1 NCC (28ms)	2.3	N.O.I	N.O.I	N.O.I	/			
Map2 NCC (34ms)	N.O.I	3.9[c]	N.O.I	N.O.I	0.9	/		
Map3 NCC (20ms)	N.O.I	N.O.I	1	N.O.I	1.2	2.1	/	
Map4 NCC (40ms)	N.O.I	N.O.I	N.O.I	5.2[c]	1.8	0.8	3[d]	/

Note. t-values of the comparisons between Map durations are shown in the table, marked by their significance level, as follows: [a] $p < 0.05$ level, [b] $p < 0.01$ level, [c] $p < 0.001$ level, [d] a nonsignificant trend. N.O.I is an abbreviation for 'Not Of Interest' denoting comparisons that were not informative for post-hoc analyses, and were thus not conducted.

Table A.2

Post-hoc Inter-map duration comparisons following 2-way Map x Cue Modality interaction – Adults, Normative

Map	**Map1 AV (25ms)**	**Map2 AV (17ms)**	**Map3 AV (26ms)**	**Map4 AV (53ms)**	**Map1 V (18ms)**	**Map2 V (30ms)**	**Map3 V (19ms)**	**Map4 V (54ms)**
Map1 AV (25ms)	/							
Map2 AV (17ms)	1.3	/						
Map3 AV (26ms)	0.1	1.4	/					
Map4 AV (53ms)	4.3[c]	5.6[c]	4.2[c]	/				
Map1 V (18ms)	1.6	N.O.I	N.O.I	N.O.I	/			
Map2 V (30ms)	N.O.I	2.8[d]	N.O.I	N.O.I	2	/		
Map3 V (19ms)	N.O.I	N.O.I	1.5	N.O.I	0.2	1.8	/	
Map4 V	N.O.I	N.O.I	N.O.I	0.2	5.7[c]	3.7[c]	5.5[c]	/

(54ms)

Note. t-values of the comparisons between Map durations are shown in the table, marked by their significance level, as follows: ^{a} $p < 0.05$ level, ^{b} $p < 0.01$ level, ^{c} $p < 0.001$ level, ^{d} a nonsignificant trend. N.O.I is an abbreviation for 'Not Of Interest' denoting comparisons that were not informative for post-hoc analyses, and were thus not conducted.

2 x 2 x 4 repeated-measures ANOVA – 9-year-olds

- Main effect of Cue Modality, $F_{(3, 75)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Cue Colour, $F_{(3, 75)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Map, $F_{(3, 75)} = 9.2$, $p < 0.001$, $\eta_p^2 = 0.3$
- Interaction of Cue Modality x Cue Colour, $F_{(3, 75)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of Cue Modality x Map, $F_{(3, 75)} = 3.4$, $p = 0.04$, $\eta_p^2 = 0.1$
- Interaction of Cue Colour x Map, $F_{(3, 75)} = 1.3$, $p = 0.3$, $\eta_p^2 = 0.05$
- Interaction of Cue Modality x Cue Colour x Map, $F_{(1, 38)} = 1$, $p = 0.2$, $\eta_p^2 = 0.05$

Table A.3

Post-hoc Inter-map duration comparisons following 2-way Map x Cue Modality interaction – 9-year-olds, Normative

Map	**Map1 AV (28ms)**	**Map2 AV (27ms)**	**Map3 AV (27ms)**	**Map4 AV (39ms)**	**Map1 V (24ms)**	**Map2 V (32ms)**	**Map3 V (11ms)**	**Map4 V (55ms)**
Map1 AV (28ms)	/							
Map2 AV (27ms)	0.2	/						
Map3 AV (27ms)	0.2	0.1	/					
Map4 AV (39ms)	1.5	1.6	1.7	/				
Map1 V (24ms)	0.7	N.O.I	N.O.I	N.O.I	/			
Map2 V (32ms)	N.O.I	0.7	N.O.I	N.O.I	1	/		
Map3 V (11ms)	N.O.I	N.O.I	2.6^a	N.O.I	1.8	2.8^a	/	
Map4 V (55ms)	N.O.I	N.O.I	N.O.I	2.5^a	4^c	3.7^c	5.8^c	/

Note. t-values of the comparisons between Map durations are shown in the table, marked by their significance level, as follows: ^{a} $p < 0.05$ level, ^{b} $p < 0.01$ level, ^{c} $p < 0.001$ level, ^{d} a nonsignificant trend. N.O.I is an abbreviation for 'Not Of Interest' denoting comparisons that were not informative for post-hoc analyses, and were thus not conducted.

2 x 2 x 4 repeated-measures ANOVA - 7-year-olds

- Main effect of Cue Modality, $F_{(3, 111)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Cue Colour, $F_{(3, 111)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Map, $F_{(2.3, 85.5)} = 9.7$, $p < 0.001$, $\eta_p^2 = 0.2$
- Interaction of Cue Modality x Cue Colour, $F_{(3, 111)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of Cue Modality x Map, $F_{(2.4, 87.3)} = 1.3$, $p = 0.3$, $\eta_p^2 = 0.03$
- Interaction of Cue Colour x Map, $F_{(3, 111)} = 0.7$, $p = 0.6$, $\eta_p^2 = 0.02$
- Interaction of Cue Modality x Cue Colour x Map, $F_{(3, 111)} = 2.9$, $p = 0.1$, $\eta_p^2 = 0.06$

2 x 2 x 4 repeated-measures ANOVA - 5-year-olds

- Main effect of Cue Modality, $F_{(3, 81)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Cue Colour, $F_{(3, 81)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Map, $F_{(3, 81)} = 6.3$, $p < 0.001$, $\eta_p^2 = 0.2$
- Interaction of Cue Modality x Cue Colour, $F_{(3, 81)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of Cue Modality x Map, $F_{(2.3, 61.6)} = 0.7$, $p = 0.5$, $\eta_p^2 = 0.03$
- Interaction of Cue Colour x Map, $F_{(2.1, 57)} = 0.8$, $p = 0.4$, $\eta_p^2 = 0.02$
- Interaction of Cue Modality x Cue Colour x Map, $F_{(3, 81)} = 1$, $p = 0.4$, $\eta_p^2 = 0.04$

Descriptive analysis – GFP

2 x 2 repeated-measures ANOVA – 9-year-olds

- Main effect of Cue Modality, $F_{(1, 25)} = 1.2$, $p = 0.3$, $\eta_p^2 = 0.05$
- Main effect of Cue Colour, $F_{(1, 25)} = 0.8$, $p = 0.4$, $\eta_p^2 = 0.03$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 25)} = 0.4$, $p = 0.5$, $\eta_p^2 = 0.02$

2 x 2 repeated-measures ANOVA - 7-year-olds

- Main effect of Cue Modality, $F_{(1, 37)} = 1.5$, $p = 0.2$, $\eta_p^2 = 0.04$
- Main effect of Cue Colour, $F_{(1,37)} = 3.07$, $p = 0.09$, $\eta_p^2 = 0.08$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 37)} = 1.5$, $p = 0.4$, $\eta_p^2 = 0.01$

2 x 2 repeated-measures ANOVA - 5-year-olds

- Main effect of Cue Modality, $F_{(1, 27)} = 0.3$, $p = 0.6$, $\eta_p^2 = 0.01$
- Main effect of Cue Colour, $F_{(1, 27)} = 0.3$, $p = 0.6$, $\eta_p^2 = 0.01$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 27)} = 0.08$, $p = 0.7$, $\eta_p^2 = 0.003$

Descriptive analysis – topography

2 x 2 x 9 repeated-measures ANOVA – 9-year-olds

- Main effect of Cue Modality, $F_{(1, 25)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Cue Colour, $F_{(1, 25)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Map, $F_{(8, 200)} = 2.7$, $p = 0.009$, $\eta_p^2 = 0.1$

- Interaction of Cue Modality x Cue Colour, $F_{(1, 25)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of Cue Modality x Map, $F_{(8, 200)} = 2.4$, $p = 0.02$, $\eta_p^2 = 0.1$
- Interaction of Cue Colour x Map, $F_{(8, 200)} = 3.4$, $p = 0.001$, $\eta_p^2 = 0.1$
- Interaction of Cue Modality x Cue Colour x Map, $F_{(8, 200)} = 2.2$, $p = 0.048$, $\eta_p^2 = 0.1$

Table A.4

Post-hoc Inter-map duration comparisons following 2-way Map x Cue Colour interaction – 9-year-olds, Descriptive

1st compared map (ms)	2nd compared map (ms)	t-values
NCC, Map91 (8ms)	TCC, Map91 (18ms)	1.8
	NCC, Map92 (13ms)	0.9
	NCC, Map93 (25ms)	2.9[d]
	NCC, Map94 (21ms)	2.2
	NCC, Map95 (24ms)	3.9[c]
	NCC, Map96 (9ms)	0.2
	NCC, Map97 (15ms)	1.2
	NCC, Map98 (16ms)	1.5
	NCC, Map99 (17ms)	1.6
NCC, Map92 (13ms)	TCC, Map92 (9ms)	0.8
	NCC, Map93 (25ms)	-2.0
	NCC, Map94 (21ms)	-1.2
	NCC, Map95 (24ms)	-1.9
	NCC, Map96 (9ms)	0.8
	NCC, Map97 (15ms)	-0.2
	NCC, Map98 (16ms)	-0.5
	NCC, Map99 (17ms)	-0.6
NCC, Map93 (25ms)	TCC, Map93 (18ms)	1.3
	NCC, Map94 (21ms)	0.7
	NCC, Map95 (24ms)	0.1
	NCC, Map96 (9ms)	2.7[d]
	NCC, Map97 (15ms)	1.7
	NCC, Map98 (16ms)	1.4
	NCC, Map99 (17ms)	1.3
NCC, Map94 (21ms)	TCC, Map94 (8ms)	3.4[b]
	NCC, Map95 (24ms)	-0.6
	NCC, Map96 (9ms)	2.0
	NCC, Map97 (15ms)	1.0
	NCC, Map98 (16ms)	0.7
	NCC, Map99 (17ms)	0.6
NCC, Map95 (24ms)	TCC, Map95 (25ms)	-0.2
	NCC, Map96 (9ms)	2.6

	NCC, Map97 (15ms)	1.6
	NCC, Map98 (16ms)	1.3
	NCC, Map99 (17ms)	1.2
NCC, Map96 (9ms)	TCC, Map96 (28ms)	-3.7[b]
	NCC, Map97 (15ms)	-1.0
	NCC, Map98 (16ms)	-1.3
	NCC, Map99 (17ms)	-1.4
NCC, Map97 (15ms)	TCC, Map97 (8ms)	1.2
	NCC, Map98 (16ms)	-0.3
	NCC, Map99 (17ms)	-0.4
NCC, Map98 (16ms)	TCC, Map98 (24ms)	-1.4
	NCC, Map99 (17ms)	-0.1
NCC, Map99 (17ms)	TCC, Map99 (9ms)	3.0[a]
TCC, Map91 (18ms)	TCC, Map92 (9ms)	1.5
	TCC, Map93 (18ms)	-0.1
	TCC, Map94 (8ms)	1.7
	TCC, Map95 (25ms)	-1.3
	TCC, Map96 (28ms)	-1.8
	TCC, Map97 (18ms)	1.6
	TCC, Map98 (24ms)	-1.1
	TCC, Map99 (9ms)	1.4
TCC, Map92 (9ms)	TCC, Map93 (18ms)	-1.5
	TCC, Map94 (8ms)	0.2
	TCC, Map95 (25ms)	-2.7[d]
	TCC, Map96 (28ms)	-3.3[a]
	TCC, Map97 (18ms)	0.1
	TCC, Map98 (24ms)	-2.5
	TCC, Map99 (9ms)	0.0
TCC, Map93 (18ms)	TCC, Map94 (8ms)	1.8
	TCC, Map95 (25ms)	-1.2
	TCC, Map96 (28ms)	-1.8
	TCC, Map97 (18ms)	1.7
	TCC, Map98 (24ms)	-1.0
	TCC, Map99 (9ms)	1.5
TCC, Map94 (8ms)	TCC, Map95 (25ms)	-3.0[a]
	TCC, Map96 (28ms)	-3.5
	TCC, Map97 (18ms)	-0.1
	TCC, Map98 (24ms)	-2.8[d]
	TCC, Map99 (9ms)	-0.3
TCC, Map95 (25ms)	TCC, Map96 (28ms)	-0.6
	TCC, Map97 (18ms)	2.9[a]

	TCC, Map98 (24ms)	0.2
	TCC, Map99 (9ms)	2.7
TCC, Map96 (28ms)	TCC, Map97 (18ms)	3.4[b]
	TCC, Map98 (24ms)	0.7
	TCC, Map99 (9ms)	3.3[b]
TCC, Map97 (18ms)	TCC, Map98 (24ms)	-2.7[d]
	TCC, Map99 (9ms)	-0.1
TCC, Map98 (24ms)	TCC, Map99 (9ms)	2.5

Note. Significance levels that mark *t*-values are as follows: [a] $p < 0.05$ level, [b] $p < 0.01$ level, [c] $p < 0.001$ level, [d] a nonsignificant trend.

