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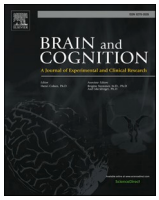

Electrophysiological responses of audiovisual integration from infancy to adulthood

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ABSTRACT

Our ability to merge information from different senses into a unified percept is a crucial perceptual process for efficient interaction with our multisensory environment. Yet, the developmental process underlying how the brain implements multisensory integration (MSI) remains poorly known. This cross-sectional study aims to characterize the developmental patterns of audiovisual events in 131 individuals aged from 3 months to 30 years. Electroencephalography (EEG) was recorded during a passive task, including simple auditory, visual, and audiovisual stimuli. In addition to examining age-related variations in MSI responses, we investigated Event-Related Potentials (ERPs) linked with auditory and visual stimulation alone. This was done to depict the typical developmental trajectory of unisensory processing from infancy to adulthood within our sample and to contextualize the maturation effects of MSI in relation to unisensory development. Comparing the neural response to audiovisual stimuli to the sum of the unisensory responses revealed signs of MSI in the ERPs, more specifically between the P2 and N2 components (P2 effect). Furthermore, adult-like MSI responses emerge relatively late in the development, around 8 years old. The automatic integration of simple audiovisual stimuli is a long developmental process that emerges during childhood and continues to mature during adolescence with ERP latencies decreasing with age.

1. Introduction

The brain's ability to merge sensory information across the senses is a fundamental process to adapt to our multisensory environment. Studies in children and adults have shown the behavioral benefits of multisensory integration (MSI) as it can adaptively guide behavior by identifying and applying optimal responses to objects or events (De Gelder and Bertelson, 2003). Similar to adults, infants are sensitive to redundant information about objects and events (Bahrick et al., 2004; Bahrick and Lickliter, 2002; Bahrick and Pickens, 1994; Lewkowicz, 2000) and learn to perceive increasingly more subtle differences and complex experiences through interaction with their environment (Gibson, 1969, 1966). For instance, behavioral findings revealed that a few hours- and month-old infants could discriminate the synchronicity of rhythm and tempo, and match intensity between visual and auditory objects (Dionne-Dostie et al., 2015; Lewkowicz and Lickliter, 2013). Although these abilities appear to be present in early infancy, developmental studies have highlighted that some multisensory processes are found to develop in late childhood and continue to evolve even during adolescence (Barutchu et al., 2010, 2009; Brandwein et al., 2011; Gori et al., 2012, 2008; Hillock et al., 2011; Hillock-Dunn and Wallace, 2012; Lewkowicz, 1996; Nardini et al., 2016). Aside from these behavioral studies, little is known about the developmental pattern of MSI in the developing human brain.

Neurophysiological animal studies have reported that, during early postnatal life, subcortical and cortical multisensory neurons remain

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immature and lack the ability to synthesize multisensory information, requiring considerable sensory experience to reach maturation (Wallace et al., 2006; Wallace and Stein, 2007; Xu et al., 2014). Single-unit recording experiments in animals deprived of sensory experience have shown a reduction in the ability of neurons to integrate multisensory inputs (Carriere et al., 2007; Royal et al., 2010; Wallace et al., 2004; Wallace and Stein, 2007). Similarly in humans, functional magnetic resonance evidence revealed that individuals who have a short visual deprivation early in life showed a reorganization of crossmodal auditory and visual functions, as well as an alteration of neuronal and behavioral responses to audiovisual (AV) signals (Collignon et al., 2015; Guerreiro et al., 2015; Putzar et al., 2007). These studies suggested that early sensory experiences play a crucial role in the emergence of MSI mechanisms (Stein et al., 2009).

Event-related potentials (ERPs) have been used to investigate how the human brain integrates AV information during development. Some studies suggested that the human brain might show signs of MSI early in development. For instance, ERP responses to bimodal stimuli were enhanced when compared to unimodal stimulation in 3-month-old infants, revealing increased auditory processing with simultaneous visual cues in the first months of life (Hyde et al., 2010). Specifically, using a passive task, auditory and audio-visual stimuli elicited prominent P150, P350, and N450 components over fronto-temporal sites. Furthermore, the authors reported an increased response to the N450 component following bimodal stimuli presentation compared to the unimodal visual response (AV-V). Differences in ERP activity between synchronous and asynchronous AV stimuli were also reported in 6-month-old infants in a habituation-test paradigm where N1 and P2 latency delays were not observed between synchronous and fused items, compared to N1 and P2 latency difference observed between synchrony and perceived asynchrony (Kopp, 2014). Altogether, these findings suggest the presence of multisensory integration in infancy.

In contrast, other studies suggested that MSI might be a late bloomer (Ernst, 2008). Using a cross-sectional approach and a simple reaction time task, one study attempted to characterize neurodevelopmental changes with ages in AV integration using ERP's in participants aged 7 years old to early adulthood (Brandwein et al., 2011). When looking at the amplitude of the N1 in the fronto-central regions, the authors reported an immature AV integration in children aged 7–9 years, as their multisensory (AV) responses were less negative than their sum responses of visual and auditory (SumAV). In contrast, 13–16-year-olds and adults showed the reversed pattern, as their AV responses were more negative than their SumAV responses. Interestingly, the multisensory response (AV) in 10–12-year-olds was not significantly different from the SumAV response, suggesting a transitional stage. In 2014, Knowland et al. (2014) used an active task comparing ERP modulation to unisensory auditory and visual stimulation, and congruent or incongruent multisensory conditions in adults and children (6- and 7-year-olds). They found that while adults showed significant N1 and P2 modulation in latency and amplitude when auditory speech sound was presented congruently with visual cues, the multisensory effect in children could mainly be observed on the amplitude of the N1-P2 complex while the latency modulation remained stable.

Although the neurodevelopmental changes of unisensory auditory and visual ERPs are well documented (Ceponiene et al., 1998, Romero et al., 2020, Didoné et al., 2021, Lippé et al., 2007, Aso et al., 1988), to our knowledge, no study has yet investigated the neurodevelopment of MSI from young infancy to adulthood. The current study aims to investigate, using event-related brain potentials (ERPs) recorded with electroencephalography, the neurodevelopmental pattern of auditory, visual, and audiovisual responses in participants aged 3 months to 30 years. ERPs were used to characterize the developmental course of AV integration and to measure how this ability may be expressed differently in ERP morphologies and topographic distributions according to age. Based on the above literature, we expect to measure ERP evidence of AV multisensory integration in infancy shown by a greater magnitude of the AV response compared to SumAV. Furthermore, we expect the AV ERPs to undergo neurodevelopmental changes such as shorter latency and amplitude increase with age. Additionally, A and V stimuli were used to illustrate typical unisensory development from infancy through adulthood in our cohort.

2. Material and methods

2.1. Participants

One hundred and thirty-one French-speaking individuals aged 3 months to 30 years participated in this study. Twenty-four participants were excluded from the original sample due to movement artifacts (7 participants between the ages of 3 months to 4 years), the presence of spike waves on the EEG (one 3-year-old), or excessive fatigue and irritability (16 participants aged between 3 and 24 months). All remaining 107 participants were divided into the following seven age groups: infants 3–12 months ($n = 15$), toddlers 2–4 years ($n = 19$), young children 5–7 years ($n = 17$), children 8–10 years ($n = 14$), young adolescents 11–14 years ($n = 18$), adolescents 15–17 years ($n = 11$), and adults 18–30 years ($n = 13$). The age groups were defined based on their corresponding typical developmental stages (Borgers et al., 2000; Piaget, 1971) and the auditory and visual cortical maturation (Lippé et al., 2007; Lippé et al., 2009). Sensitivity calculations performed in G*power (Faul et al., 2007) showed that our sample of 107 participants allows measuring medium to large size effects of gender difference (number of groups = 14, df = 1, effect size = 0.27) and age group difference (groups = 14, df = 6, effect size = 0.37) at a power of 80 % and an alpha level of 0.05. Table 1 shows the demographic characteristics of the sample. All participants were born at term, healthy, and had no history of neurological, psychiatric, congenital, or chromosomal anomalies. They all had normal hearing and normal or corrected-to-normal vision. Exclusion criteria for all age groups were a history of intrauterine growth retardation (IUGR) or seizures, the use of psychotropic medication, and major infectious diseases during pregnancy (e.g., AIDS, toxoplasmosis, and rubella). Developmental information was gathered from semi-structured interviews and a developmental questionnaire completed by the parents. Participants and parental written consent were obtained according to the Declaration of Helsinki. The Ethical, Administrative, and Scientific Committees of the Sainte-Justine University Hospital Center and the Université de Montréal approved this study. There was no significant gender difference between groups, X^2 (6, $N = 107$) = 2.24, $p = 0.897$.

