MIND, BRAIN, AND EDUCATION

Uncovering the Mechanisms of Real-World Attentional Control Over the Course of Primary Education

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ABSTRACT— Schooling may shape children's abilities to control their attention, but it is unclear if this impact extends from control over visual objects to encompass multisensory objects, which are more typical of everyday environments. We compared children across three primary school grades (Swiss first, third, and fifth grades) on their performance on a game-like audiovisual attentional control task, while recording their electroencephalogram (EEG). Behavioral markers of *visual* attentional control were present from third grade (after 2 years of schooling), whereas multisensory attentional control was not detected in any group. However, multivariate whole-brain EEG analyses ("electrical neuroimaging") revealed stable patterns of brain activity that indexed both types of attentional control—visual control in all age groups, and multisensory attentional control from third grade onward. Multivariate EEG approaches can uncover otherwise undetectable mechanisms of attentional control over visual and multisensory objects, and characterize how these mechanisms differ across educational stages.

The start of school marks a transition from a less regulated, play-oriented environment to one with increasing demands for focusing attention and ignoring distractors. The development of such attentional control and its relationship with schooling experience remains poorly understood, especially in real-world environments.

Most current knowledge about children's attentional control has come from research on executive functions (EFs; Miyake et al., 2000), which are closely linked with attentional control (Bavelier & Green, 2019). Both EFs and attentional control gradually improve over childhood (e.g., Donnelly et al., 2007) because of protracted structural changes within and between the prefrontal and parietal cortex (e.g., Casey, Tottenham, Liston, & Durston, 2005). Such findings have clarified when and how children's control skills compare to those of adults, rather than helped map how control skills function during various stages of childhood, when children are challenged by their educational environment in different ways. Although both approaches are important, we focus on the latter one for two reasons.

First, the development of attentional control skills does not need to be uniformly linear when the multisensory nature of the environment and the child's schooling experience are considered. Matusz et al. (2015) found that while 11-year-olds and adults were distracted by audiovisual shape-sound stimuli in a visual search task, 6-year-olds could be immune to such distraction. Thus, young children's

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limited attentional control can shield them from real-world distraction, rather than making them more distracted than adults, as visual-attentional research typically suggests. Similar developmental differences were observed for distraction by digits (Matusz, Merkley, Faure, & Scerif, 2019). Children with less schooling experience (i.e., less familiar with numerals) were more protected from distraction by conjunctions of visual numerals and their auditorily presented names. Second, children's attentional control skills are linked to scholastic success. Schooling is a catalyst for developing cognitive control. For example, IQ increases with education level (e.g., Brinch & Galloway, 2012), and EF skills improve when children enter formal schooling (e.g., Brod, Bunge, & Shing, 2017). Yet, the influence of schooling on attentional control in multisensory contexts is currently unknown.

To support education better, we need to understand how attention is deployed in multisensory environments like classrooms. Multisensory processes, like visual-attentional processes, undergo development. Already infant brains are sensitive to congruency across the senses (e.g., Lewkowicz & Turkewitz, 1980), but processes integrating weighted sensory jecinputs mature much later (+8 years; e.g., Gori, Del Viva, Sandini, & Burr, 2008). Studying attentional control and *distraction* gauged by audiovisual objects informs classroom learning. Distraction by unisensory content hinders classroom learning (vision: Godwin & Fisher, 2011; hearing: Massonnié, Rogers, Mareschal, & Kirkham, 2019). Skills in multisensory letter-sound mappings predict scholastic achievements (Bach, Richardson, Brandeis, Martin, & Brem, 2013) similarly to visual EF/attentional control skills (e.g., Bull, Espy, & Wiebe, 2008).

Here, we pursued two questions: (1) How do children process multisensory distractors vis-à-vis visual distractors, and what brain mechanisms govern these processes? and (2) How does audiovisual attentional control change with school experience? We investigated the behavioral and brain mechanisms of attentional control using a child-friendly multisensory spatial-cueing paradigm while recording EEG. We conducted traditional (N2pc) and multivariate (electrical neuroimaging [EN]) analyses of event-related EEG potentials (ERPs). We expected older children to show visual attentional control behaviorally; we had no strong hypotheses for multisensory attentional control or the underlying EEG mechanisms.

METHODS

Participants

In Switzerland, children enter formal education at age 4, where the first 2 years are considered kindergarten. By third grade (ages 6–7), children sit at desks and receive more structured classroom instruction. We tested 92 children from local primary schools: 26 fifth graders (10 males, $M \pm SD_{age}$: 8 years 10 months ± 5 months, range: 8 years 1 month–10 years 1 month), 38 third graders (18 females, $M \pm SD_{age}$: 6 years 10 months ± 4 months, range: 6 years 1 month–7 years 9 months), and 28 first graders (13 females, $M \pm SD_{age}$ 5 years ± 4 months, range: 4 years–5 years 7 months; full details in Appendix S1). All research procedures were approved by the Cantonal Commission for the Ethics of Human Research (CER-VD).