Table A.5

Post-hoc Inter-map duration comparisons following 2-way Map x Cue Modality interaction – 9-year-olds, Descriptive

1st compared map (ms)	2nd compared map (ms)	t-values
AV, Map91 (12ms)	V, Map91 (14ms)	-0.4
	AV, Map92 (5ms)	1.0
	AV, Map93 (29ms)	-2.9[a]
	AV, Map94 (18ms)	-1.1
	AV, Map95 (30ms)	-3.1[a]
	AV, Map96 (18ms)	-1.0
	AV, Map97 (8ms)	0.6
	AV, Map98 (16ms)	-0.8
	AV, Map99 (11ms)	0.1
AV, Map92 (5ms)	V, Map92 (17ms)	-3.1[a]
	AV, Map93 (29ms)	-4.9[c]
	AV, Map94 (18ms)	-2.1
	AV, Map95 (30ms)	-4.1[b]
	AV, Map96 (18ms)	-2.1
	AV, Map97 (8ms)	-0.4
	AV, Map98 (16ms)	-1.9
	AV, Map99 (11ms)	-0.9
AV, Map93 (29ms)	V, Map93 (14ms)	3.7[b]
	AV, Map94 (18ms)	1.8
	AV, Map95 (30ms)	-0.2
	AV, Map96 (18ms)	1.9
	AV, Map97 (8ms)	3.5[a]
	AV, Map98 (16ms)	2.1
	AV, Map99 (11ms)	3.0[a]
AV, Map94 (18ms)	V, Map94 (10ms)	1.4
	AV, Map95 (30ms)	-2.0

	AV, Map96 (18ms)	0.0
	AV, Map97 (8ms)	1.7
	AV, Map98 (16ms)	0.3
	AV, Map99 (11ms)	1.2
AV, Map95 (30ms)	V, Map95 (19ms)	2.0
	AV, Map96 (18ms)	2.0
	AV, Map97 (8ms)	3.7[b]
	AV, Map98 (16ms)	2.3
	AV, Map99 (11ms)	3.2[a]
AV, Map96 (18ms)	V, Map96 (19ms)	-0.2
	AV, Map97 (8ms)	1.6
	AV, Map98 (16ms)	0.2
	AV, Map99 (11ms)	1.2
AV, Map97 (8ms)	V, Map97 (15ms)	-1.2
	AV, Map98 (16ms)	-1.4
	AV, Map99 (11ms)	-0.5
AV, Map98 (16ms)	V, Map98 (24ms)	-1.3
	AV, Map99 (11ms)	0.9
AV, Map99 (11ms)	V, Map99 (15ms)	-0.8
V, Map91 (14ms)	V, Map92 (17ms)	-0.6
	V, Map93 (14ms)	0.0
	V, Map94 (10ms)	0.6
	V, Map95 (19ms)	-0.8
	V, Map96 (19ms)	-0.9
	V, Map97 (15ms)	-0.2
	V, Map98 (24ms)	-1.7
	V, Map99 (15ms)	-0.2
V, Map92 (17ms)	V, Map93 (14ms)	0.6
	V, Map94 (10ms)	1.1
	V, Map95 (19ms)	-0.3
	V, Map96 (19ms)	-0.3
	V, Map97 (15ms)	0.4
	V, Map98 (24ms)	-1.1
	V, Map99 (15ms)	0.3
V, Map93 (14ms)	V, Map94 (10ms)	0.6
	V, Map95 (19ms)	-0.9
	V, Map96 (19ms)	-0.9
	V, Map97 (15ms)	-0.2
	V, Map98 (24ms)	-1.7
	V, Map99 (15ms)	-0.3
V, Map94 (10ms)	V, Map95 (19ms)	-1.4

	V, Map96 (19ms)	-1.5
	V, Map97 (15ms)	-0.8
	V, Map98 (24ms)	-2.3
	V, Map99 (15ms)	-0.8
V, Map95 (19ms)	V, Map96 (19ms)	0.0
	V, Map97 (15ms)	0.7
	V, Map98 (24ms)	-0.8
	V, Map99 (15ms)	0.6
V, Map96 (19ms)	V, Map97 (15ms)	0.7
	V, Map98 (24ms)	-0.8
	V, Map99 (15ms)	0.6
V, Map97 (15ms)	V, Map98 (24ms)	-1.5
	V, Map99 (15ms)	0.0
V, Map98 (24ms)	V, Map99 (15ms)	1.4

Note. Significance levels that mark *t*-values are as follows: [a] $p < 0.05$ level, [b] $p < 0.01$ level, [c] $p < 0.001$ level, [d] a nonsignificant trend.

Table A.6

Post-hoc Inter-map duration comparisons following 3-way Map x Cue Colour x Cue Modality interaction – 9-year-olds, Descriptive

1st compared map (ms)	2nd compared map (ms)	t-values
NCC, AV, Map91 (12ms)	TCC, AV, Map91 (11ms)	0.2
	NCC, V, Map91 (3ms)	1.1
TCC, AV, Map91 (11ms)	TCC, V, Map91 (24ms)	-1.7
NCC, V, Map91 (3ms)	TCC, V, Map91 (24ms)	-3.7[b]
NCC, AV, Map92 (4ms)	TCC, AV, Map92 (7ms)	-0.4
	NCC, V, Map92 (23ms)	-3.5[b]
TCC, AV, Map92 (7ms)	TCC, V, Map92 (11ms)	-0.5
NCC, V, Map92 (23ms)	TCC, V, Map92 (11ms)	1.5
NCC, AV, Map93 (38ms)	TCC, AV, Map93 (20ms)	2.3
	NCC, V, Map93 (11ms)	4.2[b]
TCC, AV, Map93 (20ms)	TCC, V, Map93 (16ms)	0.5
NCC, V, Map93 (11ms)	TCC, V, Map93 (16ms)	-0.6
NCC, AV, Map94 (30ms)	TCC, AV, Map94 (6ms)	5.0[c]
	NCC, V, Map94 (11ms)	3.3[a]
TCC, AV, Map94 (6ms)	TCC, V, Map94 (9ms)	-0.4
NCC, V, Map94 (11ms)	TCC, V, Map94 (9ms)	0.2
NCC, AV, Map95 (27ms)	TCC, AV, Map95 (33ms)	-0.8
	NCC, V, Map95 (21ms)	0.7
TCC, AV, Map95 (33ms)	TCC, V, Map95 (17ms)	2.1
NCC, V, Map95 (21ms)	TCC, V, Map95 (17ms)	0.6

NCC, AV, Map96 (8ms)	TCC, AV, Map96 (27ms)	-2.4
	NCC, V, Map96 (9ms)	-0.1
TCC, AV, Map96 (27ms)	TCC, V, Map96 (29ms)	-0.2
NCC, V, Map96 (9ms)	TCC, V, Map96 (29ms)	-2.5
NCC, AV, Map97 (7ms)	TCC, AV, Map97 (8ms)	-0.1
	NCC, V, Map97 (22ms)	-1.7
TCC, AV, Map97 (8ms)	TCC, V, Map97 (8ms)	0.0
NCC, V, Map97 (22ms)	TCC, V, Map97 (8ms)	1.7
NCC, AV, Map98 (12ms)	TCC, AV, Map98 (21ms)	-1.0
	NCC, V, Map98 (20ms)	-1.0
TCC, AV, Map98 (21ms)	TCC, V, Map98 (27ms)	-0.8
NCC, V, Map98 (20ms)	TCC, V, Map98 (27ms)	-0.9
NCC, AV, Map99 (8ms)	TCC, AV, Map99 (14ms)	-0.7
	NCC, V, Map99 (26ms)	-3.1^a
TCC, AV, Map99 (14ms)	TCC, V, Map99 (5ms)	1.1
NCC, V, Map99 (26ms)	TCC, V, Map99 (5ms)	3.6^b

Note. Significance levels that mark *t*-values are as follows: ^{a} $p < 0.05$ level, ^{b} $p < 0.01$ level, ^{c} $p < 0.001$ level, ^{d} a nonsignificant trend.

2 x 2 x 5 repeated-measures ANOVA - 7-year-olds

- Main effect of Cue Modality, $F_{(1, 37)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Cue Colour, $F_{(1, 37)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Map, $F_{(3.2, 117.6)} = 9.8$, $p < 0.001$, $\eta_p^2 = 0.2$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 37)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of Cue Modality x Map, $F_{(3.1, 114.3)} = 8$, $p < 0.001$, $\eta_p^2 = 0.2$
- Interaction of Cue Colour x Map, $F_{(2.9\ 107)} = 2.8$, $p = 0.04$, $\eta_p^2 = 0.1$
- Interaction of Cue Modality x Cue Colour x Map, $F_{(3, 111.1)} = 3.2$, $p = 0.03$, $\eta_p^2 = 0.1$

Table A.7

Post-hoc Inter-map duration comparisons following 2-way Map x Cue Colour interaction – 7-year-olds, Descriptive

1st compared map (ms)	2nd compared map (ms)	t-values
NCC, Map71 (39ms)	TCC, Map71 (32ms)	1.1
	NCC, Map72 (41ms)	-0.3
	NCC, Map73 (14ms)	4.4^c
	NCC, Map74 (26ms)	1.7
	NCC, Map75 (5ms)	5.7^c
NCC, Map72 (41ms)	TCC, Map72 (30ms)	1.8
	NCC, Map73 (14ms)	4.7^c
	NCC, Map74 (26ms)	2.0
	NCC, Map75 (5ms)	5.0^c

NCC, Map73 (14ms)	TCC, Map73 (9ms)	1.0
	NCC, Map74 (26ms)	-1.6
	NCC, Map75 (5ms)	1.3
NCC, Map74 (26ms)	TCC, Map74 (33ms)	-1.2
	NCC, Map75 (5ms)	2.9
NCC, Map75 (5ms)	TCC, Map75 (22ms)	-3.7[c]
TCC, Map71 (32ms)	TCC, Map72 (30ms)	0.3
	TCC, Map73 (9ms)	3.3[b]
	TCC, Map74 (33ms)	-0.2
	TCC, Map75 (22ms)	1.4
TCC, Map72 (30ms)	TCC, Map73 (9ms)	3.0[b]
	TCC, Map74 (33ms)	-0.5
	TCC, Map75 (22ms)	1.2
TCC, Map73 (9ms)	TCC, Map74 (33ms)	-3.5[c]
	TCC, Map75 (22ms)	-1.8
TCC, Map74 (33ms)	TCC, Map75 (22ms)	1.6

Note. Significance levels that mark *t*-values are as follows: [a] $p < 0.05$ level, [b] $p < 0.01$ level, [c] $p < 0.001$ level, [d] a nonsignificant trend.

Table A.8

Post-hoc Inter-map duration comparisons following 2-way Map x Cue Modality interaction – 7-year-olds, Descriptive

1st compared map (ms)	2nd compared map (ms)	t-values
AV, Map71 (26ms)	V, Map71 (44ms)	-3.5[c]
	AV, Map72 (44ms)	-2.7[b]
	AV, Map73 (7ms)	2.9[b]
	AV, Map74 (38ms)	-1.7
	AV, Map75 (10ms)	2.5[b]
AV, Map72 (44ms)	V, Map72 (27ms)	3.5[c]
	AV, Map73 (7ms)	4.6[c]
	AV, Map74 (38ms)	1.0
	AV, Map75 (10ms)	5.2[c]
AV, Map73 (7ms)	V, Map73 (16ms)	-2.8[b]
	AV, Map74 (38ms)	-4.7[c]
	AV, Map75 (10ms)	-0.5
AV, Map74 (38ms)	V, Map74 (22ms)	3.2[b]
	AV, Map75 (10ms)	4.2[c]
AV, Map75 (10ms)	V, Map75 (17ms)	-1.4
V, Map71 (44ms)	V, Map72 (27ms)	2.6[b]
	V, Map73 (16ms)	4.2[c]
	V, Map74 (22ms)	3.4[c]

	V, Map75 (17ms)	4.1^{c}
V, Map72 (27ms)	V, Map73 (16ms)	1.6
	V, Map74 (22ms)	0.8
	V, Map75 (17ms)	1.5
V, Map73 (16ms)	V, Map74 (22ms)	-0.8
	V, Map75 (17ms)	-0.1
V, Map74 (22ms)	V, Map75 (17ms)	0.7

Note. Significance levels that mark *t*-values are as follows: ^{a} $p < 0.05$ level, ^{b} $p < 0.01$ level, ^{c} $p < 0.001$ level, ^{d} a nonsignificant trend.