N = number of participants; RR = retention rate number of accepted trials divided by total of recorded trials; m = months, y = years; SD = standard deviation.

2.2. Experimental design

2.2.1. Stimuli and paradigms

Visual (V): The visual stimulation consisted of a black and white checkerboard with each 3.4 cm square subtending a visual angle of 1.75°. The stimuli had a luminance of 37 cd/m2 and were displayed on a 40.5 cm × 30.5 cm ViewSonic monitor (ViewSonic, Canada) at a distance of 114 cm from the participant's eyes.

Auditory (A): The auditory stimulation consisted of a 1000 Hz tone delivered binaurally through loudspeakers (Optimus XTS 24) located bilaterally at 30 cm from the participant's head. The intensity was 65 dB SPL (sound pressure level) and the tone duration was 150 ms including 10 ms rise and fall time.

Audiovisual (AV): The audiovisual stimulation consisted of a simultaneous presentation of the black and white checkerboard synchronized to the 1000 Hz tone.

Visual mask: A uniform gray mask (RGB: 125,125,125) was used to reduce the afterimage effect. The visual mask was presented during the auditory stimuli and immediately after the visual and multisensory

Table 1
Demographic data for each age group.

Age group	N (Male: Female)	Mean Age (SD)	Retention rate AV Mean (SD)	Retention rate A Mean (SD)	Retention rate V Mean (SD)
Infants: 3–12 *m*	15 (6:9)	9.12 m (4.08)	64 (15) %	63 (14) %	65 (19) %
Toddlers: 2–4 y	19 (11:8)	3.35 y (1.04)	73 (20) %	70 (17) %	70 (14) %
Young children: 5–7 y	17 (8:9)	6.09 y (0.76)	76 (27) %	73 (18) %	76 (24) %
Children: 8–10 y	14 (8:5)	8.71 y (0.86)	76 (9) %	73 (7)%	74 (9)%
Young adolescents: 11–14 y	18 (10:8)	12.54 y (1.17)	67 (15) %	67 (14)%	67 (14)%
Adolescents: 15–17 y	11 (5:6)	16.08 y (0.65)	56 (15) %	57 (16)%	57 (17)%
Adults: 18–30 y	13 (7:6)	23.77 y (2.98)	47 (23) %	49 (21)%	52 (25) %

stimuli were presented.

Paradigm: Stimuli were presented with equal probability in random order across the three sensory conditions in blocks of 35 trials for each AV, A, and V condition. Participants completed 5 blocks for a total of 175 stimuli for each stimulus condition. Interstimulus intervals (ISI) varied randomly between 700 and 1000 ms to provide sufficient time for information processing and maintain infant engagement (Xie and Richards, 2016). All 3 stimuli had a duration of 150 ms and were generated by E-Prime Psychology Software (Psychology Software Tools Inc., Pittsburgh, USA) on a Dell GX 150 PC computer. The auditory (1000 Hz tone) and visual (checkerboard) were chosen because they have been shown to evoke consistent auditory and visual potentials in infants, children, adolescents, and adults (Ceponiene et al., 1998, Romero et al., 2020, Didoné et al., 2021, Lippé et al., 2007, Aso et al., 1988).

2.2.2. Procedure

All conditions were presented in a session of 12 min while participants sat in a comfortable chair or on their parent's lap (infants and toddlers) in a dimmed and soundproof room. Participant's alertness was monitored during data acquisition by observing their behavior and EEG data. They were instructed to maintain fixation in the center of the stimulus screen. In addition, an experimenter assisted the participant to ensure that he or she was engaged in the paradigm. An experimenter in the adjacent room in charge of the recording system monitored the participant's behavior through a camera. The stimuli were presented only when the participant looked at the stimulus screen and paused when their gaze drifted away. In younger children and infants, if

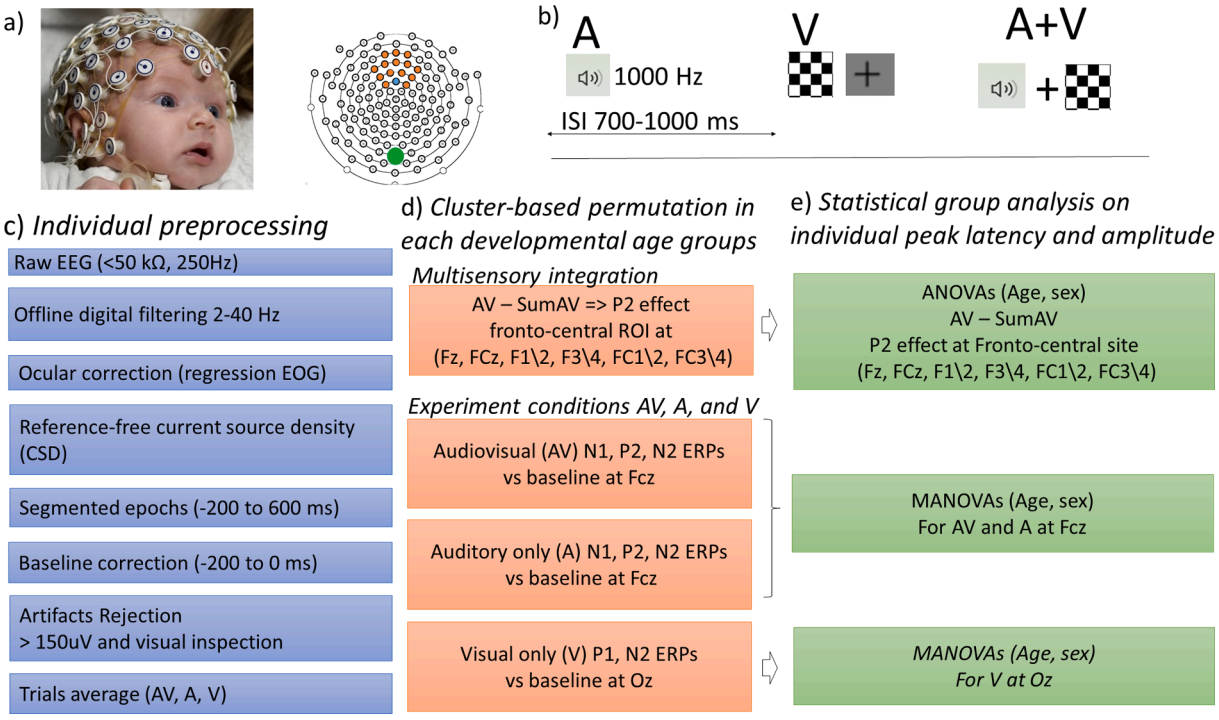

Fig. 1. Overview of the data analysis methods. a) High-density Geodesic Sensor Net on a participant and schematic representation of FCz electrode (blue), Oz electrode (green), fronto-central region (orange). b) Experimental design: the auditory condition consisted of a 1000 Hz tone presented at 65 dB during 150 ms, the visual condition consisted of a black and white checkerboard with 37 cd/m2 luminance presented during 150 ms; the audiovisual condition consisted of a simultaneous presentation of the visual and auditory stimuli. ISI varied randomly between 700 and 1000 ms and was followed by a visual mask. c) EEG individual preprocessing steps. d) Cluster-based permutation analysis by age groups. e) Statistical analysis based on individual peak latency and amplitude. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

necessary, the experimenter used a toy or verbally prompted them to continue the experiment, during which data recording was on pause and resumed when the participant looked at the stimulus screen without external stimulation (toy). At all times an experimenter was present with the participant to ensure full collaboration and a real-time video feed was captured. Rest periods were provided to maintain concentration, prevent fatigue, and verify electrode impedance. The total duration of the recording, including the installation of the EEG net, was approximately 45 min to 1 h.