Stimuli and Procedure

Participants were tested in the Lausanne University Hospital Centre (CHUV) in an experimental session lasting 1 hr–1 hr 30 min, where we recorded their behavioral performance and EEG. The paradigm was a multisensory variant of Folk, Remington, and Johnston's (1992) spatial cueing paradigm (Matusz & Eimer, 2011, Experiment 2) adapted to be child-friendly (Figure 1).

Participants searched for a target diamond of a predefined color and responded as quickly and accurately as possible to the target's orientation (horizontal or vertical; randomly determined on each trial) by pressing one of two large buttons (Lib Switch, Liberator Ltd., Swinstead) fixed onto a tray on their lap. Each diamond was preceded by a cue, which matched the target color (e.g., blue for blue target) or did not (red for blue target; red and blue were counterbalanced as target/cue colors across participants). The location of the cue was randomized and unpredictive of the location of the target, thus eliciting attentional capture. On 50% of trials, the cue coincided with the onset of a pure sine-wave tone (2000 Hz). These manipulations reflect the two cue factors in our design: Cue Color (target-color cue vs. nontarget-color cue) and Cue Modality (visual vs. audiovisual), producing four cue conditions: target-color cue visual, nontarget-color cue visual, target-color cue audiovisual, and target-color cue audiovisual (Figure 1). We measured these effects of visual and multisensory attentional control through our main dependent variable: difference in raw speed between trials where the cue and the target shared their location (thus the cue captured attention, this way facilitating response speed) versus trials where the target appeared in a location different from that of the preceding cue (after the cue captured attention, attention had to be disengaged from the cue location and shifted to the target location, leading to slower responses). The third design factor, Cue-Target Location, defined by this difference between speeding and slowing of raw responses (Same vs. Different location), measured how strongly a given cue captured attention. See Appendix S1 for further details of the experimental procedures.

EEG Acquisition and Preprocessing

Continuous EEG was recorded using a 129-channel HydroCel Geodesic Sensor Net (1000 Hz sampling rate)