Table A.9

Post-hoc Inter-map duration comparisons following 3-way Map x Cue Colour x Cue Modality interaction – 7-year-olds, Descriptive

1st compared map (ms)	2nd compared map (ms)	t-values
NCC, AV, Map71 (27ms)	TCC, AV, Map71 (26ms)	0.2
	NCC, V, Map71 (50ms)	-3.1^{c}
TCC, AV, Map71 (26ms)	TCC, V, Map71 (38ms)	-1.6
NCC, V, Map71 (50ms)	TCC, V, Map71 (38ms)	-1.5
NCC, AV, Map72 (56ms)	TCC, AV, Map72 (32ms)	2.9^{c}
	NCC, V, Map72 (25ms)	4.1^{c}
TCC, AV, Map72 (32ms)	TCC, V, Map72 (28ms)	0.6
NCC, V, Map72 (25ms)	TCC, V, Map72 (28ms)	-0.3
NCC, AV, Map73 (8ms)	TCC, AV, Map73 (6ms)	0.3
	NCC, V, Map73 (21ms)	-2.7^{c}
TCC, AV, Map73 (6ms)	TCC, V, Map73 (11ms)	-0.8
NCC, V, Map73 (21ms)	TCC, V, Map73 (11ms)	1.1
NCC, AV, Map74 (27ms)	TCC, AV, Map74 (48ms)	-2.5^{c}
	NCC, V, Map74 (25ms)	0.3
TCC, AV, Map74 (48ms)	TCC, V, Map74 (18ms)	4.0^{c}
NCC, V, Map74 (25ms)	TCC, V, Map74 (18ms)	0.8
NCC, AV, Map75 (7ms)	TCC, AV, Map75 (13ms)	-0.8
	NCC, V, Map75 (4ms)	0.4
TCC, AV, Map75 (13ms)	TCC, V, Map75 (30ms)	-2.2
NCC, V, Map75 (4ms)	TCC, V, Map75 (30ms)	-3.2^{c}

Note. Significance levels that mark *t*-values are as follows: ^{a} $p < 0.05$ level, ^{b} $p < 0.01$ level, ^{c} $p < 0.001$ level, ^{d} a nonsignificant trend.

2 x 2 x 8 repeated-measures ANOVA - 5-year-olds

- Main effect of Cue Modality, $F_{(1, 27)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Cue Colour, $F_{(1, 27)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Map, $F_{(4.7, 127.2)} = 4$, $p = 0.003$, $\eta_p^2 = 0.1$

- Interaction of Cue Modality x Cue Colour, $F_{(1, 27)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of Cue Modality x Map, $F_{(7, 189)} = 0.9$, $p = 0.4$, $\eta_p^2 = 0.04$
- Interaction of Cue Colour x Map, $F_{(7, 189)} = 4.2$, $p < 0.001$, $\eta_p^2 = 0.1$
- Interaction of Cue Modality x Cue Colour x Map, $F_{(7, 189)} = 2.2$, $p = 0.04$, $\eta_p^2 = 0.1$

Table A.10

Post-hoc Inter-map duration comparisons following 2-way Map x Cue Colour interaction – 5-year-olds, Descriptive

1st compared map (ms)	2nd compared map (ms)	t-values
NCC, Map51 (21ms)	TCC, Map51 (27ms)	-0.8
	NCC, Map52 (17ms)	0.4
	NCC, Map53 (13ms)	0.8
	NCC, Map54 (52ms)	-3.5[c]
	NCC, Map55 (20ms)	0.1
	NCC, Map56 (27ms)	-0.7
	NCC, Map57 (30ms)	-1.0
	NCC, Map58 (14ms)	0.7
NCC, Map52 (17ms)	TCC, Map52 (9ms)	1.0
	NCC, Map53 (13ms)	0.4
	NCC, Map54 (52ms)	-3.9[c]
	NCC, Map55 (20ms)	-0.3
	NCC, Map56 (27ms)	-1.1
	NCC, Map57 (30ms)	-1.4
	NCC, Map58 (14ms)	0.3
NCC, Map53 (13ms)	TCC, Map53 (47ms)	-4.3[c]
	NCC, Map54 (52ms)	-4.3[c]
	NCC, Map55 (20ms)	-0.7
	NCC, Map56 (27ms)	-1.5
	NCC, Map57 (30ms)	-1.8
	NCC, Map58 (14ms)	-0.1
NCC, Map54 (52ms)	TCC, Map54 (28ms)	3.1[b]
	NCC, Map55 (20ms)	3.6[c]
	NCC, Map56 (27ms)	2.8[b]
	NCC, Map57 (30ms)	2.5[b]
	NCC, Map58 (14ms)	4.2[c]
NCC, Map55 (20ms)	TCC, Map55 (6ms)	2.8[b]
	NCC, Map56 (27ms)	-0.8
	NCC, Map57 (30ms)	-1.1
	NCC, Map58 (14ms)	0.6
NCC, Map56 (27ms)	TCC, Map56 (30ms)	-0.4
	NCC, Map57 (30ms)	-0.3

	NCC, Map58 (14ms)	1.4
NCC, Map57 (30ms)	TCC, Map57 (26ms)	0.4
	NCC, Map58 (14ms)	1.7
NCC, Map58 (14ms)	TCC, Map58 (20ms)	-0.7
TCC, Map51 (27ms)	TCC, Map52 (9ms)	2.0
	TCC, Map53 (47ms)	-2.3
	TCC, Map54 (28ms)	-0.1
	TCC, Map55 (6ms)	2.3
	TCC, Map56 (30ms)	-0.4
	TCC, Map57 (26ms)	0.1
	TCC, Map58 (20ms)	0.7
TCC, Map52 (9ms)	TCC, Map53 (47ms)	-4.3[c]
	TCC, Map54 (28ms)	-2.1
	TCC, Map55 (6ms)	0.4
	TCC, Map56 (30ms)	-2.4[a]
	TCC, Map57 (26ms)	-2.0
	TCC, Map58 (20ms)	-1.2
TCC, Map53 (47ms)	TCC, Map54 (28ms)	2.2[a]
	TCC, Map55 (6ms)	4.6[c]
	TCC, Map56 (30ms)	2.0
	TCC, Map57 (26ms)	2.4[a]
	TCC, Map58 (20ms)	3.1
TCC, Map54 (28ms)	TCC, Map55 (6ms)	2.5[b]
	TCC, Map56 (30ms)	-0.2
	TCC, Map57 (26ms)	0.2
	TCC, Map58 (20ms)	0.9
TCC, Map55 (6ms)	TCC, Map56 (30ms)	-2.7[b]
	TCC, Map57 (26ms)	-2.3[a]
	TCC, Map58 (20ms)	-1.6
TCC, Map56 (30ms)	TCC, Map57 (26ms)	0.4
	TCC, Map58 (20ms)	1.1
TCC, Map57 (26ms)	TCC, Map58 (20ms)	0.7

Note. Significance levels that mark *t*-values are as follows: [a] $p < 0.05$ level, [b] $p < 0.01$ level, [c] $p < 0.001$ level, [d] a nonsignificant trend.

Table A.11

Post-hoc Inter-map duration comparisons following 3-way Map x Cue Colour x Cue Modality interaction – 5-year-olds, Descriptive

1st compared map (ms)	2nd compared map (ms)	t-values
NCC, AV, Map51 (15ms)	TCC, AV, Map51 (29ms)	-1.2
	NCC, V, Map51 (26ms)	-0.8

TCC, AV, Map51 (29ms)	TCC, V, Map51 (24ms)	0.4
NCC, V, Map51 (26ms)	TCC, V, Map51 (24ms)	0.1
NCC, AV, Map52 (12ms)	TCC, AV, Map52 (5ms)	0.6
	NCC, V, Map52 (22ms)	-0.8
TCC, AV, Map52 (5ms)	TCC, V, Map52 (13ms)	-0.7
NCC, V, Map52 (22ms)	TCC, V, Map52 (13ms)	0.7
NCC, AV, Map53 (21ms)	TCC, AV, Map53 (43ms)	-1.9
	NCC, V, Map53 (6ms)	1.3
TCC, AV, Map53 (43ms)	TCC, V, Map53 (52ms)	-0.7
NCC, V, Map53 (6ms)	TCC, V, Map53 (52ms)	-4.0[c]
NCC, AV, Map54 (50ms)	TCC, AV, Map54 (36ms)	1.2
	NCC, V, Map54 (55ms)	-0.4
TCC, AV, Map54 (36ms)	TCC, V, Map54 (20ms)	1.3
NCC, V, Map54 (55ms)	TCC, V, Map54 (20ms)	2.9[a]
NCC, AV, Map55 (28ms)	TCC, AV, Map55 (4ms)	2.6[a]
	NCC, V, Map55 (11ms)	1.4
TCC, AV, Map55 (4ms)	TCC, V, Map55 (8ms)	-0.3
NCC, V, Map55 (11ms)	TCC, V, Map55 (8ms)	0.3
NCC, AV, Map56 (21ms)	TCC, AV, Map56 (47ms)	-2.2
	NCC, V, Map56 (33ms)	-1.0
TCC, AV, Map56 (47ms)	TCC, V, Map56 (13ms)	2.8[a]
NCC, V, Map56 (33ms)	TCC, V, Map56 (13ms)	1.6
NCC, AV, Map57 (29ms)	TCC, AV, Map57 (27ms)	0.1
	NCC, V, Map57 (30ms)	-0.1
TCC, AV, Map57 (27ms)	TCC, V, Map57 (25ms)	0.2
NCC, V, Map57 (30ms)	TCC, V, Map57 (25ms)	0.4
NCC, AV, Map58 (16ms)	TCC, AV, Map58 (2ms)	1.2
	NCC, V, Map58 (12ms)	0.4
TCC, AV, Map58 (2ms)	TCC, V, Map58 (38ms)	-3.0[b]
NCC, V, Map58 (12ms)	TCC, V, Map58 (38ms)	-2.2[a]

Note. Significance levels that mark *t*-values are as follows: [a] $p < 0.05$ level, [b] $p < 0.01$ level, [c] $p < 0.001$ level, [d] a nonsignificant trend.

Appendix 4 – Developmental study, Correlational analyses

Behaviour – education correlations

Table A.12

Behaviour–education correlation results in 9-year-olds

	Skipped Pearson		Skipped Spearman	
Educational skills	**TAC**	**MSE**	**TAC**	**MSE**
Reading	0.13	-0.15	-0.07	-0.21
Comprehension	-0.17	-0.15	-0.13	-0.22
Mathematics	0.11	0.08	-0.19	-0.18

Note. No correlations were significant at the $p < 0.05$ level

Table A.13

Behaviour–education correlation results in 7-year-olds

	Skipped Pearson		Skipped Spearman	
Educational skills	**TAC**	**MSE**	**TAC**	**MSE**
Reading	-0.19	0.28	-0.23	0.25
Mathematics	-0.13	-0.18	-0.26	0.04

Note. No correlations were significant at the $p < 0.05$ level

Table A.14

Behaviour–education correlation results in 5-year-olds

	Skipped Pearson		Skipped Spearman	
Educational skills	**TAC**	**MSE**	**TAC**	**MSE**
Phonological skills	0.02	0.27	0.08	0.33
Numeracy	0.17	-0.27	0.08	-0.35

Note. No correlations were significant at the $p < 0.05$ level

Topography – education correlations

Table A.15

Topography–education correlation results in 9-year-olds

Edu. skills	Skipped Pearson Map 94	Map 96	Map 99	Map 92	Map 93	Skipped Spearman Map 94	Map 96	Map 99	Map 92	Map 93
Reading	0.06	0.11	-0.51[b]	-0.17	0.02	0.12	0.14	-0.56[c]	-0.24	-0.02
Compr.	-0.09	0.34	-0.04	-0.21	-0.08	-0.03	0.40[a]	-0.09	-0.22	-0.15
Math.	-0.15	0.28	-0.58[**b**]	-0.49[b]	-0.27	-0.19	0.125	-0.48[b]	-0.45[a]	-0.29

Note. Correlation coefficients are shown in the table, marked by their significance level, as follows: [a] $p < 0.05$ level, [b] $p < 0.01$ level, [c] $p < 0.001$ level, [d] a nonsignificant trend. Edu. is an abbreviation of Educational, Compr. Is an abbreviation of Comprehension, and Math. of Mathematics.

Table A.16

Topography–education correlation results in 7-year-olds

Edu. skills	Skipped Pearson Map 75	Map 71	Map 72	Map 73	Map 74	Skipped Spearman Map 75	Map 71	Map 72	Map 73	Map 74
Reading	-0.04	0.05	0.01	0.22	-0.30	-0.10	0.13	-0.03	0.26[d]	-0.17
Math.	0.13	0.24	-0.05	0.06	-0.16	0.08	0.26[d]	-0.17	0.02	-0.09

Note. Correlation coefficients are shown in the table, marked by their significance level, as follows: [a] $p < 0.05$ level, [b] $p < 0.01$ level, [c] $p < 0.001$ level, [d] a nonsignificant trend. Edu. is an abbreviation of Educational, Compr. Is an abbreviation of Comprehension, and Math. of Mathematics.