2.2.3. Data acquisition and analysis

EEG data were recorded using a high-density Geodesic Sensor Net equipped with 128 electrodes (Fig. 1) (Electrical Geodesics Inc., Eugene, OH, USA), with the reference located at the vertex. Electrode impedance was kept below 50 kΩ (Tucker, 1993). EEG signals were acquired at a sampling rate of 250 Hz with an analog bandpass of 0.01–100 Hz using the NetStation EEG Software (Electrical Geodesics Inc., Eugene, OH, USA).

Raw EEG data were analyzed using BrainVision Analyzer software version 2.2 (Brain Products, Germany). Preprocessing included offline digital filtering of the 2–40 Hz bandwidth with a slope of 24 dB/octave and a 2 Hz high-pass filter was used to eliminate the DC drift from the data frequently present in infants (Ruhnau et al., 2011). Although such a high-pass filter needs to be used with caution since it could reduce response after 500 ms (Tanner et al., 2015), it was suitable in our experimental design that aimed to measure the ERP responses occurring between 0–400 ms (auditory and audiovisual N1, P2, N2; Visual P1, N2). Electrodes surrounding the neck region were excluded due to poor skin contact. The remaining 98 electrodes covering the entire head were kept for further analysis. Noisy channels were replaced by linear interpolation of adjacent electrodes. An ocular correction was conducted using a regression-based approach (Gratton et al., 1983). Raw data were segmented into epochs ranging from −200 ms pre-stimulus to 600 ms after stimulus onset. Afterward, artifact rejection was conducted to reject artifacts over or below the threshold of ± 150uV. In addition, a visual inspection was performed on the EEG signals to identify and reject remaining artifacts. Reference-free current source density (CSD) was used offline to avoid the volume conduction effect resulting in a sharpened resolution of local cortical generators (Kamarajan et al., 2015). A spherical spline of order 4 was applied to the global potential of all artifact-free electrodes to estimate the CSD transformation on a unit sphere (Perrin et al., 1989). For each participant, the artifact-free segments were baseline corrected using the −200 ms pre-stimulus onset and then averaged across trials for each stimulus type (average of good segments: AV = 82.90 ± 34.29, A = 84.19 ± 34.42, and V = 84.32 ± 33.84).

2.2.4. Statistical analyses

2.2.4.1. Cluster-based permutation test. First, a cluster-based permutation test using a clustering and nonparametric randomization test implemented in Fieldtrip, a MATLAB toolbox (Oostenveld et al., 2011), was performed to visualize the spatio-temporal topographic distribution across ages underlying the multisensory integration effect (AV vs. SumAV) and AV, A, and V responses. This approach has the advantage of controlling for Type I error rates involving multiple comparisons. Monte Carlo randomization was used to compute the sampling distributions for the cluster sizes. The threshold for cluster formation was set at $p \leq 0.05$ following 1000 randomizations (Oostenveld et al., 2011) for a mean of 8 ms. Spatio-temporal clusters had to contain at least two adjacent electrodes within 4 cm in the spatial coordinates of the Hydrocel sensor-net and adjacent time windows. This method was used to identify objectively the common spatiotemporal distribution across age groups and guide ERPs peak detection for all participants.

2.2.4.2. Multisensory integration. An established method to assess multisensory integration in ERPs is to compare multisensory responses (AV) with the summation of respective unisensory-A and unisensory-V constituents (SumAV) (Calvert, 2001; Fort et al., 2002a, 2002b; Molholm et al., 2020; Talsma and Woldorff, 2005). The AV response and the summation of A + V (SumAV) are then compared by subtraction to identify the MSI difference (MSI = AV-(SumAV)), resulting in a super-additive MSI effect compared to the summation of unisensory effects. To test the multisensory integration effect, the time series from 0 to 400 ms after stimulus onset was used for each electrode in each group. Cluster-based permutation detected an MSI difference just after the P2 component peak, the P2 effect, during the P2-N2 time window in the fronto-central region (see Fig. 2 (a): 3m-30y). Based on this result, individuals' P2 effect peak latency and amplitude over the fronto-central region (ROIs: Fz, FCz, F1\2, F3\4, FC1\2, and FC3\4) were identified (Fig. 1 (a)) and exported for subsequent statistical analysis to test for age and sex related differences (IBM SPSS Statistics for Windows, version 27.0. Armonk, NY: IBM Corp.).

Individual's P2 effect latency and amplitude were used to test the age-related multisensory integration. These electrodes were selected based on all groups (3 m-30y) topographic localization depicted in Fig. 2 (a) and in agreement with a previous study showing the peak difference in ERP waveforms between the AV and SumAV conditions in the fronto-central region (Brandwein et al., 2011). A two-way ANOVA was performed separately for P2 effect latencies and amplitudes, as previously defined by the cluster-based permutation, with groups (seven age groups) and sexes (male vs. female) as the between-subjects variables, over the fronto-central region defined by the cluster-based permutation. Post hoc tests with Bonferroni correction were applied to further investigate significant interactions. Variances were homogeneous for latencies and amplitudes, as assessed by Levene's test for equality of variances ($p = 0.71$ and $p = 0.93$, respectively).

2.2.4.3. Experiment conditions AV, A, and V. To put in perspective the MSI age-related changes in latency and amplitude, and to allow for a more comprehensive interpretation, unisensory auditive (A) and visual (V) results were included in the subsequent analysis. The activation of AV, A, and V ERP components (0 to 400 ms after stimulus onset) was statistically compared to their baseline (−200 to 0 ms) using cluster-based permutations. Detection of maximum (P1 and P2) and minimum (N1 and N2) peak components was carried out on FCz for AV and A conditions and on Oz for the V condition. The following time windows were used for N1 and P1 = 70–120 ms, P2 = 80–220 ms, and N2 = 200–400 ms. Single site Fcz and Oz were selected for statistical analysis because of their higher mean amplitude and better signal-to-noise ratio (SNR) compared to multisite comparisons (Zhang and Kappenman, 2024). ERPs SNR, measured individually by dividing the mean amplitude signal of each component by the standardized noise measurement error (SME; Luck et al., 2021) are reported in supplementary Table 1. Kolmogorov-Smirnov tests were used to test the normality assumption required by the statistical test ANOVA (Feng et al., 2014, Mishra et al., 2019). To obtain a normal distribution, a logarithmic transformation (Log10) was performed in N1, P1, P2, and N2 latencies and amplitudes for all three stimulus conditions. To help the interpretation of all figures and tables, descriptive statistics were reported without the log transforms.

Multivariate ANOVAs were then conducted separately for latencies and amplitudes with three dependent variables for AV and A (N1, P2, and N2) or two dependent variables for V (P1 and N2), and groups (seven age groups) and sexes (male vs. female) as independent variables. Post hoc tests with Bonferroni correction were applied to further investigate significant interactions between groups and stimulus conditions (AV, A, and V).