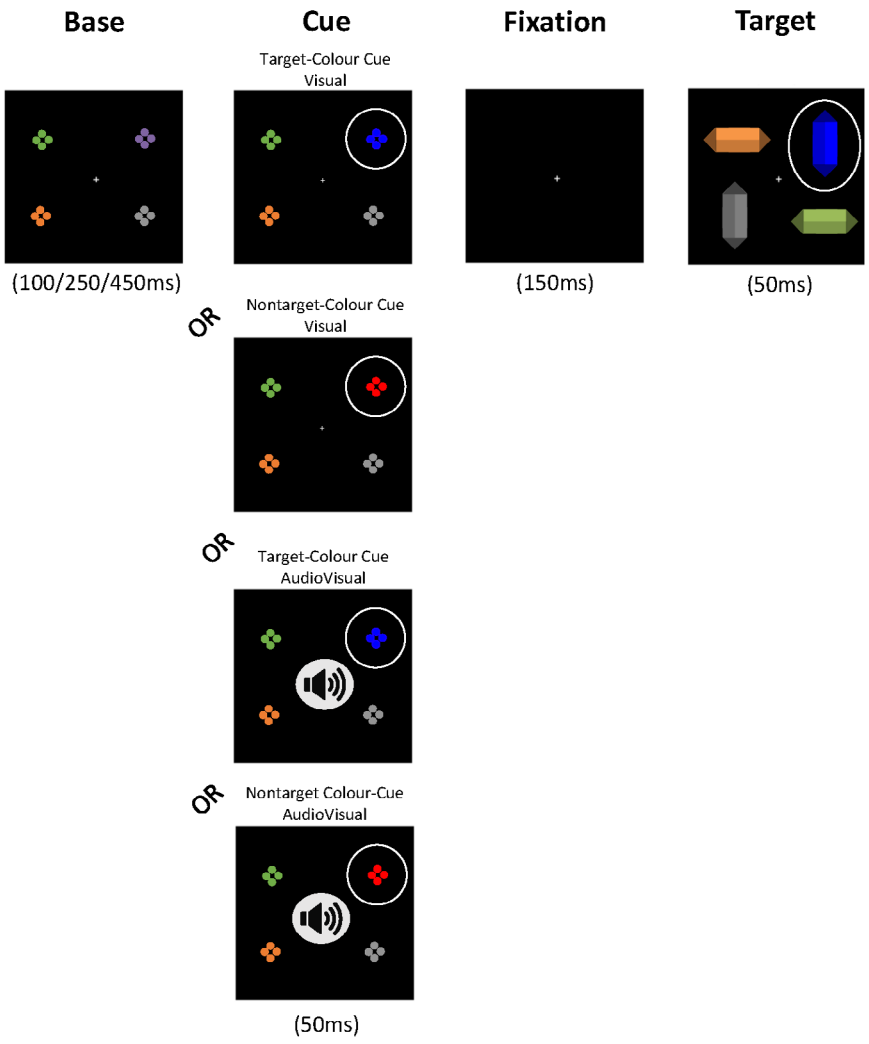

Fig. 1. Experimental trial sequence for our paradigm. The base array contained four differently colored elements. In the cue array, one of these elements changed color—to a target-matching color (a blue cue for a blue diamond), or a nontarget color (red cue). On 50% of all trials, the color-change cue was accompanied by a tone (here indicated symbolically by a speaker). The cue color and sound presence manipulations created the four cue conditions shown in the figure. The cue and target could appear in the same location (here indicated symbolically by white circles) or different locations.

connected to a NetStation amplifier (Net Amps 400; Electrical Geodesics Inc.). Impedances were kept <50 kΩ, and electrodes were online referenced to Cz. Preprocessing involved: offline filtering (0.1 Hz high-pass, 40 Hz low-pass, 50 Hz notch, and a second-order Butterworth filter with a linear −12 dB/octave roll-off with forward and backward passes to eliminate phase-shift), segmentation into epochs around cue onset (−100 ms; 500 ms), and semi-automated rejection of transient noise, eye movements, and muscle artifacts. Artifact rejection criteria were $\pm 150\ \mu V$, with visual inspection (Shimi, Kuo, Astle, Nobre, & Scerif, 2014). Artifact-contaminated electrodes were interpolated using three-dimensional splines (average numbers of epochs removed and interpolated electrodes, in Appendix S1). Cleaned epochs were averaged, baseline-corrected (100 ms precue time interval), and re-referenced to the average reference. EEG/ERP analyses were anchored to the cue array. An additional 50 Hz notch filter was applied because of persistent environmental noise despite initial filtering. Only data from trials with correct responses and from blocks with >50% accuracy were analyzed.

Preprocessing was performed separately for ERPs from the four cue conditions, and for cues in left and right hemifields. To analyze cue-elicited lateralized ERPs, data from both hemiscalps were anchored to a "reference" side. Labels of single-trial data from trials with cues presented on the left were relabeled to represent activity over the right hemiscalp, creating veridical "cue-on-the-right" data and mirrored "cue-on-the-right" data. Next, we averaged these two data types, for the four cue conditions, creating

four single lateralized average ERPs. We performed all preprocessing and analyses using Cartool (v.3521, www.fbmlab.com/cartool-software/).

Data Analysis Design

Behavioral Analyses

We analyzed mean reaction-time (RT) attentional capture effects, following related literature (Folk et al., 1992; Gaspelin, Margett-Jordan, & Ruthruff, 2015; RT cleaning described in Appendix S1). We submitted mean RTs to a mixed four-way repeated-measures analysis of variance (rmANOVA) with a between-subject factor Age (fifth graders vs. third graders vs. first graders) and three within-subject factors: Cue Color (target-color cue vs. nontarget-color cue), Cue Modality (visual vs. audiovisual), and Cue-Target Location (same vs. different). Here, task-set contingent attentional capture was tested via a Cue-Target Location × Cue Color interaction (*stronger* attentional capture by target-color cues than nontarget-color cues). Multisensory enhancement of attentional capture was assessed via a Cue-Target Location × Cue Modality interaction (stronger attentional capture by audiovisual than visual cues). All analyses were conducted using SPSS for Macintosh 26.0 (Armonk, NY: IBM Corp). Detailed behavioral results were reported in our previous study on adult-like audiovisual attentional skills over childhood (Turoman et al., 2021), so here we report only the most relevant results.

EEG Analyses

The N2pc component is a spatially selective enhancement of negative potentials over occipital electrodes on the side contralateral (vs. ipsilateral) to the selected object. It is a traditional marker of attentional selection (Eimer, 1996). We combined N2pc analyses with an EN approach. As no reliable cue-elicited N2pcs were found in any age group, we report only the EN analyses of the cue-elicited ERPs in the N2pc time-window (see Appendix S1 for details of the N2pc analysis design and results).