Table A.17

Topography–education correlation results in 5-year-olds

Educational skills	Skipped Pearson Map53	Map54	Map55	Skipped Spearman Map53	Map54	Map55
Phonological skills	-0.02	-0.07	0.01	-0.01	-0.13	-0.05
Numeracy	-0.27	-0.28	-0.04	-0.29	-0.40[a]	-0.25

Note. Correlation coefficients are shown in the table, marked by their significance level, as follows: [a] $p < 0.05$ level, [b] $p < 0.01$ level, [c] $p < 0.001$ level, [d] a nonsignificant trend. Edu. is an abbreviation of Educational, Compr. Is an abbreviation of Comprehension, and Math. of Mathematics.

Appendix 5 – Adult study, behavioural analyses

RT results

2 x 2 x 2 x 2 repeated-measures ANOVA

- Main effect of MR, $F_{(1, 38)} = 1.9$, $p = 0.18$, $\eta_p^2 = 0.06$
- Main effect of DO, $F_{(1, 38)} = 0.3$, $p = 0.6$, $\eta_p^2 = 0.02$
- Main effect of Cue Modality, $F_{(1, 38)} = 13.5$, $p = 0.001$, $\eta_p^2 = 0.3$
- Main effect of Cue Colour, $F_{(1, 38)} = 340.4$, $p < 0.001$, $\eta_p^2 = 0.9$
- Interaction of MR x DO, $F_{(1, 38)} = 8.3$, $p = 0.007$, $\eta_p^2 = 0.2$
- Interaction of MR x Cue Modality, $F_{(1, 38)} = 1$, $p = 0.3$, $\eta_p^2 = 0.03$
- Interaction of DO x Cue Modality, $F_{(1, 38)} = 3.6$, $p = 0.07$, $\eta_p^2 = 0.1$
- Interaction of MR x Cue Colour, $F_{(1, 38)} = 4.5$, $p = 0.041$, $\eta_p^2 = 0.1$
- Interaction of DO x Cue Colour, $F_{(1, 38)} = 2$, $p = 0.16$, $\eta_p^2 = 0.08$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 38)} = 6.4$, $p = 0.015$, $\eta_p^2 = 0.2$
- Interaction of MR x DO x Cue Modality, $F_{(1, 38)} = 1.6$, $p = 0.2$, $\eta_p^2 = 0.04$
- Interaction of MR x DO x Cue Colour, $F_{(1, 38)} = 0.1$, $p = 0.7$, $\eta_p^2 = 0.03$
- Interaction of MR x Cue Modality x Cue Colour, $F_{(1, 38)} = 0.03$, $p = 0.9$, $\eta_p^2 = 0.001$
- Interaction of DO x Cue Modality x Cue Colour, $F_{(1, 38)} = 0.2$, $p = 0.7$, $\eta_p^2 = 0.05$
- Interaction of MR x DO x Cue Modality x Cue Colour, $F_{(1, 38)} = 0.1$, $p = 0.7$, $\eta_p^2 = 0.03$

2 x 2 repeated-measures ANOVA – Experiment 1

- Main effect of Cue Modality, $F_{(1, 38)} = 3.4$, $p = 0.07$, $\eta_p^2 = 0.1$
- Main effect of Cue Colour, $F_{(1, 38)} = 169.1.4$, $p < 0.001$, $\eta_p^2 = 0.8$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 38)} = 2.7$, $p = 0.11$, $\eta_p^2 = 0.07$

2 x 2 repeated-measures ANOVA – Experiment 2

- Main effect of Cue Modality, $F_{(1, 38)} = 0.5$, $p = 0.5$, $\eta_p^2 = 0.01$
- Main effect of Cue Colour, $F_{(1, 38)} = 141.9$, $p < 0.001$, $\eta_p^2 = 0.8$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 38)} = 2.6$, $p = 0.11$, $\eta_p^2 = 0.05$

2 x 2 repeated-measures ANOVA – Experiment 3

- Main effect of Cue Modality, $F_{(1, 38)} = 16.8$, $p < 0.001$, $\eta_p^2 = 0.3$
- Main effect of Cue Colour, $F_{(1, 38)} = 148.3$, $p < 0.001$, $\eta_p^2 = 0.8$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 38)} = 1.2$, $p = 0.29$, $\eta_p^2 = 0.03$

2 x 2 repeated-measures ANOVA – Experiment 4

- Main effect of Cue Modality, $F_{(1, 38)} = 1$, $p = 0.3$, $\eta_p^2 = 0.03$
- Main effect of Cue Colour, $F_{(1, 38)} = 139$, $p < 0.001$, $\eta_p^2 = 0.8$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 38)} = 1.7$, $p = 0.20$, $\eta_p^2 = 0.06$

Error rates

1-way Kruskal–Wallis *H* test

- Main effect of Experiment, $\chi^2(3) = 34.7$, $p < 0.001$

3-way Durbin test – Experiment 1

- Main effect of Cue Modality, $\chi^2(1) = 6.9$, $p = 0.009$
- Main effect of Cue Colour, $\chi^2(1) = 0.09$, $p = 0.9$
- Main effect of Cue-Target Location, $\chi^2(1) = 6.9$, $p = 0.003$

3-way Durbin test – Experiment 2

- Main effect of Cue Modality, $\chi^2(1) = 0.5$, $p = 0.5$
- Main effect of Cue Colour, $\chi^2(1) = 0.006$, $p = 0.8$
- Main effect of Cue-Target Location, $\chi^2(1) = 13.9$, $p < 0.001$

3-way Durbin test – Experiment 3

- Main effect of Cue Modality, $\chi^2(1) = 2.3$, $p = 0.1$
- Main effect of Cue Colour, $\chi^2(1) = 0.3$, $p = 0.6$
- Main effect of Cue-Target Location, $\chi^2(1) = 10.4$, $p < 0.001$

3-way Durbin test – Experiment 4

- Main effect of Cue Modality, $\chi^2(1) = 0.03$, $p = 0.9$
- Main effect of Cue Colour, $\chi^2(1) = 0.006$, $p = 0.8$
- Main effect of Cue-Target Location, $\chi^2(1) = 8.3$, $p = 0.004$

Appendix 6 – Adult study, N2pc analyses

Canonical analysis

2 x 2 x 2 x 2 repeated-measures ANOVA

- Main effect of MR, $F_{(1, 38)} = 1.4$, $p = 0.2$, $\eta_p^2 = 0.04$
- Main effect of DO, $F_{(1, 38)} = 3$, $p = 0.08$, $\eta_p^2 = 0.08$
- Main effect of Cue Modality, $F_{(1, 38)} = 0.7$, $p = 0.4$, $\eta_p^2 = 0.4$
- Main effect of Cue Colour, $F_{(1, 38)} = 22$, $p < 0.001$, $\eta_p^2 = 0.4$
- Interaction of MR x DO, $F_{(1, 38)} = 1.4$, $p = 0.2$, $\eta_p^2 = 0.04$
- Interaction of MR x Cue Modality, $F_{(1, 38)} = 1$, $p = 0.4$, $\eta_p^2 = 0.6$
- Interaction of DO x Cue Modality, $F_{(1, 38)} = 0.08$, $p = 0.8$, $\eta_p^2 = 0.002$
- Interaction of MR x Cue Colour, $F_{(1, 38)} = 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of DO x Cue Colour, $F_{(1, 38)} = 2.8$, $p = 0.1$, $\eta_p^2 = 0.09$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 38)} = 0.8$, $p = 0.4$, $\eta_p^2 = 0.02$
- Interaction of MR x DO x Cue Modality, $F_{(1, 38)} = 0.1$, $p = 0.8$, $\eta_p^2 = 0.003$
- Interaction of MR x DO x Cue Colour, $F_{(1, 38)} = 0.4$, $p = 0.6$, $\eta_p^2 = 0.01$
- Interaction of MR x Cue Modality x Cue Colour, $F_{(1, 38)} = 0.8$, $p = 0.4$, $\eta_p^2 = 0.02$
- Interaction of DO x Cue Modality x Cue Colour, $F_{(1, 38)} = 2.9$, $p = 0.1$, $\eta_p^2 = 0.07$
- Interaction of MR x DO x Cue Modality x Cue Colour, $F_{(1, 38)} = 0.006$, $p = 0.9$, $\eta_p^2 < 0.001$

Cluster-based analysis

2 x 2 x 2 x 2 repeated-measures ANOVA

- Main effect of MR, $F_{(1, 38)} = 0.4$, $p = 0.5$, $\eta_p^2 = 0.01$
- Main effect of DO, $F_{(1, 38)} = 0.8$, $p = 0.4$, $\eta_p^2 = 0.02$
- Main effect of Cue Modality, $F_{(1, 38)} = 0.7$, $p = 0.4$, $\eta_p^2 = 0.02$
- Main effect of Cue Colour, $F_{(1, 38)} = 5.5$, $p = 0.03$, $\eta_p^2 = 0.1$
- Interaction of MR x DO, $F_{(1, 38)} = 0.2$, $p = 0.6$, $\eta_p^2 = 0.006$
- Interaction of MR x Cue Modality, $F_{(1, 38)} = 0.2$, $p = 0.7$, $\eta_p^2 = 0.004$
- Interaction of DO x Cue Modality, $F_{(1, 38)} = 0.2$, $p = 0.7$, $\eta_p^2 = 0.05$
- Interaction of MR x Cue Colour, $F_{(1, 38)} = 0.05$, $p = 0.8$, $\eta_p^2 = 0.001$
- Interaction of DO x Cue Colour, $F_{(1, 38)} = 2.7$, $p = 0.1$, $\eta_p^2 = 0.07$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 38)} = 2.2$, $p = 0.2$, $\eta_p^2 = 0.05$
- Interaction of MR x DO x Cue Modality, $F_{(1, 38)} = 2.2$, $p = 0.2$, $\eta_p^2 = 0.05$
- Interaction of MR x DO x Cue Colour, $F_{(1, 38)} = 1.8$, $p = 0.2$, $\eta_p^2 = 0.05$
- Interaction of MR x Cue Modality x Cue Colour, $F_{(1, 38)} = 0.3$, $p = 0.6$, $\eta_p^2 = 0.009$
- Interaction of DO x Cue Modality x Cue Colour, $F_{(1, 38)} = 2.6$, $p = 0.1$, $\eta_p^2 = 0.06$
- Interaction of MR x DO x Cue Modality x Cue Colour, $F_{(1, 38)} = 1.4$, $p = 0.3$, $\eta_p^2 = 0.04$

Appendix 7 – Adult study, Developmental analogue EN analyses

GFP

2 x 2 x 2 x 2 repeated-measures ANOVA

- Main effect of MR, $F_{(1, 38)} = 0.7$, $p = 0.4$, $\eta_p^2 = 0.02$
- Main effect of DO, $F_{(1, 38)} = 0.06$, $p = 0.8$, $\eta_p^2 = 0.002$
- Main effect of Cue Modality, $F_{(1, 38)} = 0.1$, $p = 0.8$, $\eta_p^2 = 0.002$
- Main effect of Cue Colour, $F_{(1, 38)} = 10.2$, $p = 0.003$, $\eta_p^2 = 0.2$
- Interaction of MR x DO, $F_{(1, 38)} = 6.4$, $p = 0.2$, $\eta_p^2 = 0.1$
- Interaction of MR x Cue Modality, $F_{(1, 38)} = 0.3$, $p = 0.6$, $\eta_p^2 = 0.009$
- Interaction of DO x Cue Modality, $F_{(1, 38)} = 0.05$, $p = 0.8$, $\eta_p^2 = 0.001$
- Interaction of MR x Cue Colour, $F_{(1, 38)} = 0.3$, $p = 0.6$, $\eta_p^2 = 0.008$
- Interaction of DO x Cue Colour, $F_{(1, 38)} = 0.005$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 38)} = 0.03$, $p = 0.9$, $\eta_p^2 = 0.001$
- Interaction of MR x DO x Cue Modality, $F_{(1, 38)} = 0.4$, $p = 0.5$, $\eta_p^2 = 0.01$
- Interaction of MR x DO x Cue Colour, $F_{(1, 38)} = 0.07$, $p = 0.8$, $\eta_p^2 = 0.002$
- Interaction of MR x Cue Modality x Cue Colour, $F_{(1, 38)} = 0.06$, $p = 0.8$, $\eta_p^2 = 0.002$
- Interaction of DO x Cue Modality x Cue Colour, $F_{(1, 38)} = 0.7$, $p = 0.4$, $\eta_p^2 = 0.02$
- Interaction of MR x DO x Cue Modality x Cue Colour, $F_{(1, 38)} = 0.01$, $p = 0.9$, $\eta_p^2 < 0.001$