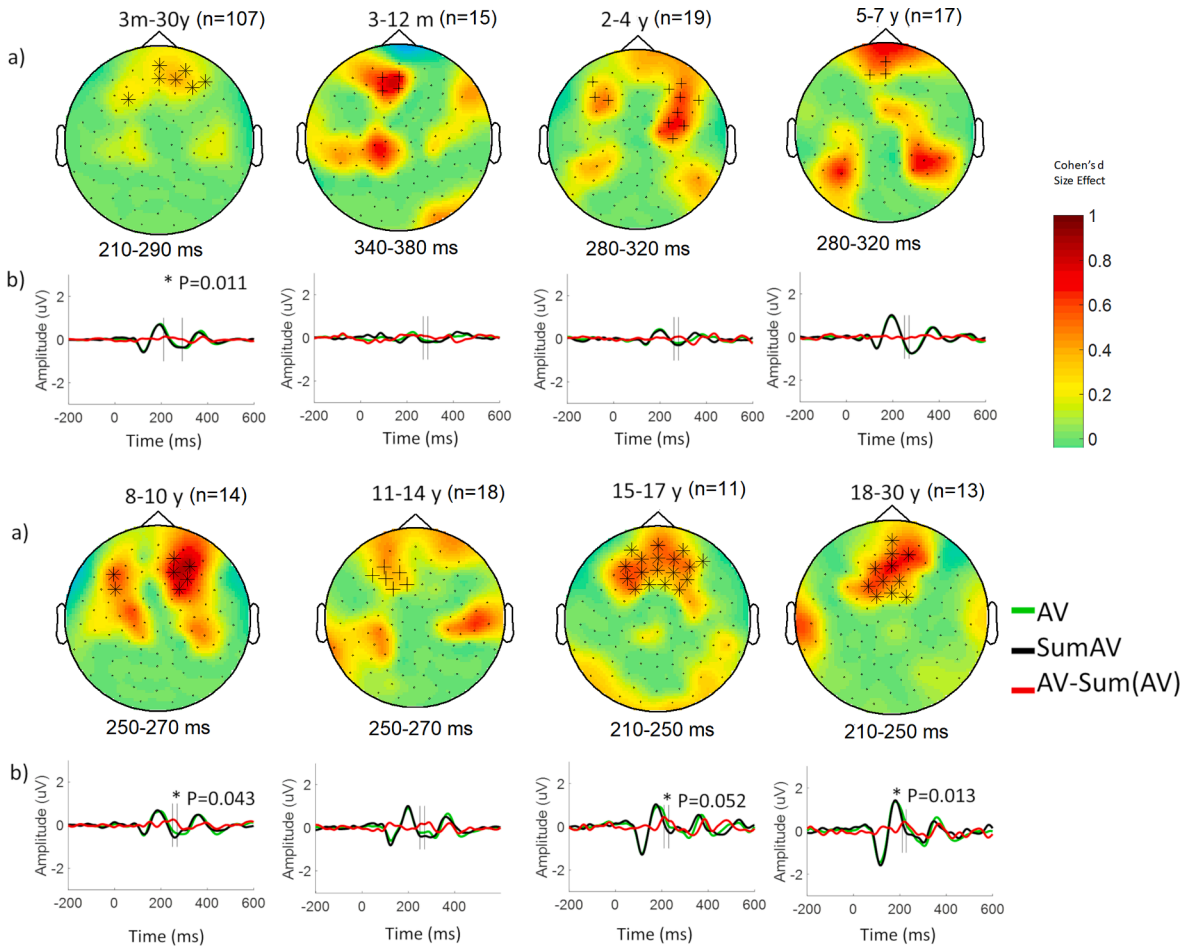

Fig. 2. MSI difference across groups (AV-SumAV) (a) MSI Cohen's d topographic maps of the difference occurring between P2 and N2 peak in the fronto-central region (P2 effect) for all participants (3 months to 30 years: 3 m-30y), 3–12 month, 2–4 year, 5–7 year, 8–10 year, 11–14 year, 15–17 year, and 18–30 year groups. Electrodes with statistically significant differences (corrected $p < 0.05$) between AV minus SumAV are shown with asterisks(*), and results (uncorrected $p < 0.05$) are shown with a cross (+). (B) Grand-average ERPs in response to AV (green), SumAV (black), and the resulting subtraction (AV-SumAV) (red). Time (ms) is plotted on the x-axis and amplitude on the y-axis. Cluster-based corrected p values are specified within the vertical lines. The corresponding topographic maps (maxima and minima of scalp field potentials) are displayed with positive values in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Results

3.1. Multisensory integration (MSI)

3.1.1. Topographic permutation tests on MSI difference

The cluster-based permutation test on the 0–400 ms time window revealed a difference between AV and SumAV. AV condition elicited an enhanced amplitude (superadditive effect) that was greater than the summed responses of the constituents in all our participants. This difference appeared shortly after the P2 maximum peak (P2 effect) between 210 and 290 ms over the fronto-central region ($p = 0.001$). In the adult and adolescent groups, the P2 effect was most pronounced in the latency range of 210–230 ms in adults ($p = 0.013$) and in 15–17 years-old adolescents ($p = 0.052$). Children (8-10y) had different activation profiles with their P2 effect reaching its maximum in the latency range from 230-270 ms ($p = 0.043$). The MSI difference was detectable but did not reach statistical significance after correction for multiple comparisons in the 3–12m, 2-4y, 5-7y, and 11-14y groups for the P2 effect observed in the fronto-central region within 340–380 ms in 3–12m, 280–320 ms in 2-4y, 280–320 in 5-7y, and 250–270 ms in 11-14y groups. See Fig. 2 for the P2 effect topographic distribution. This result identifies the prevalent fronto-central region among all participants and guides the individual MSI peak analysis to investigate differences across groups.

3.1.2. MSI difference across groups

Individual peak analysis showed a significant difference between groups in latency [$F(6, 92) = 10.897$, $p = 0.001$] but not for sex [$F(1, 92) = 0.375$, $p = 0.542$] or interaction [$F(6, 92) = 1.038$, $p = 0.406$]. Post hoc comparisons using Bonferroni corrections indicated later latency for the multisensory effect in infants (3–12 m; 320 ± 40 ms) compared to the six older groups (2-4y; 271 ± 39, $p = 0.003$), (5-7y; 265 ± 27, $p < 0.001$), (8-10y; 253 ± 31, $p < 0.001$), (11-14y; 241 ± 37, $p < 0.001$), (15-17y; 232 ± 41, $p < 0.001$), (18-30y; 224 ± 25, $p < 0.001$). In addition, the 18-30y group showed a significantly shorter latency compared to the 3–12 m ($p = 0.001$) and 2-4y ($p = 0.009$) and an almost significant late latency compared to the 5-7y group ($p = 0.06$). No difference in latency was found between the 18-30y and the 8-10y ($p = 0.830$), 11-14y ($p = 1.000$), and 16-17y ($p = 1.000$) groups. For the amplitude of the P2 effect, no main effect of group [$F(6, 92) = 0.333$, $p = 0.918$] or sex [$F(1, 92) = 2.788$, $p = 0.098$] and no interaction [$F(6, 92) = 0.367$, $p = 0.898$] was found.

3.2. Experiment condition AV, A, and V conditions

3.2.1. Topographic permutation tests

Distinct ERP waveforms and topographic maps were observed across the seven age groups. The grand-average ERP waveforms and topographic maps for time windows of ERP components according to all age groups and experimental conditions are presented as follows: Audiovisual (AV) (Fig. 4), Auditory (A) (Fig. 5), and Visual (V) (Fig. 6) conditions. The figures display each group's ERP components (a) and topographic maps (b-c-d). The ERP N1, P2, and N2 components are represented over FCz for AV and A conditions, whereas P1, P1b, and N2 components are represented over Oz for the V condition. ERPs and topographic distributions show electrodes with enhanced amplitude compared to the baseline with asterisks * ($p \leq 0.05$). supplementary Table 1 summarizes the results of the ERP latencies, amplitudes, SNR, and corrected p values following the cluster-based permutation tests.

3.2.2. Developmental group differences on AV, A, and V ERPs

Two-way MANOVA was used to examine the association between latency and amplitude of each AV, A, and V ERPs between age groups and sexes. The maximum amplitudes and latencies of N1, P2, and N2 for AV and A conditions on FCz were used for group comparison. Group comparisons for the V condition were assessed in Oz for P1 and N2 amplitudes and latencies. Fig. 7 shows the MANOVA results for N1, P2, and N2 latency and amplitude for AV (a) and A (b) conditions, and for P1 and N2 latency and amplitude of the V(c) condition.