The EN approach encompasses a set of multivariate, reference-independent analyses of global features of the electric field at the scalp across the whole electrode montage. Combining EN measures with established ERP correlates of cognitive processes can help elucidate the cognitive and brain mechanisms underlying multisensory attentional control (e.g., Matusz, Turoman, Tivadar, Retsa, & Murray, 2019), as EN analyses are capable of uncovering the brain mechanisms that give rise to modulations in ERPs. To obtain global EN measures of *lateralized* N2pc effects, the contralateral-ipsilateral difference ERPs created for N2pc analyses were mirrored onto the other hemiscalp, constructing "mirrored" 129-channel datasets. From these "mirrored" 129-channel difference-ERPs, global field power (GFP) and topographical EEG patterns were analyzed.

For GFP analyses, each age group's mean GFP over their N2pc time-windows was extracted from group-averaged "mirrored" ERPs per condition and submitted to separate two-way rmANOVAs with factors: Cue Color and Cue Modality. Differences in GFP would indicate that visual and/or multisensory control (main effects of Cue Color and Cue Modality, respectively) modulate cue-elicited lateralized ERPs by altering the *strength* of response within a similar (statistically indistinguishable) brain network (detailed explanations of GFP and topographic analyses for lateralized ERPs in Appendix S1, also Matusz, Turoman, et al., 2019; Turoman, Tivadar, Retsa, Murray, & Matusz, 2020).

For topographical analyses, first, stable periods of topographic activity ("topographic maps") were identified through a clustering ("segmentation") procedure, which was conducted on group-averaged ERPs. Here, we clustered the ERPs for the four cue conditions within each grade's respective N2pc time-window. The optimal set of maps was chosen based on the largest global variance they explain, and the cross-validation and Krzanowski-Lai criterions. Clustering necessarily means that similar patterns have been identified across one participant group (here, grade). Next, the results of the segmentation of the grand-averaged ERPs were fitted back onto the single-subject data to see how much each of the maps identified in the segmentation characterized individual participants. This is how we obtained map durations (in milliseconds) over each child's N2pc time-window, which we then submitted to three separate three-way rmANOVAs, with factors: Cue Color, Cue Modality, and Map (different levels because of different numbers of maps in each age group). Differences in topographic maps would indicate that visual and/or multisensory control (Map × Cue Color and Map × Cue Modality interactions, respectively) modulated cue-elicited lateralized ERPs by altering the recruited brain networks. Multiple comparisons between map durations were Holm-Bonferroni corrected. Comparisons passed the correction unless otherwise stated.

RESULTS

Behavioral Analyses

A main effect of Age, $F(2, 89) = 32.8$, $p < .001$, $\eta_p^2 = .4$, revealed that mean RTs sped up reliably from first graders (1,309 ms) through third graders (1,107 ms) to fifth graders (836 ms; all $p < .001$, see Appendix S1). Although Age did not interact with other factors (all $F < 2$, $p > .1$), RT capture effects were analyzed per age group to clarify visual and multisensory distraction effects across school grades.

Fifth graders showed visual task-set contingent attentional capture (Cue-Target Location × Cue Color

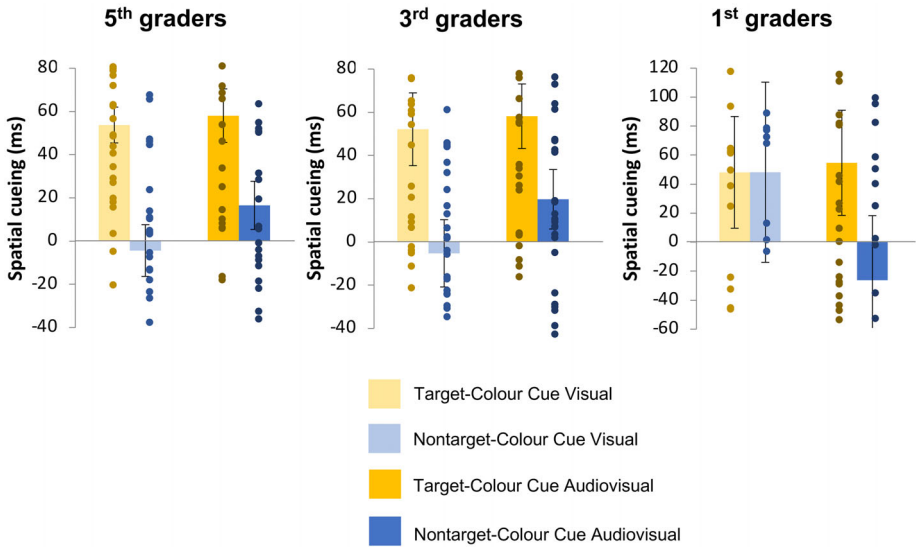

Fig. 2. Mean reaction-time (RT) attentional capture effects. Error bars represent standard errors of the mean, and vertical dots represent individual RT attentional capture effects. Third and fifth graders showed larger behavioral capture for target-color than nontarget-color cues; no groups showed multisensory capture enhancements.