Topography

2 x 2 x 2 x 2 x 3 repeated-measures ANOVA

- Main effect of MR, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of DO, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Cue Modality, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Cue Colour, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Map, $F_{(1.6, 61.4)} = 54.7$, $p < 0.001$, $\eta_p^2 = 0.6$
- Interaction of MR x DO, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of MR x Cue Modality, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of DO x Cue Modality, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of MR x Cue Colour, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of DO x Cue Colour, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of Cue Modality x Cue Colour, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of MR x Map, $F_{(1.5, 55)} = 0.003$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of DO x Map, $F_{(1.8, 67.7)} = 5.9$, $p = 0.006$, $\eta_p^2 = 0.1$
- Interaction of Cue Colour x Map, $F_{(1.5, 58.4)} = 5.4$, $p = 0.02$, $\eta_p^2 = 0.1$
- Interaction of Cue Modality x Map, $F_{(1.7, 63.9)} = 0.7$, $p = 0.5$, $\eta_p^2 = 0.02$
- Interaction of MR x DO x Cue Modality, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of MR x DO x Cue Colour, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$

- Interaction of MR x Cue Modality x Cue Colour, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of DO x Cue Modality x Cue Colour, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of MR x DO x Map, $F_{(1.3, 49)} = 5.4$, $p = 0.02$, $\eta_p^2 = 0.1$
- Interaction of MR x Cue Colour x Map, $F_{(2, 76)} = 0.5$, $p = 0.6$, $\eta_p^2 = 0.01$
- Interaction of DO x Cue Colour x Map, $F_{(1.5, 57.6)} = 0.4$, $p = 0.6$, $\eta_p^2 = 0.01$
- Interaction of MR x Cue Modality x Map, $F_{(1.7, 64)} = 1.3$, $p = 0.3$, $\eta_p^2 = 0.04$
- Interaction of DO x Cue Modality x Map, $F_{(1.6, 58.9)} = 0.7$, $p = 0.5$, $\eta_p^2 = 0.02$
- Interaction of Cue Modality x Cue Colour x Map, $F_{(1.7, 62.6)} = 0.04$, $p = 1$, $\eta_p^2 = 0.001$
- Interaction of MR x DO x Cue Modality x Cue Colour, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of MR x DO x Cue Colour x Map, $F_{(1.5, 55.8)} = 3$, $p = 0.06$, $\eta_p^2 = 0.1$
- Interaction of MR x DO x Cue Modality x Map, $F_{(1.7, 64)} = 2$, $p = 0.2$, $\eta_p^2 = 0.05$
- Interaction of MR x Cue Modality x Cue Colour x Map, $F_{(1.7, 63.6)} = 0.1$, $p = 0.8$, $\eta_p^2 = 0.003$
- Interaction of DO x Cue Modality x Cue Colour x Map, $F_{(1.4, 53.6)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of MR x DO x Cue Modality x Cue Colour x Map, $F_{(1.4, 54.2)} = 0.5$, $p = 0.5$, $\eta_p^2 = 0.01$

Table A.18

Post-hoc Inter-map duration comparisons following 2-way Map x Cue Colour interaction – Adult, Developmental analogue

Map	**MapA1 TCC (41ms)**	**MapA2 TCC (25ms)**	**MapA3 TCC (56ms)**	**MapA1 NCC (57ms)**	**MapA2 NCC (14ms)**	**MapA3 NCC (56ms)**
MapA1 TCC (41ms)	/					
MapA2 TCC (25ms)	3.3[a]	/				
MapA3 TCC (56ms)	3.2[a]		/			
MapA1 NCC (57ms)	3.1[a]	N.O.I	N.O.I	/		
MapA2 NCC (14ms)	N.O.I	3.0[a]	N.O.I	7.9[c]	/	

MapA3 NCC (56ms)	N.O.I	N.O.I	0.1	0.8	8.7^{c}	/

Note. t-values of the comparisons between Map durations are shown in the table, marked by their significance level, as follows: ^{a} $p < 0.05$ level, ^{b} $p < 0.01$ level, ^{c} $p < 0.001$ level, ^{d} a nonsignificant trend. N.O.I is an abbreviation for ‘Not Of Interest’ denoting comparisons that were not informative for post-hoc analyses, and were thus not conducted.

Table A.19

Post-hoc Inter-map duration comparisons following 2-way Map x DO interaction – Adults, Developmental analogue

Map	**MapA1 Unpr. (48ms)**	**MapA2 Unpr. (22ms)**	**MapA3 Unpr. (52ms)**	**MapA1 Pred. (45ms)**	**MapA2 Pred. (17ms)**	**MapA3 Pred. (60ms)**
MapA1 Unpr. (48ms)	/					
MapA2 Unpr. (22ms)	6.3^{c}	/				
MapA3 Unpr. (52ms)	1.1	7.4^{c}	/			
MapA1 Pred. (45ms)	1.3	N.O.I	N.O.I	/		
MapA2 Pred. (17ms)	N.O.I	2.1^{b}	N.O.I	6.8^{c}	/	
MapA3 Pred. (60ms)	N.O.I	N.O.I	3.4^{c}	3.6^{c}	10.4^{c}	/

Note. t-values of the comparisons between Map durations are shown in the table, marked by their significance level, as follows: ^{a} $p < 0.05$ level, ^{b} $p < 0.01$ level, ^{c} $p < 0.001$ level, ^{d} a nonsignificant trend. N.O.I is an abbreviation for ‘Not Of Interest’ denoting comparisons that were not informative for post-hoc analyses, and were thus not conducted.

Table A.20

Post-hoc Inter-map duration comparisons following 3-way Map x MR x DO interaction – Adults, Developmental analogue

1st compared map (ms)	**2nd compared map (ms)**	**t-values**

Simult., Unpred., MapA1 (53ms)	Cong., Unpred., MapA1 (42ms)	2.4[a]
	Simult., Pred., MapA1 (39ms)	3.4[c]
Cong., Unpred., MapA1 (42ms)	Cong., Pred., MapA1 (50ms)	-2.0
Simult., Pred., MapA1 (39ms)	Cong., Pred., MapA1 (50ms)	-2.5[a]
Simult., Unpred., MapA2 (19ms)	Cong., Unpred., MapA2 (24ms)	-1.1
	Simult., Pred., MapA2 (19ms)	-0.1
Cong., Unpred., MapA2 (24ms)	Cong., Pred., MapA2 (14ms)	2.6[a]
Simult., Pred., MapA2 (19ms)	Cong., Pred., MapA2 (14ms)	1.2
Simult., Unpred., MapA3 (49ms)	Cong., Unpred., MapA3 (55ms)	-1.5
	Simult., Pred., MapA3 (63ms)	-3.5[c]
Cong., Unpred., MapA3 (55ms)	Cong., Pred., MapA3 (57ms)	-0.5
Simult., Pred., MapA3 (63ms)	Cong., Pred., MapA3 (57ms)	1.4

Note. Significance levels that mark *t*-values are as follows: [a] $p < 0.05$ level, [b] $p < 0.01$ level, [c] $p < 0.001$ level, [d] a nonsignificant trend.

Appendix 8 – Adult study, Exploratory EN analyses

Exploratory adult analysis – voltage

2 x 2 x 2 repeated-measures ANOVA

- Main effect of MR, 140 – 162ms, $p < 0.05$
- Main effect of DO, none
- Main effect of Target Difference, 53 – 99ms, 141 – 179ms, p’s < 0.05
- Interaction of MR x DO, none
- Interaction of MR x Target Difference, 65 – 103ms, 143 – 171ms, x 194 – 221ms, p’s < 0.05
- Interaction of DO x Target Difference, none
- Interaction of MR x DO x Target Difference, none

Exploratory adult analysis – GFP

2 x 2 x 2 repeated-measures ANOVA

- Main effect of MR, 23 – 180ms, 188 – 234ms, 242 – 261ms, p’s < 0.05
- Main effect of DO, 13 – 34ms, 97 – 118ms, 304 – 335ms, p’s < 0.05
- Main effect of Target Difference, 19 – 213ms, 221 – 255ms, 275 – 290ms, p’s < 0.05
- Interaction of MR x DO, 168 – 193ms, 212 – 251ms, $p < 0.05$
- Interaction of MR x Target Difference, 23 – 255ms, $p < 0.05$
- Interaction of DO x Target Difference, 88 – 127, $p < 0.05$
- Interaction of MR x DO x Target Difference, 102 – 124ms x 234 – 249ms, $p < 0.05$

Exploratory adult analysis – Topography

2 x 2 x 2 x 4 repeated-measures ANOVA – canonical N2pc time-window

- Main effect of MR, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of DO, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Target Difference, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Map, $F_{(2.4, 90.5)} = 19.7$, $p < 0.001$, $\eta_p^2 = 0.34$
- Interaction of MR x DO, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of MR x Target Difference, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of DO x Target Difference, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of MR x Map, $F_{(2.1, 78.2)} = 1.4$, $p = 0.3$, $\eta_p^2 = 0.01$
- Interaction of DO x Map, $F_{(2.9, 109.2)} = 1.2$, $p = 0.3$, $\eta_p^2 = 0.01$
- Interaction of Target Difference x Map, $F_{(2.1, 80)} = 2.3$, $p = 0.1$, $\eta_p^2 = 0.04$
- Interaction of MR x DO x Target Difference, $F_{(2.3, 87.5)} = 110.8$, $p < 0.001$, $\eta_p^2 = 0.75$
- Interaction of MR x DO x Map, $F_{(2.3, 87.5)} = 3.1$, $p = 0.04$, $\eta_p^2 = 0.08$
- Interaction of MR x Target Difference x Map, $F_{(2.4, 89.2)} = 4.85$, $p = 0.007$, $\eta_p^2 = 0.113$
- Interaction of DO x Target Difference x Map, $F_{(2.7, 101.3)} = 0.2$, $p = 0.9$, $\eta_p^2 = 0.001$
- Interaction of MR x DO x Target Difference x Map, $F_{(2.4, 90)} = 0.3$, $p = 0.8$, $\eta_p^2 = 0.001$

Table A.21

Post-hoc Inter-map duration comparisons following 3-way Map x MR x DO interaction – Adults, Exploratory, canonical N2pc time-window

1st compared map (ms)	2nd compared map (ms)	t-values
Simult., Unpred., MapAA1 (13ms)	Cong., Unpred., MapAA1 (12ms)	0.4
	Simult., Pred., MapAA1 (18ms)	-0.9
Cong., Unpred., MapAA1 (12ms)	Cong., Pred., MapAA1 (12ms)	-0.1
Simult., Pred., MapAA1 (18ms)	Cong., Pred., MapAA1 (12ms)	1.1
Simult., Unpred., MapAA2 (23ms)	Cong., Unpred., MapAA2 (22ms)	0.2
	Simult., Pred., MapAA2 (26ms)	-0.5
Cong., Unpred., MapAA2 (22ms)	Cong., Pred., MapAA2 (20ms)	0.3
Simult., Pred., MapAA2 (26ms)	Cong., Pred., MapAA2 (20ms)	1.0
Simult., Unpred., MapAA3 (31ms)	Cong., Unpred., MapAA3 (45ms)	-2.7[a]
	Simult., Pred., MapAA3 (41ms)	-2.0
Cong., Unpred., MapAA3 (45ms)	Cong., Pred., MapAA3 (39ms)	1.1
Simult., Pred., MapAA3 (41ms)	Cong., Pred., MapAA3 (39ms)	0.3
Simult., Unpred., MapAA4 (54ms)	Cong., Unpred., MapAA4 (43ms)	2.1
	Simult., Pred., MapAA4 (37ms)	3.4[c]
Cong., Unpred., MapAA4 (43ms)	Cong., Pred., MapAA4 (49ms)	-1.3
Simult., Pred., MapAA4 (37ms)	Cong., Pred., MapAA4 (49ms)	-2.3

Note. Significance levels that mark *t*-values are as follows: [a] *p* < 0.05 level, [b] *p* < 0.01 level, [c] *p* < 0.001 level, [d] a nonsignificant trend.