Audiovisual (AV) N1, P2, and N2 latencies and amplitudes

Latency. The multivariate tests were significant for N1, P2, and N2 latencies for group (Pillai's Trace = 0.304, F (18,279) = 1.751, p = 0.031, partial $\eta^2 = 0.101$, observed power = 0.953) but no sex difference [F (3, 91) = 0.110, $p = 0.954$] or interaction [F (18, 279) = 0.857, p = 0.632]. Post hoc analysis with Bonferroni adjustment revealed that N1 latency was significantly higher of the younger age group (3–12 m: 142 ± 26 ms) than older groups (2-4y: 120 ± 14, p = 0.015), (5-7y: 118 ± 10, p = 0.008), (8-10y: 120 ± 21, p = 0.016), (11-14y: 121 ± 19, p = 0.019), (15-17y: 114 ± 10, $p = 0.003$), (18-30y: 114 ± 8, $p = 0.001$). Similarly, P2 latency was significantly delayed in infants (3–12m: 216 ± 29 ms) compared to older groups (15-17y: 185 ± 14, $p = 0.032$). No significant difference was found between groups for N2 latency (p = 0.255).

Amplitude. Results showed statistically significant N1, P2, and N2 amplitude effect for group (Pillai's Trace = 0.583, F (18,279) = 3.741, p = 0.001, partial $\eta^2 = 0.194$, observed power = 1.00) but no sex difference [F (3, 91) = 2.448, $p = 0.08$] or interaction [F (18, 279) = 1.350, p = 0.157]. Post hoc analysis with a Bonferroni adjustment revealed that N1 amplitude was significantly larger in adults (18-30y: −15.88 ± 7.16μv/m^2) compared to the younger age groups: (3–12m: −6.91 ± 6.17, $p < 0.001$), (2-4y: −8.56 ± 3.39, $p < 0.001$), (5-7y: −8.72 ± 4.58, $p < 0.001$), (8-10y: −8.06 ± 4.20, $p < 0.001$). N1 amplitude was also significantly larger in the 15-17y group (−14.52 ± 5.66) compared to the younger group (3–12m: −6.91 ± 6.17, $p < 0.03$).

For P2 amplitude, the comparison between groups showed significantly higher amplitude for 5-7y (20.67 ± 10.57) compared to 3–12m (7.93 ± 5.23, $p = 0.006$) and 2-4y (9.91 ± 8.46, $p = 0.004$). No significant difference was found between groups for N2 amplitude (p = 0.407).

Auditory (A) N1, P2, and N2 latencies and amplitudes.

Latency. The multivariate tests were statistically significant for N1, P2, and N2 latencies for group (Pillai's Trace = 0.502, F (18,279) = 3.115, $p < 0.001$, partial $\eta^2 = 0.167$, observed power = 0.999) but no sex difference [F (3, 91) = 2.406, $p = 0.072$] or interaction [F (18, 279) = 1.044, $p = 0.410$]. Post hoc analysis with a Bonferroni adjustment

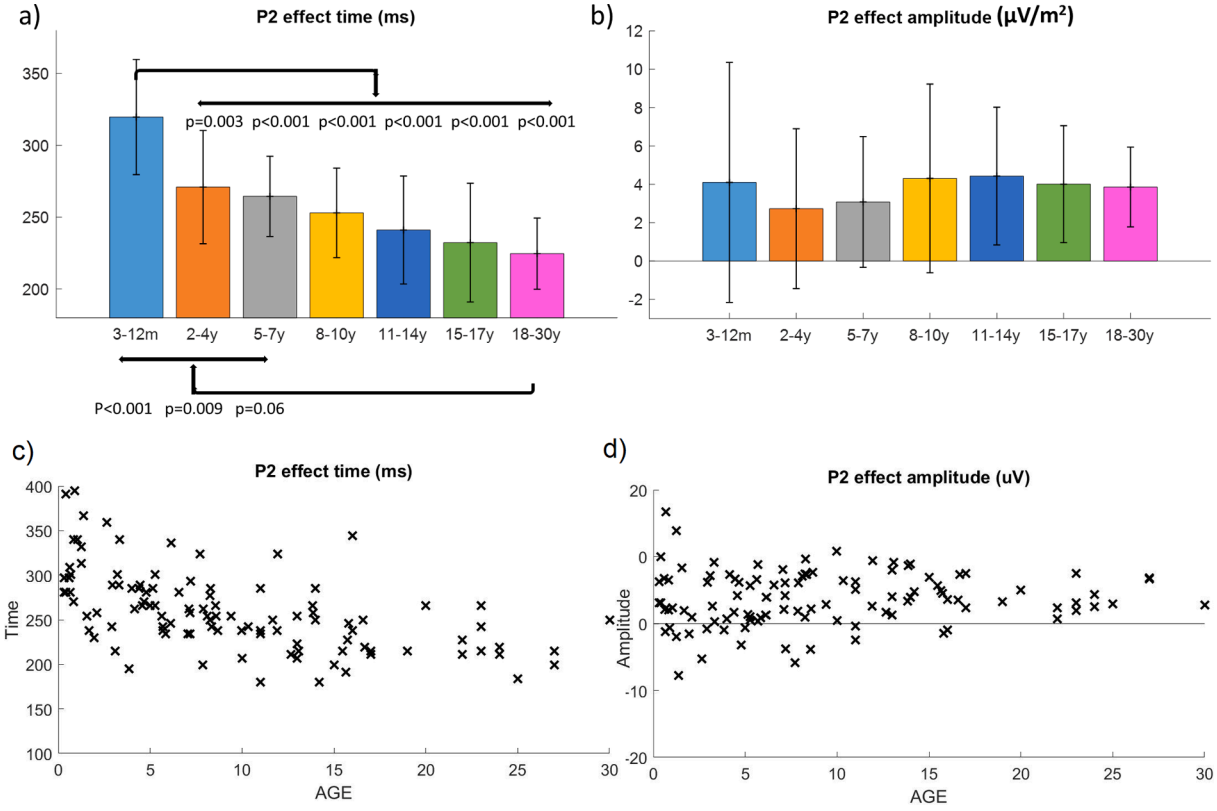

Fig. 3. ANOVA results of the MSI integration at P2 effect for latency (a) and amplitude (b) for the different age groups. Each bar illustrates an age group (3–12 months, 2–4 years, 5–7 years, 8–10 years, 11–14 years, 15–17 years, and 18–30 years). The direction of the black arrow indicates statistical difference between groups and the Bonferroni corrected p-value for significant and tendency results. Individual peaks c) for latency (ms) and (d) for amplitude (uV) in fronto-central area with age.