interaction, $F(1, 25) = 19.5$, $p < .001$, $\eta_p^2 = .4$); their attention was captured by target-color cues (56 ms), but not nontarget-color cues (Figure 2, left panel). However, their attention was not enhanced for audiovisual over visual cues (no Cue-Target Location × Cue Modality interaction, $F(1, 25) = 1.4$, $p = .3$). Third graders also showed task-set contingent attentional capture ($F = 6.4$, $p = .02$, $\eta_p^2 = .2$), with their attention captured by target-color cues (55 ms), but not nontarget-color cues (Figure 2, middle panel). Third graders also showed no evidence for multisensory enhancement of attentional capture ($F(1, 37) = 2.1$, $p = .2$). Contrastingly, first graders showed no evidence for visual task-set contingent attentional capture ($F(1, 27) = 1.4$, $p = .2$) or multisensory enhancement of attentional capture ($F(1, 27) = .4$, $p = .5$; Figure 2, right panel).

EEG Analyses

Three separate 2 × 2 rmANOVAs on the average GFP over each age group's N2pc time-window revealed no evidence for main effects or interactions in fifth and first graders ($p > .1$), with a trend in third graders for a main effect of Cue Color ($F = 3.07$, $p = .09$). Full results are reported in Appendix S1.

Segmentations of the post-cue period per age group resulted in: 14 clusters in fifth graders (explaining 91.5% of the global variance in the group-averaged difference ERPs), 11 clusters in third graders (88.3% global-explained variance), and 11 clusters in first graders (84.9% global-explained variance). Next, the fitting procedure revealed the template maps that characterized each age-group's N2pc time-window: fifth graders—nine maps over 144–290 ms; third graders—five maps over 151–275 ms; and first graders—eight maps over 110–302-ms post-cue. Age-specific maps were differentiated using grade-related prefixes ('5' for fifth graders, etc.). Statistically nonsignificant map duration differences ($p > .1$) were not reported.

In fifth graders, a 2 × 2 × 9 rmANOVA revealed a main effect of Map in ERPs within the N2pc time-window, $F = 2.7$, $p = .009$, $\eta_p^2 = .1$, confirming that children of this age show stable patterns of topographic lateralized activity (that are captured by the N2pc). Follow-up analyses focused on comparisons investigating visual and multisensory attentional control in ERP topography. Visual control modulated the topography of fifth graders' cue-elicited ERPs (Map × Cue Color interaction, $F(8, 200) = 3.4$, $p = .001$, $\eta_p^2 = .1$), which was driven by three maps: Map54, Map56, and Map59 (Figure 3a, left panel). Map56 was more active during the processing of target-color cues than nontarget-color cues (28 vs. 8 ms, $t(25) = 3.7$, $p = .005$). Meanwhile, Map54 and Map59 were more active during the processing of nontarget-color cues than target-color cues (Map54 20 vs. 7 ms, $t(25) = 3.4$, $p = .008$; Map59 16 vs. 9 ms, $t(25) = 3$, $p = .04$, Figure 3a, left panel).

Additionally, multisensory control modulated the topography of fifth graders' ERPs (Map × Cue Modality interaction, $F(8, 200) = 2.4$, $p = .02$, $\eta_p^2 = .1$), driven by two maps: Map52 and Map53 (Figure 3a, right panel). Map53 was more active during the processing of audiovisual cues than visual cues (29 vs. 13 ms, $t(25) = 3.7$, $p = .007$), while Map52 was more active during the processing of visual cues than audiovisual cues (17 vs. 5 ms, $t(25) = 3.1$, $p = .03$). Visual