Table A.22

Post-hoc Inter-map duration comparisons following 3-way Map x Target Difference x MR interaction – Adults, Exploratory, canonical N2pc time-window

1st compared map (ms)	2nd compared map (ms)	t-values
Simult., DAV, MapAA1 (16ms)	Cong., DAV, MapAA1 (10ms)	1.4[a]
	Simult., DV, MapAA1 (15ms)	0.2
Cong., DAV, MapAA1 (10ms)	Cong., DV, MapAA1 (14ms)	-0.8
Simult., DV, MapAA1 (15ms)	Cong., DV, MapAA1 (14ms)	0.3
Simult., DAV, MapAA2 (24ms)	Cong., DAV, MapAA2 (21ms)	0.6
	Simult., DV, MapAA2 (25ms)	-0.2

Cong., DAV, MapAA2 (21ms)	Cong., DV, MapAA2 (21ms)	-0.2
Simult., DV, MapAA2 (25ms)	Cong., DV, MapAA2 (21ms)	0.7
Simult., DAV, MapAA3 (37ms)	Cong., DAV, MapAA3 (34ms)	0.5
	Simult., DV, MapAA3 (35ms)	0.3
Cong., DAV, MapAA3 (34ms)	Cong., DV, MapAA3 (50ms)	-3.0^{b}
Simult., DV, MapAA3 (35ms)	Cong., DV, MapAA3 (50ms)	-3.2^{b}
Simult., DAV, MapAA4 (45ms)	Cong., DAV, MapAA4 (56ms)	-2.4^{b}
	Simult., DV, MapAA4 (46ms)	-0.3
Cong., DAV, MapAA4 (56ms)	Cong., DV, MapAA4 (36ms)	3.9^{c}
Simult., DV, MapAA4 (46ms)	Cong., DV, MapAA4 (36ms)	2.1

Note. Significance levels that mark *t*-values are as follows: ^{a} $p < 0.05$ level, ^{b} $p < 0.01$ level, ^{c} $p < 0.001$ level, ^{d} a nonsignificant trend.

2 x 2 x 2 x 6 repeated-measures ANOVA – 13-106ms time-window

- Main effect of MR, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of DO, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Target Difference, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Map, $F_{(1.9, 72)} = 18$, $p < 0.001$, $\eta_p^2 = 0.3$
- Interaction of MR x DO, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of MR x Target Difference, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of DO x Target Difference, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of MR x Map, $F_{(4, 153.4)} = 1.6$, $p = 0.2$, $\eta_p^2 = 0.04$
- Interaction of DO x Map, $F_{(4, 152.1)} = 0.8$, $p = 0.5$, $\eta_p^2 = 0.02$
- Interaction of Target Difference x Map, $F_{(3.5, 134)} = 4.43$, $p = 0.003$, $\eta_p^2 = 0.1$
- Interaction of MR x DO x Target Difference, $F_{(2.3, 87.5)} = 110.8$, $p < 0.001$, $\eta_p^2 = 0.75$
- Interaction of MR x DO x Map, $F_{(4, 143.9)} = 2$, $p = 0.1$, $\eta_p^2 = 0.08$
- Interaction of MR x Target Difference x Map, $F_{(3.2, 122)} = 5.6$, $p = 0.001$, $\eta_p^2 = 0.1$
- Interaction of DO x Target Difference x Map, $F_{(3.9, 149)} = 0.5$, $p = 0.7$, $\eta_p^2 = 0.01$
- Interaction of MR x DO x Target Difference x Map, $F_{(2.4, 90)} = 1.1$, $p = 0.3$, $\eta_p^2 = 0.03$

Table A.23

Post-hoc Inter-map duration comparisons following 2-way Map x Target Difference interaction – Adults, Exploratory, 13-106ms time-window

1st compared map (ms)	2nd compared map (ms)	t-values
DAV, MapAB1 (29ms)	DV, MapAB1 (18ms)	3.8^{c}
	DAV, MapAB2 (7ms)	7.0^{c}
	DAV, MapAB3 (11ms)	5.6^{c}
	DAV, MapAB4 (18ms)	3.5^{c}
	DAV, MapAB5 (11ms)	5.8^{c}
	DAV, MapAB6 (19ms)	3.3^{b}

DAV, MapAB2 (7ms)	DV, MapAB2 (5ms)	0.6
	DAV, MapAB3 (11ms)	-1.4
	DAV, MapAB4 (18ms)	-3.5^{c}
	DAV, MapAB5 (11ms)	-1.2
	DAV, MapAB6 (19ms)	-3.8^{c}
DAV, MapAB3 (11ms)	DV, MapAB3 (17ms)	-1.9^{a}
	DAV, MapAB4 (18ms)	-2.1
	DAV, MapAB5 (11ms)	0.2
	DAV, MapAB6 (19ms)	-2.3^{b}
DAV, MapAB4 (18ms)	DV, MapAB4 (26ms)	-2.7^{a}
	DAV, MapAB5 (11ms)	2.3^{b}
	DAV, MapAB6 (19ms)	-0.2
DAV, MapAB5 (11ms)	DV, MapAB5 (12ms)	-0.5
	DAV, MapAB6 (19ms)	-2.5^{b}
DAV, MapAB6 (19ms)	DV, MapAB6 (17ms)	0.7
DV, MapAB1 (18ms)	DV, MapAB2 (5ms)	4.0^{c}
	DV, MapAB3 (17ms)	0.3
	DV, MapAB4 (26ms)	-2.6^{b}
	DV, MapAB5 (12ms)	1.9^{a}
	DV, MapAB6 (19ms)	0.4
DV, MapAB2 (5ms)	DV, MapAB3 (17ms)	-3.7^{c}
	DV, MapAB4 (26ms)	-6.6^{c}
	DV, MapAB5 (12ms)	-2.2^{a}
	DV, MapAB6 (19ms)	-3.6^{c}
DV, MapAB3 (17ms)	DV, MapAB4 (26ms)	-2.9^{b}
	DV, MapAB5 (12ms)	1.5
	DV, MapAB6 (19ms)	0.1
DV, MapAB4 (26ms)	DV, MapAB5 (12ms)	4.4^{c}
	DV, MapAB6 (19ms)	2.9^{b}
DV, MapAB5 (12ms)	DV, MapAB6 (19ms)	-1.5

Note. Significance levels that mark *t*-values are as follows: ^{a} $p < 0.05$ level, ^{b} $p < 0.01$ level, ^{c} $p < 0.001$ level, ^{d} a nonsignificant trend.

Table A.24

Post-hoc Inter-map duration comparisons following 3-way Map x Target Difference x MR interaction – Adults, Exploratory, 13-106ms time-window

1st compared map (ms)	2nd compared map (ms)	t-values
Simult., DAV, MapAB1 (20ms)	Cong., DAV, MapAB1 (38ms)	-4.8^{c}
	Simult., DV, MapAB1 (21ms)	-0.3
Cong., DAV, MapAB1 (38ms)	Cong., DV, MapAB1 (15ms)	6.0^{c}
Simult., DV, MapAB1 (21ms)	Cong., DV, MapAB1 (15ms)	1.7

Simult., DAV, MapAB2 (11ms)	Cong., DAV, MapAB2 (3ms)	2.0
	Simult., DV, MapAB2 (6ms)	1.2
Cong., DAV, MapAB2 (3ms)	Cong., DV, MapAB2 (4ms)	0.3
Simult., DV, MapAB2 (6ms)	Cong., DV, MapAB2 (4ms)	0.5
Simult., DAV, MapAB3 (11ms)	Cong., DAV, MapAB3 (12ms)	-0.4
	Simult., DV, MapAB3 (18ms)	-2.0
Cong., DAV, MapAB3 (12ms)	Cong., DV, MapAB3 (15ms)	-0.8
Simult., DV, MapAB3 (18ms)	Cong., DV, MapAB3 (15ms)	0.8
Simult., DAV, MapAB4 (18ms)	Cong., DAV, MapAB4 (18ms)	-0.1
	Simult., DV, MapAB4 (23ms)	-1.2
Cong., DAV, MapAB4 (18ms)	Cong., DV, MapAB4 (29ms)	-2.9[b]
Simult., DV, MapAB4 (23ms)	Cong., DV, MapAB4 (29ms)	-1.7
Simult., DAV, MapAB5 (12ms)	Cong., DAV, MapAB5 (9ms)	0.8
	Simult., DV, MapAB5 (12ms)	0.1
Cong., DAV, MapAB5 (9ms)	Cong., DV, MapAB5 (12ms)	-0.7
Simult., DV, MapAB5 (12ms)	Cong., DV, MapAB5 (12ms)	0.1
Simult., DAV, MapAB6 (23ms)	Cong., DAV, MapAB6 (14ms)	2.4[a]
	Simult., DV, MapAB6 (14ms)	2.3[a]
Cong., DAV, MapAB6 (14ms)	Cong., DV, MapAB6 (19ms)	-1.3
Simult., DV, MapAB6 (14ms)	Cong., DV, MapAB6 (19ms)	-1.3

Note. Significance levels that mark *t*-values are as follows: [a] $p < 0.05$ level, [b] $p < 0.01$ level, [c] $p < 0.001$ level, [d] a nonsignificant trend.

2 x 2 x 2 x 4 repeated-measures ANOVA – 107-184ms time-window

- Main effect of MR, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of DO, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Target Difference, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Map, $F_{(2.3, 87.9)} = 15.9$, $p < 0.001$, $\eta_p^2 = 0.3$
- Interaction of MR x DO, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of MR x Target Difference, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of DO x Target Difference, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of MR x Map, $F_{(2.3, 87.9)} = 1.9$, $p = 0.2$, $\eta_p^2 = 0.05$
- Interaction of DO x Map, $F_{(2.9, 109.2)} = 1.3$, $p = 0.3$, $\eta_p^2 = 0.03$
- Interaction of Target Difference x Map, $F_{(2.4, 90.9)} = 7.12$, $p = 0.001$, $\eta_p^2 = 0.16$
- Interaction of MR x DO x Target Difference, $F_{(2.3, 87.5)} = 110.8$, $p < 0.001$, $\eta_p^2 = 0.75$
- Interaction of MR x DO x Map, $F_{(2.5, 94)} = 0.5$, $p = 0.4$, $\eta_p^2 = 0.008$
- Interaction of MR x Target Difference x Map, $F_{(2.4, 90)} = 3.6$, $p = 0.03$, $\eta_p^2 = 0.1$
- Interaction of DO x Target Difference x Map, $F_{(2.7, 101.3)} = 1.2$, $p = 0.3$, $\eta_p^2 = 0.001$
- Interaction of MR x DO x Target Difference x Map, $F_{(2.4, 91)} = 2.2$, $p = 0.1$, $\eta_p^2 = 0.05$

Table A.25

Post-hoc Inter-map duration comparisons following 2-way Map x Target Difference interaction – Adults, Exploratory, 107-184ms time-window

Map	**Map AC1 D_{AV} (7ms)**	**Map AC2 D_{AV} (20ms)**	**Map AC3 D_{AV} (28ms)**	**Map AC4 D_{AV} (23ms)**	**Map AC1 D_{V} (11ms)**	**Map AC2 D_{V} (30ms)**	**Map AC3 D_{V} (16ms)**	**Map AC4 D_{V} (21ms)**
MapAC1 D_{AV} (7ms)	/							
MapAC2 D_{AV} (20ms)	3.7 ^{c}	/						
MapAC3 D_{AV} (28ms)	5.8 ^{c}	2.1 ^{a}	/					
MapAC4 D_{AV} (23ms)	4.5 ^{c}	0.7	1.3	/				
MapAC1 D_{V} (11ms)	1.3	N.O.I	N.O.I	N.O.I	/			
MapAC2 D_{V} (30ms)	N.O.I	3.4^{c}	N.O.I	N.O.I	5.5 ^{c}	/		
MapAC3 D_{V} (16ms)	N.O.I	N.O.I	3.9^{c}	N.O.I	1.4	4.1 ^{c}	/	
MapAC4 D_{V} (21ms)	N.O.I	N.O.I	N.O.I	0.7	2.8 ^{b}	2.8 ^{b}	1.3	/

Note. t-values of the comparisons between Map durations are shown in the table, marked by their significance level, as follows: ^{a} $p < 0.05$ level, ^{b} $p < 0.01$ level, ^{c} $p < 0.001$ level, ^{d} a nonsignificant trend. N.O.I is an abbreviation for 'Not Of Interest' denoting comparisons that were not informative for post-hoc analyses, and were thus not conducted.

Table A.26

Post-hoc Inter-map duration comparisons following 3-way Map x Target Difference x MR interaction – Adults, Exploratory, 107-184ms time-window

1st compared map (ms)	**2nd compared map (ms)**	**t-values**
Simult., DAV, MapAC1 (9ms)	Cong., DAV, MapAC1 (5ms)	1.5^{a}
	Simult., DV, MapAC1 (12ms)	-0.5

Cong., DAV, MapAC1 (5ms)	Cong., DV, MapAC1 (10ms)	-1.3
Simult., DV, MapAC1 (12ms)	Cong., DV, MapAC1 (10ms)	0.3
Simult., DAV, MapAC2 (21ms)	Cong., DAV, MapAC2 (19ms)	0.5
	Simult., DV, MapAC2 (30ms)	-2.2
Cong., DAV, MapAC2 (19ms)	Cong., DV, MapAC2 (31ms)	-2.7^{b}
Simult., DV, MapAC2 (22ms)	Cong., DV, MapAC2 (31ms)	-0.1
Simult., DAV, MapAC3 (20ms)	Cong., DAV, MapAC3 (36ms)	-3.8^{c}
	Simult., DV, MapAC3 (17ms)	0.7
Cong., DAV, MapAC3 (36ms)	Cong., DV, MapAC3 (15ms)	4.9^{c}
Simult., DV, MapAC3 (17ms)	Cong., DV, MapAC3 (15ms)	0.4
Simult., DAV, MapAC4 (28ms)	Cong., DAV, MapAC4 (18ms)	2.2
	Simult., DV, MapAC4 (19ms)	2.0^{b}
Cong., DAV, MapAC4 (18ms)	Cong., DV, MapAC4 (22ms)	-0.9
Simult., DV, MapAC4 (19ms)	Cong., DV, MapAC4 (22ms)	-0.6

Note. Significance levels that mark *t*-values are as follows: ^{a} $p < 0.05$ level, ^{b} $p < 0.01$ level, ^{c} $p < 0.001$ level, ^{d} a nonsignificant trend.