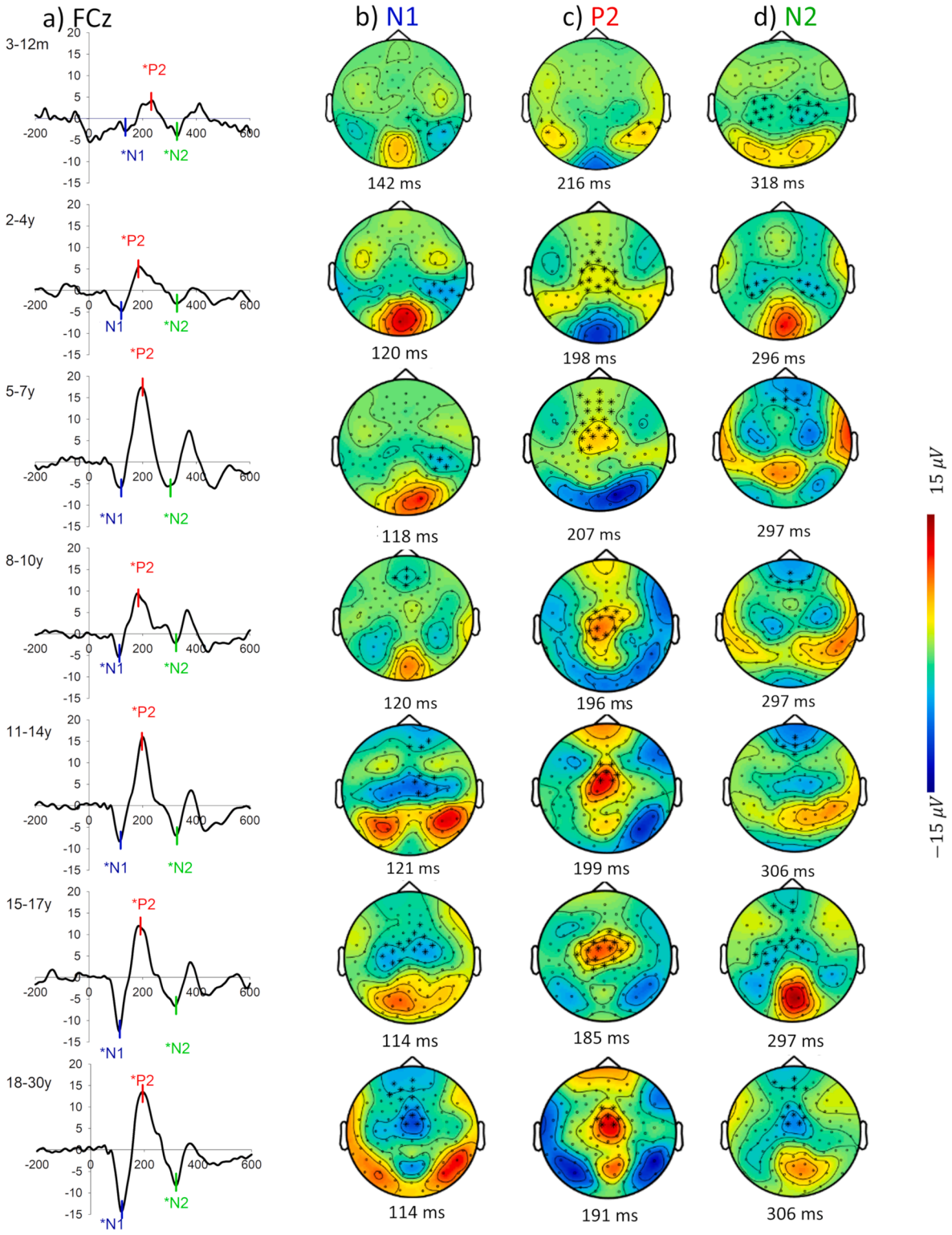

Fig. 4. Grand-average audiovisual (AV) ERPs on the FCz electrode are depicted in panel (a); time (ms) is plotted on the *x*-axis and amplitude on the *y*-axis. For 3–12 month, 2–4 year, 5–7 year, 8–10 year, 11–14 year, 15–17 year, and 18–30 year groups, the topographic maps illustrate the brain activation for N1 (b), P2 (c), and N2 (d), respectively. The ERPs and scalp distributions show electrodes with higher amplitude than the baseline. Statistical significance ($p \leq 0.05$) is represented with an asterisk *. The corresponding topographic maps (maxima and minima of scalp field potentials) are displayed with positive values in red and negative values in blue. supplementary video 1 and supplementary dataset 1 illustrate how ERPs at FCz vary across ages using a moving average of 10 close-in-age participants. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

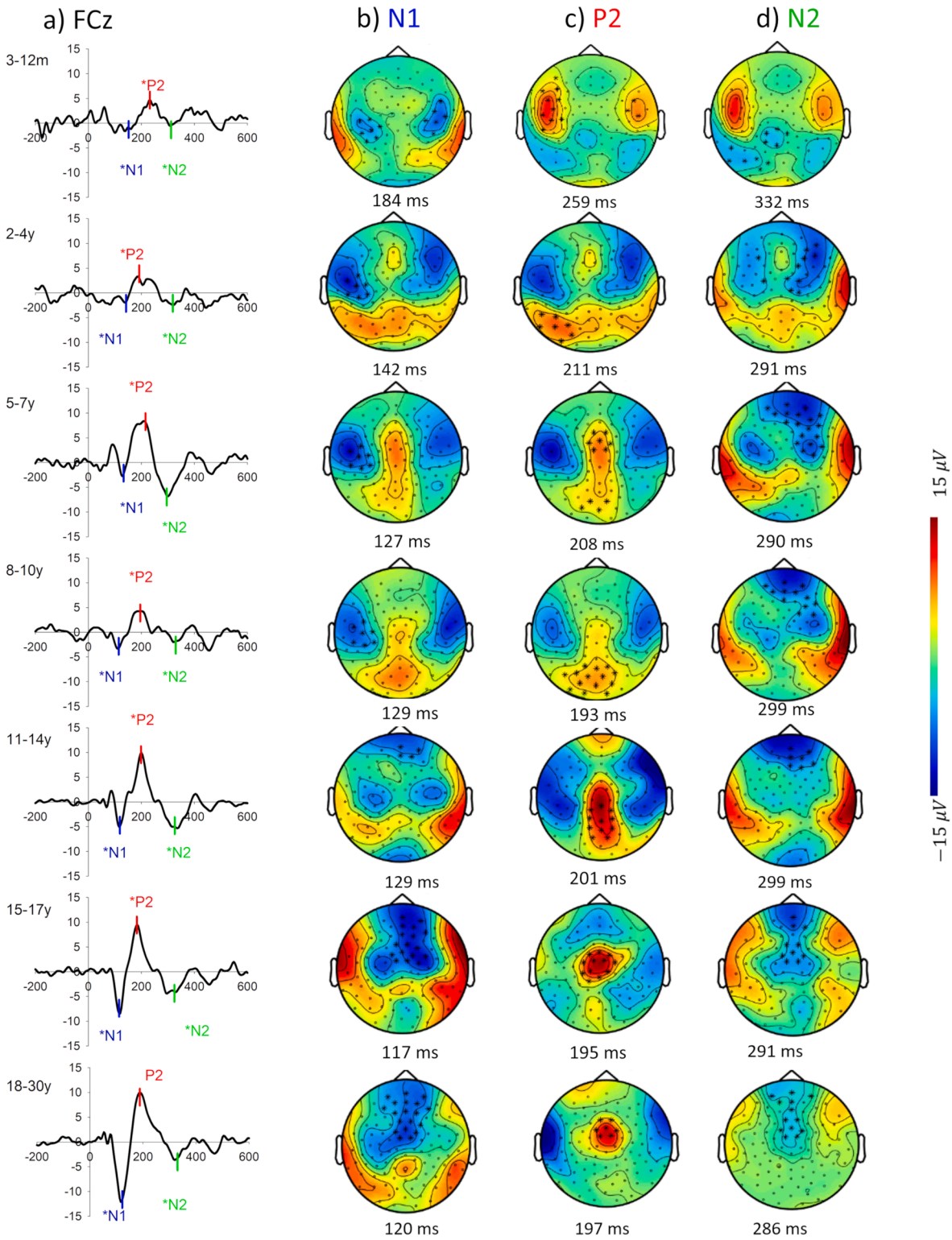

Fig. 5. Grand-average auditory (A) ERPs on electrode FCz are shown in panels (a); time (ms) is plotted on the *x*-axis and amplitude on the *y*-axis. For 3–12 month, 2–4 year, 5–7 year, 8–10 year, 11–14 year, 15–17 year, and 18–30 year groups, topographic maps illustrate the brain activation for N1 (b), P2 (c), and N2 (d), respectively. The ERPs and scalp distributions show electrodes with higher amplitude than the baseline. Statistical significance ($p \leq 0.05$) is represented with an asterisk *. The corresponding topographic maps (maxima and minima of scalp field potentials) are displayed with positive values in red and negative values in blue. supplementary video 2 and supplementary dataset 2 illustrate how ERPs at FCz vary across ages using a moving average of 10 close-in-age participants. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