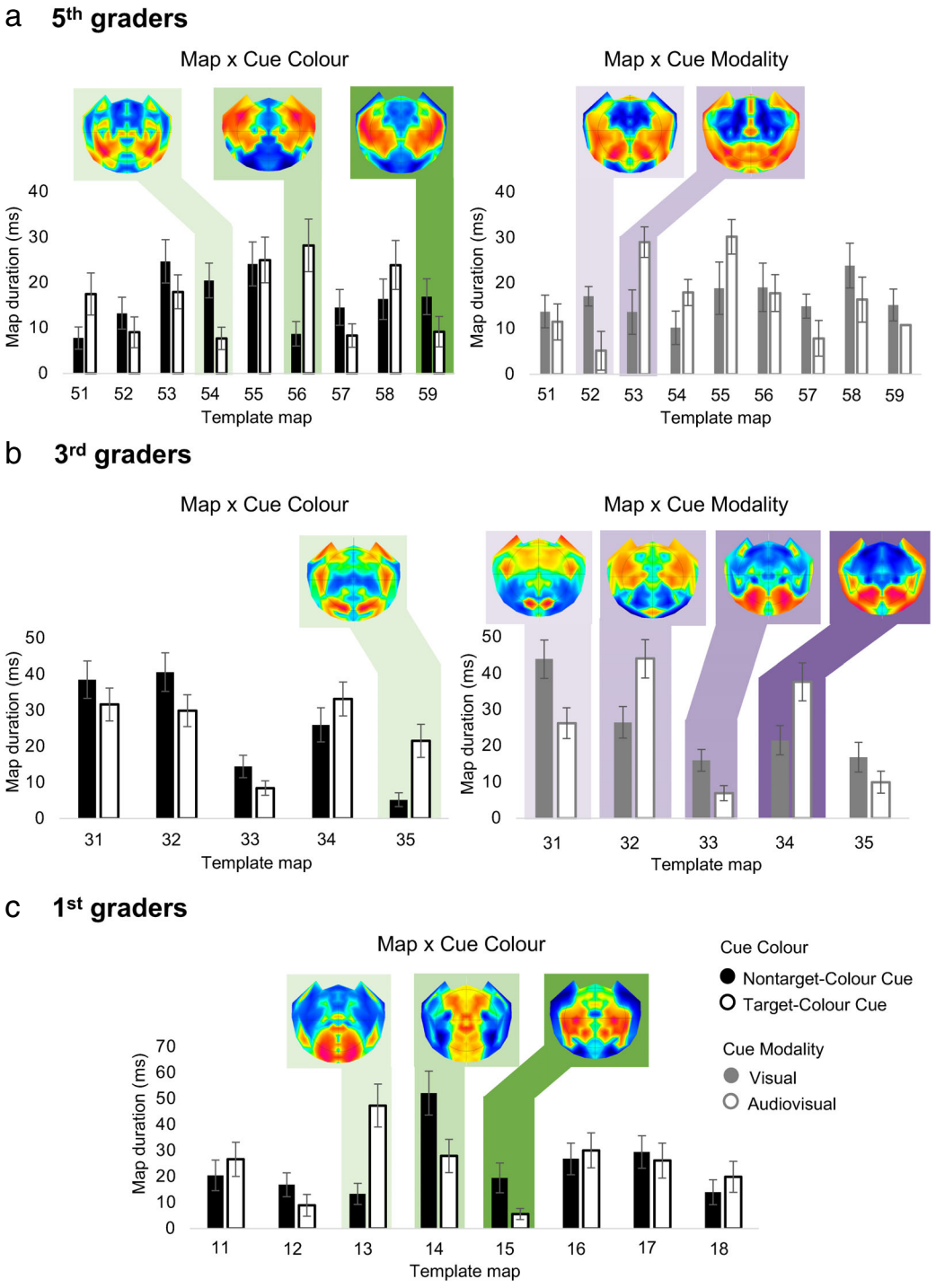

Fig. 3. (a–c) Electrical neuroimaging analyses of visual and multisensory control effects in EEG potential topography. Bars represent mean durations (ms) of maps present in the N2pc time-window in each age group, where black/black-outlined bars represent Map × Cue Color interaction, gray/gray-outlined bars represent Map × Cue Modality interaction. Maps in shades of green and purple were modulated by Cue Color and Cue Modality, respectively. Error bars represent standard errors of the mean.

and multisensory control also interacted (Map × Cue Color × Cue Modality interaction, $F(8, 200) = 2.2$, $p = .048$, $\eta_p^2 = .1$; post-hoc analyses in Appendix S1).