2 x 2 x 2 x 4 repeated-measures ANOVA – 185-275ms time-window

- Main effect of MR, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of DO, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Target Difference, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Map, $F_{(2.4, 90)} = 18.7$, $p < 0.001$, $\eta_p^2 = 0.3$
- Interaction of MR x DO, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of MR x Target Difference, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of DO x Target Difference, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of MR x Map, $F_{(2.2, 85)} = 0.6$, $p = 0.6$, $\eta_p^2 = 0.01$
- Interaction of DO x Map, $F_{(2.7, 104)} = 0.2$, $p = 0.9$, $\eta_p^2 = 0.005$
- Interaction of Target Difference x Map, $F_{(2.2, 83.4)} = 3.4$, $p = 0.03$, $\eta_p^2 = 0.08$
- Interaction of MR x DO x Target Difference, $F_{(2.3, 87.5)} = 110.8$, $p < 0.001$, $\eta_p^2 = 0.75$
- Interaction of MR x DO x Map, $F_{(2.3, 85.9)} = 1.9$, $p = 0.1$, $\eta_p^2 = 0.05$
- Interaction of MR x Target Difference x Map, $F_{(2.4, 90.9)} = 7.8$, $p < 0.001$, $\eta_p^2 = 0.2$
- Interaction of DO x Target Difference x Map, $F_{(2.4, 92.9)} = 0.1$, $p = 0.9$, $\eta_p^2 = 0.003$
- Interaction of MR x DO x Target Difference x Map, $F_{(2.2, 85)} = 0.4$, $p = 0.7$, $\eta_p^2 = 0.01$

Table A.27

Post-hoc Inter-map duration comparisons following 2-way Map x Target Difference interaction – Adults, Exploratory, 107-184ms time-window

Map	**Map AD1 D_{AV} (7ms)**	**Map AD2 D_{AV} (15ms)**	**Map AD3 D_{AV} (18ms)**	**Map AD4 D_{AV} (33ms)**	**Map AD1 D_{V} (7ms)**	**Map AD2 D_{V} (16ms)**	**Map AD3 D_{V} (24ms)**	**Map AD4 D_{V} (26ms)**

Map AD1 D_{AV} (7ms)	/							
Map AD2 D_{AV} (15ms)	2.2^a	/						
Map AD3 D_{AV} (18ms)	2.8^a	0.6	/					
Map AD4 D_{AV} (33ms)	6.9^c	4.7^c	4.1^c	/				
Map AD1 D_V (7ms)	0.2	N.O.I	N.O.I	N.O.I	/			
Map AD2 D_V (16ms)	N.O.I	0.1	N.O.I	N.O.I	2.2^a	/		
Map AD3 D_V (24ms)	N.O.I	N.O.I	2.5^a	N.O.I	4.5^c	2.3	/	
Map AD4 D_V (26ms)	N.O.I	N.O.I	N.O.I	2.7^a	4.9^c	2.7^a	0.4	/

Note. *t*-values of the comparisons between Map durations are shown in the table, marked by their significance level, as follows: ^{a} $p < 0.05$ level, ^{b} $p < 0.01$ level, ^{c} $p < 0.001$ level, ^{d} a nonsignificant trend. N.O.I is an abbreviation for ‘Not Of Interest’ denoting comparisons that were not informative for post-hoc analyses, and were thus not conducted.

Table A.28

Post-hoc Inter-map duration comparisons following 3-way Map x Target Difference x MR interaction – Adults, Exploratory, 107-184ms time-window

1st compared map (ms)	2nd compared map (ms)	t-values
Simult., DAV, MapAD1 (10ms)	Cong., DAV, MapAD1 (4ms)	1.7^a
	Simult., DV, MapAD1 (7ms)	0.8
Cong., DAV, MapAD1 (4ms)	Cong., DV, MapAD1 (8ms)	-1.0
Simult., DV, MapAD1 (7ms)	Cong., DV, MapAD1 (8ms)	-0.2
Simult., DAV, MapAD2 (15ms)	Cong., DAV, MapAD2 (16ms)	-0.2
	Simult., DV, MapAD2 (17ms)	-0.4
Cong., DAV, MapAD2 (16ms)	Cong., DV, MapAD2 (15ms)	0.3
Simult., DV, MapAD2 (17ms)	Cong., DV, MapAD2 (15ms)	0.6

Simult., DAV, MapAD3 (21ms)	Cong., DAV, MapAD3 (15ms)	1.9[a]
	Simult., DV, MapAD3 (20ms)	0.3
Cong., DAV, MapAD3 (15ms)	Cong., DV, MapAD3 (29ms)	-4.1[c]
Simult., DV, MapAD3 (20ms)	Cong., DV, MapAD3 (29ms)	-3.0[b]
Simult., DAV, MapAD4 (28ms)	Cong., DAV, MapAD4 (39ms)	-3.4[c]
	Simult., DV, MapAD4 (30ms)	-0.6
Cong., DAV, MapAD4 (39ms)	Cong., DV, MapAD4 (22ms)	4.8[c]
Simult., DV, MapAD4 (30ms)	Cong., DV, MapAD4 (22ms)	2.6

Note. Significance levels that mark *t*-values are as follows: [a] $p < 0.05$ level, [b] $p < 0.01$ level, [c] $p < 0.001$ level, [d] a nonsignificant trend.

2 x 2 x 2 x 7 repeated-measures ANOVA – 74-154ms time-window

- Main effect of MR, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of DO, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Target Difference, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Map, $F_{(4, 154.3)} = 16.66$, $p < 0.001$, $\eta_p^2 = 0.31$
- Interaction of MR x DO, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of MR x Target Difference, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of DO x Target Difference, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of MR x Map, $F_{(4, 153.2)} = 0.3$, $p = 1$, $\eta_p^2 = 0.007$
- Interaction of DO x Map, $F_{(4.7, 180)} = 0.8$, $p = 0.5$, $\eta_p^2 = 0.02$
- Interaction of Target Difference x Map, $F_{(2.2, 83.4)} = 2.7$, $p = 0.04$, $\eta_p^2 = 0.07$
- Interaction of MR x DO x Target Difference, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of MR x DO x Map, $F_{(4.1, 156.9)} = 2.8$, $p = 0.027$, $\eta_p^2 = 0.07$
- Interaction of MR x Target Difference x Map, $F_{(4.4, 167.8)} = 5.45$, $p < 0.001$, $\eta_p^2 = 0.13$
- Interaction of DO x Target Difference x Map, $F_{(4.2, 161)} = 0.5$, $p = 0.7$, $\eta_p^2 = 0.01$
- Interaction of MR x DO x Target Difference x Map, $F_{(4.7, 179.3)} = 0.8$, $p = 0.6$, $\eta_p^2 = 0.02$

Table A.29

Post-hoc Inter-map duration comparisons following 2-way Map x Target Difference interaction – Adults, Exploratory, 74-154ms time-window

1st compared map (ms)	**2nd compared map (ms)**	**t-values**
DAV, MapAE1 (18ms)	DV, MapAE1 (15ms)	1.5
	DAV, MapAE2 (5ms)	5.0[c]
	DAV, MapAE3 (8ms)	4.1[c]
	DAV, MapAE4 (15ms)	1.1
	DAV, MapAE5 (15ms)	1.1
	DAV, MapAE6 (5ms)	5.0[c]
	DAV, MapAE7 (14ms)	1.6
DAV, MapAE2 (5ms)	DV, MapAE2 (4ms)	0.6

	DAV, MapAE3 (8ms)	-0.9
	DAV, MapAE4 (15ms)	-3.9[c]
	DAV, MapAE5 (15ms)	-3.9[c]
	DAV, MapAE6 (5ms)	0.1
	DAV, MapAE7 (14ms)	-3.4[c]
DAV, MapAE3 (8ms)	DV, MapAE3 (15ms)	-3.0[c]
	DAV, MapAE4 (15ms)	-3.0[c]
	DAV, MapAE5 (15ms)	-3.0[c]
	DAV, MapAE6 (5ms)	0.9
	DAV, MapAE7 (14ms)	-2.5[b]
DAV, MapAE4 (15ms)	DV, MapAE4 (10ms)	2.1[a]
	DAV, MapAE5 (15ms)	0.1
	DAV, MapAE6 (5ms)	4.0[c]
	DAV, MapAE7 (14ms)	0.5
DAV, MapAE5 (15ms)	DV, MapAE5 (19ms)	-1.5
	DAV, MapAE6 (5ms)	4.6[c]
	DAV, MapAE7 (14ms)	0.5
DAV, MapAE6 (5ms)	DV, MapAE6 (4ms)	0.4
	DAV, MapAE7 (14ms)	-3.5[c]
DAV, MapAE7 (14ms)	DV, MapAE7 (14ms)	0.1
DV, MapAE1 (15ms)	DV, MapAE2 (4ms)	4.1[c]
	DV, MapAE3 (15ms)	-0.2
	DV, MapAE4 (10ms)	1.7
	DV, MapAE5 (19ms)	-1.7
	DV, MapAE6 (4ms)	4.0[c]
	DV, MapAE7 (14ms)	0.2
DV, MapAE2 (4ms)	DV, MapAE3 (15ms)	-4.3[c]
	DV, MapAE4 (10ms)	-2.5[b]
	DV, MapAE5 (19ms)	-5.8[c]
	DV, MapAE6 (4ms)	-0.1
	DV, MapAE7 (14ms)	-3.9[c]
DV, MapAE3 (15ms)	DV, MapAE4 (10ms)	1.8
	DV, MapAE5 (19ms)	-1.5
	DV, MapAE6 (4ms)	4.2[c]
	DV, MapAE7 (14ms)	0.4
DV, MapAE4 (10ms)	DV, MapAE5 (19ms)	-3.4[c]
	DV, MapAE6 (4ms)	2.3[b]
	DV, MapAE7 (14ms)	-1.5
DV, MapAE5 (19ms)	DV, MapAE6 (4ms)	5.7[c]
	DV, MapAE7 (14ms)	1.9
DV, MapAE6 (4ms)	DV, MapAE7 (14ms)	-3.8[c]

Note. Significance levels that mark *t*-values are as follows: [a] $p < 0.05$ level, [b] $p < 0.01$ level, [c] $p < 0.001$ level, [d] a nonsignificant trend.

Table A.30

Post-hoc Inter-map duration comparisons following 3-way Map x Target Difference x MR interaction – Adults, Exploratory, 74-154ms time-window

1st compared map (ms)	2nd compared map (ms)	t-values
Simult., DAV, MapAE1 (13ms)	Cong., DAV, MapAE1 (24ms)	-3.3[c]
	Simult., DV, MapAE1 (19ms)	-1.8
Cong., DAV, MapAE1 (24ms)	Cong., DV, MapAE1 (10ms)	4.0[c]
Simult., DV, MapAE1 (19ms)	Cong., DV, MapAE1 (10ms)	2.6[b]
Simult., DAV, MapAE2 (7ms)	Cong., DAV, MapAE2 (4ms)	0.9
	Simult., DV, MapAE2 (3ms)	1.6[a]
Cong., DAV, MapAE2 (4ms)	Cong., DV, MapAE2 (4ms)	-0.2
Simult., DV, MapAE2 (3ms)	Cong., DV, MapAE2 (4ms)	-0.4
Simult., DAV, MapAE3 (9ms)	Cong., DAV, MapAE3 (7ms)	0.6
	Simult., DV, MapAE3 (14ms)	-1.6
Cong., DAV, MapAE3 (7ms)	Cong., DV, MapAE3 (16ms)	-3.0[c]
Simult., DV, MapAE3 (14ms)	Cong., DV, MapAE3 (16ms)	-0.9
Simult., DAV, MapAE4 (12ms)	Cong., DAV, MapAE4 (19ms)	-2.3[a]
	Simult., DV, MapAE4 (12ms)	-0.1
Cong., DAV, MapAE4 (19ms)	Cong., DV, MapAE4 (9ms)	3.2[c]
Simult., DV, MapAE4 (12ms)	Cong., DV, MapAE4 (9ms)	1.0
Simult., DAV, MapAE5 (16ms)	Cong., DAV, MapAE5 (14ms)	0.7
	Simult., DV, MapAE5 (19ms)	-0.7
Cong., DAV, MapAE5 (14ms)	Cong., DV, MapAE5 (19ms)	-1.6
Simult., DV, MapAE5 (19ms)	Cong., DV, MapAE5 (19ms)	-0.2
Simult., DAV, MapAE6 (6ms)	Cong., DAV, MapAE6 (4ms)	0.7
	Simult., DV, MapAE6 (3ms)	0.9
Cong., DAV, MapAE6 (4ms)	Cong., DV, MapAE6 (5ms)	-0.3
Simult., DV, MapAE6 (3ms)	Cong., DV, MapAE6 (5ms)	-0.5
Simult., DAV, MapAE7 (19ms)	Cong., DAV, MapAE7 (10ms)	2.7[b]
	Simult., DV, MapAE7 (11ms)	2.1[a]
Cong., DAV, MapAE7 (10ms)	Cong., DV, MapAE7 (17ms)	-2.1
Simult., DV, MapAE7 (11ms)	Cong., DV, MapAE7 (17ms)	-1.6

Note. Significance levels that mark *t*-values are as follows: [a] $p < 0.05$ level, [b] $p < 0.01$ level, [c] $p < 0.001$ level, [d] a nonsignificant trend.