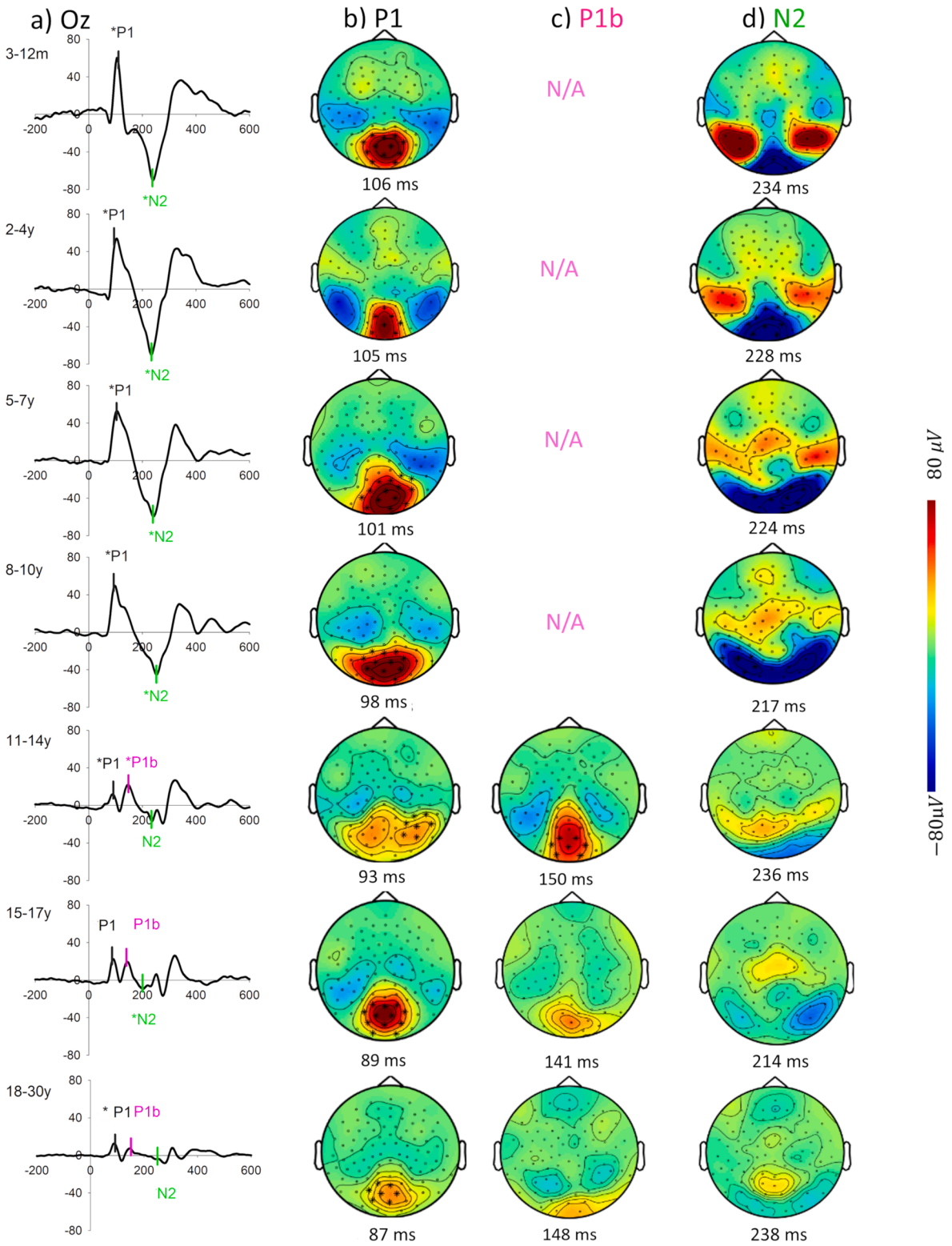

Fig. 6. Grand-average visual (V) ERPs on the Oz electrode are shown in panels (a); time (ms) is plotted on the *x*-axis and amplitude on the *y*-axis. For 3–12 month, 2–4 year, 5–7 year, 8–10 year, 11–14 year, 15–17 year, and 18–30 year groups, the topographic maps illustrate the brain activation for P1 (b), P1b (c), and N2 (d) for each age group. The ERPs and scalp distributions show electrodes with higher amplitude than the baseline. Statistical significance ($p \leq 0.05$) is represented with an asterisk *. The corresponding topographic maps (maxima and minima of scalp field potentials) are displayed with positive values in red and negative values in blue. supplementary video 3 and supplementary dataset 3 illustrate how ERPs at Oz vary across ages using a moving average of 10 close-in-age participants. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