In third graders, a 2 × 2 × 5 rmANOVA revealed a main effect of Map, $F(3.2, 117.6) = 9.8$, $p < .001$, $\eta_p^2 = .2$. Visual control modulated the topography of third graders' cue-elicited ERPs (Map × Cue Color interaction, $F(2.9, 107) = 2.8$, $p = .04$, $\eta_p^2 = .1$), driven by Map35 being more active during the processing of target-color cues than nontarget-color cues (21 vs. 5 ms, $t(37) = 3.7$, $p = .002$, Figure 3b, left panel). Third graders' ERP topography was modulated by multisensory control (Map × Cue Modality interaction, $F(3.1, 114.3) = 8$, $p < .001$, $\eta_p^2 = .2$), driven by Maps31–34 (Figure 3b, right panel). Specifically, Map32 and Map34 were more active during the processing of audiovisual over visual cues (Map32 44 vs. 26 ms, $t(37) = 3.5$, $p = .002$; Map34 37 vs. 21 ms, $t(37) = 3.2$, $p = .01$). Conversely, Map31 and Map33 were more active during the processing of visual over audiovisual cues (Map31 43 vs. 26 ms, $t(37) = 3.5$, $p = .004$; Map33 16 vs. 6 ms, $t(37) = 2.8$, $p = .006$). Again, visual and multisensory control interacted (Map × Cue Color × Cue Modality interaction, $F = 3.2$, $p = .03$, $\eta_p^2 = .1$; post-hoc analyses in Appendix S1).

In first graders, a 2 × 2 × 8 rmANOVA revealed a main effect of Map, $F(4.7, 127.2) = 4$, $p = .003$, $\eta_p^2 = .1$. Like in the older groups, visual control modulated first graders' cue-elicited ERP topography (Map × Cue Color interaction, $F(7, 189) = 4.2$, $p < .001$, $\eta_p^2 = .1$), driven by Maps13–15. Map13 was more active during the processing of target-color cues over nontarget-color cues (47 vs. 13 ms, $t(27) = 4.3$, $p = .003$). Conversely, Map14 and Map15 were more active during the processing of nontarget-color cues than target-color cues (Map14 52 vs. 27 ms, $t(27) = 3.1$, $p = .007$; Map15 19 vs. 5 ms, $t(27) = 2.8$, $p = .05$). Unlike the older groups, however, first graders showed no evidence for multisensory control in ERP topography (no Map × Cue Modality, interaction, $F(7, 189) = .9$, $p = .4$). That said, visual and multisensory control interacted (Map × Cue Color × Cue Modality, $F(7, 189) = 2.2$, $p = .04$, $\eta_p^2 = .1$; post-hoc analyses in Appendix S1).

DISCUSSION

Using multivariate analyses of the N2pc, a well-known ERP marker of attentional selection in adults, we have shown that brains of children's brains are sensitive to the visual task relevance of objects and the multisensory nature of objects early during primary education.

Top-Down Visual Attentional Control Is Present Even at School Entry

In behavior, robust feature-specific (color) goal-based visual attentional control, indexed by task-set contingent attentional capture, was observed in third and fifth graders. This is younger than what most extant research on attentional control processes demonstrates. Importantly, EN topographical analyses demonstrated distinct stable patterns of global brain activity that were sensitive to such visual control already at school entry.

In older groups, EN revealed the brain mechanisms underlying the behaviorally-observed patterns of visual attentional control. In third graders, behavioral task-set contingent attentional capture may emerge from enhanced target-matching distractor (target-color cue) processing, via the recruitment of brain networks that preferentially process goal-relevant information. In fifth graders, task-set contingent attentional capture may be driven by a combination of enhanced processing of goal-relevant information and suppressed processing of goal-irrelevant (nontarget-color cue) information. Namely, one map was primarily active during the processing of target-matching distractors, and two other maps during the processing of nontarget-matching distractors. While it cannot be ascertained if increased presence of nontarget-matching maps shows the inhibition of goal-irrelevant information, the concomitant behavioral inhibition of nontarget-matching distractors would support this notion. A similar pattern of results was found in adults' visual N2pc's (Hickey, Di Lollo, & McDonald, 2009). Although the relationship between topographic map modulations and distractor processing is not clear-cut, we reveal that children's brains execute visual feature-based (color) attentional control via differential brain network recruitment (and not via differences in brain response strength, i.e., gain control).

In first graders, EN revealed nascent visual attentional control. Despite no behavioral task-set contingent attentional capture, first graders showed two maps predominating responses to nontarget-matching distractors, and one map recruited for target-matching distractors, mirroring our findings in fifth graders. These results strengthen past findings by directly showing early onset of feature-specific top-down visual control at 4 years, and adding novel mechanistic insights at the brain level. Most studies on control processes in 4-year-olds used behavioral (e.g., Bull et al., 2008; Gaspelin et al., 2015) or hemodynamic measures (e.g., Brod et al., 2017; Fiske & Holmboe, 2019). It is a novel, exciting finding that separable sets of brain networks are preferentially active in response to goal-relevant and goal-irrelevant information even earlier than the 5-to-7-year shift.