Table A.31

Post-hoc Inter-map duration comparisons following 3-way Map x MR x DO interaction – Adults, Exploratory, 74-154ms time-window

1st compared map (ms)	2nd compared map (ms)	t-values
Simult., Unpred., MapAE1 (16ms)	Cong., Unpred., MapAE1 (16ms)	0.1
	Simult., Pred., MapAE1 (15ms)	0.3
Cong., Unpred., MapAE1 (16ms)	Cong., Pred., MapAE1 (18ms)	-0.6
Simult., Pred., MapAE1 (15ms)	Cong., Pred., MapAE1 (18ms)	-0.8
Simult., Unpred., MapAE2 (3ms)	Cong., Unpred., MapAE2 (3ms)	0.1
	Simult., Pred., MapAE2 (6ms)	-0.9
Cong., Unpred., MapAE2 (3ms)	Cong., Pred., MapAE2 (5ms)	-0.5
Simult., Pred., MapAE2 (6ms)	Cong., Pred., MapAE2 (5ms)	0.4
Simult., Unpred., MapAE3 (14ms)	Cong., Unpred., MapAE3 (7ms)	2.3[b]
	Simult., Pred., MapAE3 (8ms)	1.8
Cong., Unpred., MapAE3 (7ms)	Cong., Pred., MapAE3 (16ms)	-3.2[c]
Simult., Pred., MapAE3 (6ms)	Cong., Pred., MapAE3 (16ms)	-2.5[b]
Simult., Unpred., MapAE4 (10ms)	Cong., Unpred., MapAE4 (15ms)	-1.4[a]
	Simult., Pred., MapAE4 (14ms)	-1.1
Cong., Unpred., MapAE4 (15ms)	Cong., Pred., MapAE4 (13ms)	0.4
Simult., Pred., MapAE4 (14ms)	Cong., Pred., MapAE4 (13ms)	0.1
Simult., Unpred., MapAE5 (18ms)	Cong., Unpred., MapAE5 (20ms)	-0.5
	Simult., Pred., MapAE5 (17ms)	0.4
Cong., Unpred., MapAE5 (20ms)	Cong., Pred., MapAE5 (14ms)	1.9[a]
Simult., Pred., MapAE5 (17ms)	Cong., Pred., MapAE5 (14ms)	0.9
Simult., Unpred., MapAE6 (5ms)	Cong., Unpred., MapAE6 (4ms)	0.2
	Simult., Pred., MapAE6 (5ms)	0.2
Cong., Unpred., MapAE6 (4ms)	Cong., Pred., MapAE6 (5ms)	-0.1
Simult., Pred., MapAE6 (5ms)	Cong., Pred., MapAE6 (5ms)	0.1
Simult., Unpred., MapAE7 (14ms)	Cong., Unpred., MapAE7 (16ms)	-0.7
	Simult., Pred., MapAE7 (16ms)	-0.6
Cong., Unpred., MapAE7	Cong., Pred., MapAE7 (10ms)	2.0[a]

(16ms)		
Simult., Pred., MapAE7 (16ms)	Cong., Pred., MapAE7 (10ms)	1.8^a

Note. Significance levels that mark *t*-values are as follows: ^{a} $p < 0.05$ level, ^{b} $p < 0.01$ level, ^{c} $p < 0.001$ level, ^{d} a nonsignificant trend.

2 x 2 x 2 x 5 repeated-measures ANOVA – 168-186ms time-window

- Main effect of MR, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of DO, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Target Difference, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Main effect of Map, $F_{(3.4, 128.5)} = 7.4$, $p < 0.001$, $\eta_p^2 = 0.2$
- Interaction of MR x DO, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of MR x Target Difference, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of DO x Target Difference, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of MR x Map, $F_{(4, 152)} = 2.6$, $p = 0.04$, $\eta_p^2 = 0.06$
- Interaction of DO x Map, $F_{(3.8, 143)} = 0.7$, $p = 0.6$, $\eta_p^2 = 0.02$
- Interaction of Target Difference x Map, $F_{(3.2,120.3)} = 1.2$, $p = 0.3$, $\eta_p^2 = 0.03$
- Interaction of MR x DO x Target Difference, $F_{(1, 38)} < 0.001$, $p = 1$, $\eta_p^2 < 0.001$
- Interaction of MR x DO x Map, $F_{(3.3, 124.1)} = 1.9$, $p = 0.1$, $\eta_p^2 = 0.05$
- Interaction of MR x Target Difference x Map, $F_{(4, 152)} = 2.3$, $p = 0.06$, $\eta_p^2 = 0.06$
- Interaction of DO x Target Difference x Map, $F_{(3.2, 120.5)} = 0.2$, $p = 1$, $\eta_p^2 = 0.004$
- Interaction of MR x DO x Target Difference x Map, $F_{(4, 152)} = 2.5$, $p = 0.04$, $\eta_p^2 = 0.1$

Table A.32

Post-hoc Inter-map duration comparisons following 2-way Map x MR interaction – Adults, Exploratory, 168-186ms time-window

1st compared map (ms)	2nd compared map (ms)	t-values
Simult, MapAF1 (3ms)	Cong, MapAF1 (2ms)	1.6^a
	Simult, MapAF2 (4ms)	-1.6
	Simult, MapAF3 (3ms)	-0.1
	Simult, MapAF4 (3ms)	-0.3
	Simult, MapAF5 (6ms)	-3.1^c
Simult, MapAF2 (4ms)	Cong, MapAF2 (5ms)	0.9
	Simult, MapAF3 (3ms)	1.6^a
	Simult, MapAF4 (3ms)	1.3
	Simult, MapAF5 (6ms)	-1.6^a
Simult, MapAF3 (3ms)	Cong, MapAF3 (5ms)	-2.4^b
	Simult, MapAF4 (3ms)	-0.2
	Simult, MapAF5 (6ms)	-3.1^c
Simult, MapAF4 (3ms)	Cong, MapAF4 (2ms)	1.3
	Simult, MapAF5 (6ms)	-2.9^c

Simult, MapAF5 (6ms)	Cong, MapAF5 (5ms)	-0.7
Cong, MapAF1 (2ms)	Cong, MapAF2 (5ms)	-3.6^{c}
	Cong, MapAF3 (5ms)	-3.6^{c}
	Cong, MapAF4 (2ms)	-0.5
	Cong, MapAF5 (6ms)	-3.8^{c}
Cong, MapAF2 (5ms)	Cong, MapAF3 (5ms)	0.1
	Cong, MapAF4 (2ms)	3.1^{c}
	Cong, MapAF5 (6ms)	0.2
Cong, MapAF3 (5ms)	Cong, MapAF4 (2ms)	3.1
	Cong, MapAF5 (6ms)	-0.3
Cong, MapAF4 (2ms)	Cong, MapAF5 (5ms)	-3.3^{c}

Note. Significance levels that mark *t*-values are as follows: ^{a} $p < 0.05$ level, ^{b} $p < 0.01$ level, ^{c} $p < 0.001$ level, ^{d} a nonsignificant trend.

Table A.33

Post-hoc follow-up of 4-way Target Difference x Map x MR x DO interaction – 3-way ANOVA on Congruence data - inter-map duration comparisons following 2-way Map x Target Difference interaction – Adults, Exploratory, 168-186ms time-window

1st compared map (ms)	**2nd compared map (ms)**	**t-values**
DAV, MapAF1 (1ms)	DV, MapAF1 (2ms)	-0.4
	DAV, MapAF2 (4ms)	-2.0^{a}
	DAV, MapAF3 (7ms)	-4.4^{c}
	DAV, MapAF4 (2ms)	-0.5
	DAV, MapAF5 (5ms)	-2.7^{b}
DAV, MapAF2 (4ms)	DV, MapAF2 (6ms)	-2.0
	DAV, MapAF3 (7ms)	-2.4^{a}
	DAV, MapAF4 (2ms)	1.5
	DAV, MapAF5 (5ms)	-0.7
DAV, MapAF3 (7ms)	DV, MapAF3 (3ms)	3.2^{b}
	DAV, MapAF4 (2ms)	3.8^{b}
	DAV, MapAF5 (5ms)	1.6
DAV, MapAF4 (2ms)	DV, MapAF4 (2ms)	0.1
	DAV, MapAF5 (5ms)	-2.2^{a}
DAV, MapAF5 (5ms)	DV, MapAF5 (6ms)	-0.8
DV, MapAF1 (2ms)	DV, MapAF2 (6ms)	-3.5^{b}
	DV, MapAF3 (3ms)	-1.1
	DV, MapAF4 (2ms)	-0.2
	DV, MapAF5 (5ms)	-3.1^{b}
DV, MapAF2 (6ms)	DV, MapAF3 (3ms)	2.4
	DV, MapAF4 (2ms)	3.3^{b}
	DV, MapAF5 (5ms)	0.4

DV, MapAF3 (3ms)	DV, MapAF4 (2ms)	0.9
	DV, MapAF5 (5ms)	-2.0[a]
DV, MapAF4 (2ms)	DV, MapAF5 (5ms)	-2.9[b]

Note. Significance levels that mark *t*-values are as follows: [a] $p < 0.05$ level, [b] $p < 0.01$ level, [c] $p < 0.001$ level, [d] a nonsignificant trend.

Table A.34

Post-hoc follow-up of 4-way Target Difference x Map x MR x DO interaction – 3-way ANOVA on Unpredictable data - inter-map duration comparisons following 3-way Map x Target Difference x MR interaction – Adults, Exploratory, 168-186ms time-window

1st compared map (ms)	2nd compared map (ms)	t-values
Simult., DAV, MapAF1 (3ms)	Cong., DAV, MapAF1 (1ms)	-0.6
	Simult., DV, MapAF1 (3ms)	0.1
Cong., DAV, MapAF1 (1ms)	Cong., DV, MapAF1 (2ms)	-0.6
Simult., DV, MapAF1 (3ms)	Cong., DV, MapAF1 (2ms)	0.6
Simult., DAV, MapAF2 (5ms)	Cong., DAV, MapAF2 (4ms)	0.6
	Simult., DV, MapAF2 (2ms)	1.5
Cong., DAV, MapAF2 (4ms)	Cong., DV, MapAF2 (8ms)	-2.7[b]
Simult., DV, MapAF2 (2ms)	Cong., DV, MapAF2 (8ms)	-3.7[c]
Simult., DAV, MapAF3 (2ms)	Cong., DAV, MapAF3 (6ms)	-2.8[b]
	Simult., DV, MapAF3 (3ms)	-0.9
Cong., DAV, MapAF3 (6ms)	Cong., DV, MapAF3 (2ms)	2.7[b]
Simult., DV, MapAF3 (3ms)	Cong., DV, MapAF3 (2ms)	0.9
Simult., DAV, MapAF4 (2ms)	Cong., DAV, MapAF4 (2ms)	-0.3
	Simult., DV, MapAF4 (3ms)	-0.9
Cong., DAV, MapAF4 (2ms)	Cong., DV, MapAF4 (2ms)	0.3
Simult., DV, MapAF4 (3ms)	Cong., DV, MapAF4 (2ms)	0.9
Simult., DAV, MapAF5 (7ms)	Cong., DAV, MapAF5 (5ms)	1.2
	Simult., DV, MapAF5 (7ms)	0.3
Cong., DAV, MapAF5 (5ms)	Cong., DV, MapAF5 (5ms)	0.3
Simult., DV, MapAF5 (7ms)	Cong., DV, MapAF5 (5ms)	1.2

Note. Significance levels that mark *t*-values are as follows: [a] $p < 0.05$ level, [b] $p < 0.01$ level, [c] $p < 0.001$ level, [d] a nonsignificant trend.