Attentional Control Over Multisensory Objects Develops After 2 Years of Schooling

Behavioral analyses did not detect multisensory enhancement of capture in any group. However, in the older

groups, EN revealed distinct brain networks over 200-ms post-stimulus recruited by visual *and* audiovisual distractors. This finding supports the idea that salient multisensory stimuli, even when task-irrelevant, control attention independently of top-down goal relevance (Matusz & Eimer, 2011). Our results suggest that multisensory distraction emerges earlier than previously thought. While previous studies demonstrated that multisensory interference develops only around 6–7 years (Matusz et al., 2015; Matusz, Merkley, et al., 2019), we show that involuntary attention to multisensory objects develops already after 2 years of schooling. Thus, 6-to-7-year-olds are not protected from it, as previous work would suggest.

First graders showed no evidence for multisensory attentional control modulating cue-elicited ERP topography. If anything, sounds accompanying visual distractors *attenuated* their visually elicited ERPs, as shown by suppressed contralateral ERP responses. It may be that in first graders, but not older children, attentional resources are separably allocated to vision and audition (e.g., Welch & Warren, 1980, but see Matusz et al., 2015), but this requires further investigation.

Our EN analyses revealed that less than one year of schooling experience affords children's brain networks sensitivity to the goal relevance of visual stimuli; two additional years—to audiovisual stimuli. Our EN results were mirrored by behavioral results (partly, for visual control) but not by N2pc results. By extension, the EN results that were uncovered despite null behavioral results (for multisensory control; potentially driven by still-developing motor processes, e.g., Kail & Ferrer, 2007) should also be genuine effects. The validity and reproducibility of the identified topographic maps is supported by several direct sources of evidence. First, their optimal number was selected based on criteria of residual noise, reliability, and optimal map configuration. Second, the maps were statistically analyzed at single-subject level, during the fitting procedure. Finally, maps derived across similar tasks are highly reproducible, both in clinical (Baradits, Bitter, & Czobor, 2020) and basic research. For example, different groups across 10 studies reliably identify 4–7 EEG resting-state maps, which match the networks identified using magnetic resonance imaging (Michel & Koenig, 2018).

Studying Developing Attentional Control With EEG/ERPs

Crucially, our findings reveal EN analyses as more sensitive than canonical N2pc analyses. Why? First, mounting evidence suggests that the N2pc is not an automatic marker of attentional selection, readily measurable whenever attention is studied with ERPs. It might require optimal conditions to appear, spanning characteristics related to participant (age), attended stimuli (physical, e.g., bright; cognitive, e.g., task-relevant features), and/or the task (no other stimuli within 200–250 ms after presentation of main stimulus). We discuss those points in detail in the Appendix S1. Second, this higher sensitivity is well-explained by the ability of multivariate methods to capture patterns in data that univariate analyses are not sensitive to, for example, spatial regularities in brain activity across time and/or experimental conditions (e.g., Kriegeskorte, Formisano, Sorger, & Goebel, 2007; Matusz et al., 2018).

This issue is especially relevant for neurophysiological data. Recording from only one electrode of the EEG montage forcibly reduces the sensitivity of traditional ERP analyses, by decreasing the amount of signal. It also injects bias through the experimenter's forcible decision that activity at other electrode sites is irrelevant to the studied cognitive process: for N2pc — the control of attention in space (we discuss the limitations this brings for neuroscience and psychology in Matusz, Turoman, et al., 2019). Additionally, by relying on the choice of a reference electrode, results from canonical ERP analyses are necessarily less reproducible, across time, labs, etc. Finally, by recording from the same electrodes across *all* participants, such analyses rely on a fundamental, albeit difficult to defend, assumption that brain anatomy of all participants is uniform.

EN analyses surpass all of the above limitations; these analyses are independent of the reference electrode, are data-driven, and consider data from the whole electrode montage. Importantly, EN analyses are robust against the variability in the underlying brain anatomy—if one set of brain sources in a participant is too different from the whole sample, a given map will simply not be fit to them, but their remaining brain activity will be captured by other maps. This makes EN analyses also more reproducible (more details in Appendix S1). Together, our approach, involving comparing specific cognitive processes, systematically across children from specific age groups (and adults; Turoman et al. 2021), and analyses of well-known ERP correlates with multivariate approaches, holds multiple advantages for investigating the development of cognitive and brain mechanisms of attentional control.

Implications for Education

Our findings confirm the idea that schooling supports neurocognitive development and enriches it with findings on real-world distraction. Effects of in-classroom clutter and noise (+5 years; Fisher et al., 2014; Massonnié et al., 2019) may be exacerbated by children's sensitivity to distraction by audiovisual objects, but only from age 6. Thus, classrooms, but not kindergartens, could support learning by reducing decoration or use of new technologies—unless these are related to the subject of instruction.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Appendix S1. Supplementary Information.

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