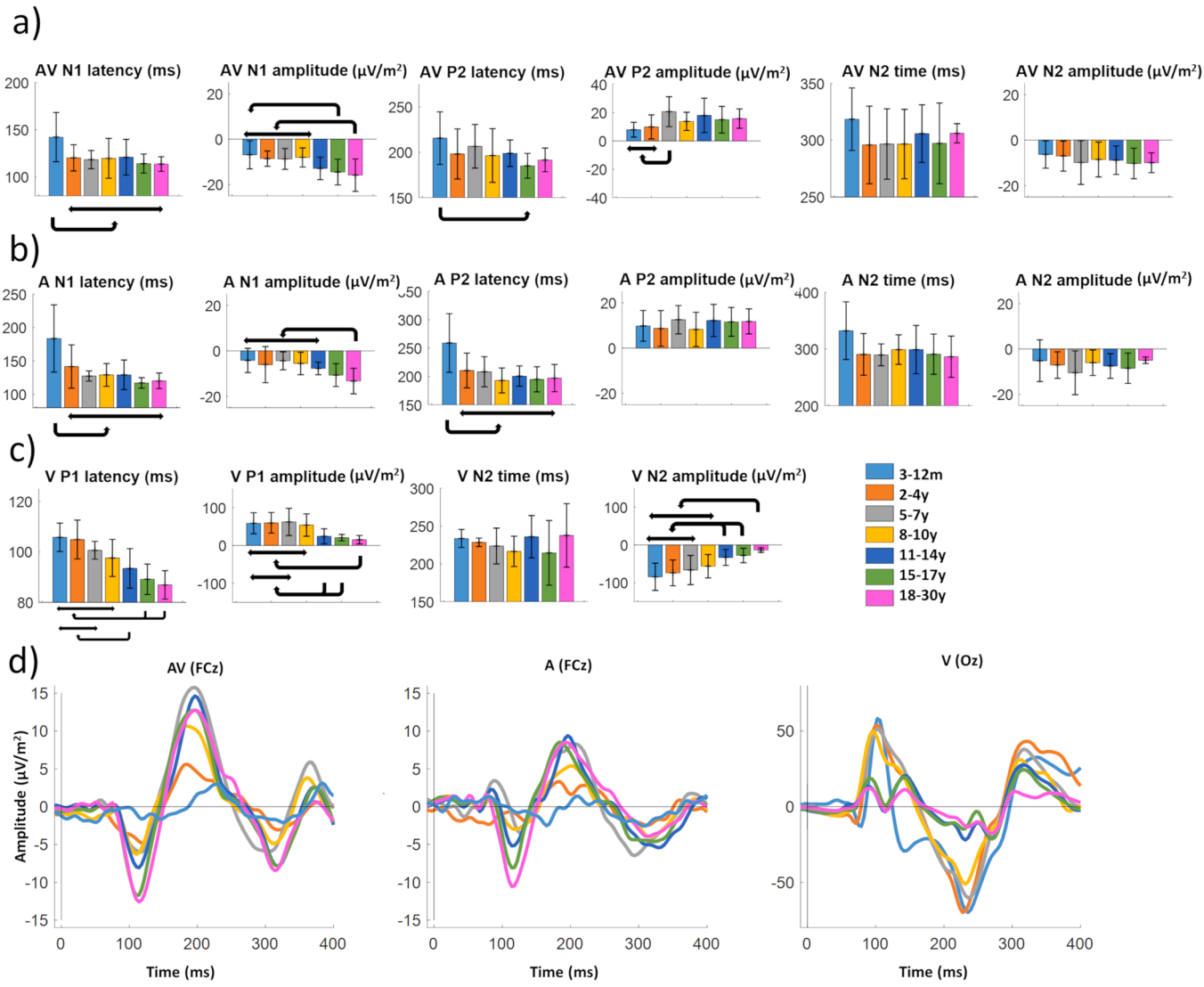

Fig. 7. MANOVA results comparing the seven age groups for N1, P2, and N2 latencies and amplitudes for AV (a) and A (b) conditions, and P1 and N2 latencies and amplitudes for the V(c) condition. supplementary Table 1 reports ERP components' latency and amplitude. The direction of the black arrow shows the statistical difference ($p \leq 0.05$) between groups. The black line ↔ indicates numerous groups showing a significant difference compared to one other age group. d) ERP waveforms of the AV (Fcz), A (Fcz), and V (Oz) conditions. 3–12 months are shown in light blue, 2–4 years in orange, 5–7 years in gray, 8–10 years in yellow, 11–14 years darker blue, 15–17 years in green, and 18–30 years in pink. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

revealed that N1 latency was delayed in infants (3–12 m: 184 ± 50 ms) compared to all older groups: (2-4y: 142 ± 32, $p < 0.001$), (5-7y: 127 ± 8, $p < 0.001$), (8-10y: 129 ± 17, $p < 0.001$), (11-14y: 129 ± 22, $p < 0.001$), (15-17y: 117 ± 8, $p < 0.001$), (18-30y: 120 ± 12, $p < 0.001$).

Similarly, P2 latency was significantly delayed in infants (3–12 m: 259 ± 52 ms) compared to older groups (2-4y: 211 ± 31, $p < 0.001$), (5-7y: 208 ± 27, $p < 0.001$), (8-10y: 193 ± 26, $p < 0.001$), (11-14y: 201 ± 18, $p < 0.001$), (15-17y: 195 ± 22, $p < 0.001$), (18-30y: 197 ± 24, $p < 0.001$). No significant difference was found between groups for N2 latency ($p = 0.325$).

Amplitude. The results of N1, P2 and N2 amplitudes showed a statistically significant group effect (Pillai's Trace = 0.537, F (18,279) = 3.381, $p < 0.001$, partial $\eta^2 = 0.179$, observed power = 1.000) but no sex effect [F (3, 91) = 0.703, $p = 0.553$] or interaction [F (18, 279) = 1.254, $p = 0.218$]. N1 amplitude was significantly larger in adults (18-30y: −13.26 ± 5.26 μv/m^2) compared to infants through young adolescents: (3–12 m: −4.19 ± 5.33, $p < 0.001$); (2-4y: −6.04 ± 7.93, $p < 0.001$); (5-7y: −4.36 ± 3.93, $p < 0.001$); (8-10y: −5.53 ± 4.92, $p < 0.001$); (11–14: −7.71 ± 2.76, $p = 0.002$). No significant group differences were found for P2 ($p = 0.097$) and N2 ($p = 0.066$) amplitudes.

Visual (V) P1 and N2 latencies and amplitudes.

Latency. Significant multivariate effects were found for visual P1 and N2 latency for group (Pillai's Trace = 0.641, F (12,186) = 7.304, $p < 0.001$, partial $\eta^2 = 0.320$, observed power = 1.000) but not for sex [F (2, 92) = 2.701, $p = 0.072$], and no interaction was found [F (12, 186) = 0.554, $p = 0.877$]. P1 latency Post hoc analysis with a Bonferroni adjustment indicated shorter latencies in young adolescents (11-14y: 93 ± 8 ms), adolescents (15-17y: 89 ± 6), and adults (18-30y: 87 ± 6) than in younger groups. The results of P1 in adults (18-30y) had the shorter latency compared to the 3–12 m (106 ± 6, $p < 0.001$), 2-4y (105 ± 8, $p < 0.001$), 5-7y (101 ± 4, $p < 0.001$), 8-10y (98 ± 7, $p < 0.001$) groups. They were followed by adolescents (15-17y) whose latency was significantly shorter than those of 3–12 m ($p < 0.001$), 2-4y ($p < 0.001$), and 5-7y ($p < 0.001$) and 8-10y ($p = 0.021$) groups, and by 11-14y whose latency was significantly shorter than 3–12 m ($p < 0.001$), 2-4y ($p < 0.001$), and 5-7y ($p < 0.018$). However, no significant difference between groups was found in N2 latency ($p = 0.157$).

Amplitude. For P1 amplitude, significant multivariate effects were found for visual P1 and N2 for group (Pillai's Trace = 0.543, F (12,186) = 5.771, $p < 0.001$, partial $\eta^2 = 0.271$, observed power = 1.000) but not for sex [F (2, 92) = 0.313, $p = 0.732$] and no interaction was found [F (12, 186) = 1.597, $p = 0.096$]. Pairwise comparisons showed that young adolescents (11-14y: 24.51 ± 19.72 μv/m^2), adolescents (15-17y: 20.69 ± 8.41), and adults (18-30y: 15.45 ± 11.21), had a smaller P1 amplitude than 3–12 m (58.88 ± 27.76), 2-4y (59.76 ± 27.22), 5-7y (62.37 ± 35.93), and 8-10y (54.84 ± 29.48) groups. Specifically, a significant difference was found between adults, showing a much smaller P1 amplitude in adults compared to 3 months to 10 years old (3–12 m: $p <$ 0.001), (2-4y: $p < 0.001$), (5–7: $p < 0.001$), (8-10y: $p < 0.001$). A smaller P1 amplitude was found between adolescents (15-17y) and infants (3–12 m: $p = 0.001$), (2-4y: $p < 0.001$), (5–7: $p < 0.001$) and significant differences between young adolescents and younger groups, with a smaller P1 amplitude in 11-14y (24.51 ± 19.72 μv/m^2) compared to younger groups: (3–12 m: $p < 0.001$), (2-4y: $p = 0.001$); (5–7: $p =$ 0.001). Similarly, young adolescents (11-14y: –33.07 ± 21.19), adolescents (15-17y: −27.80 ± 19.13), and adults (18-30y: −13.56 ± 5.86), had a smaller N2 amplitude than 3–12 m (−84.28 ± 35.97), 2-4y (−73.92 ± 34.08), 5-7y (66.35 ± 38.54), and 8-10y (56.19 ± 31.06) groups. Post hoc tests showed that the N2 amplitude was significantly smaller between adults (18-30y) and younger groups (3–12 m: p < 0.001), (2-4y: p < 0.001), (5-7y: $p < 0.001$) and (8-10y: $p < 0.042$) and significant differences between adolescents (15-17y) and younger groups (3–12 m: p < 0.001), (2-4y: p = 0.005), (5-7y: $p = 0.048$) and between young adolescents (11-14y) and younger groups (3–12 m: p < 0.001), (2-4y: p = 0.003), (5-7y: $p = 0.045$).

4. Discussion

The objective of this study was to examine how multisensory integration develops from 3 months old until adulthood. We conducted a cross-sectional study on a cohort of 131 individuals between 3 months and 30 years old to investigate how the brain automatically integrates simple audiovisual information. In addition, unisensory auditory and visual conditions were used to investigate the correlates of ERP responses development across ages.

4.1. MSI across ages and sex

In the present study, we measured the presence of MSI over the fronto-central area using a cluster-based permutation test when all participants (3m to 30y) were taken together between 210 and 290 ms. Our results suggest that adult-like, but still immature, multisensory integration appears relatively late in the ERP waveforms, between 8 and 10 years. Furthermore, a clear mature pattern could be seen between 15 and 17 years old. In our paradigm, the MSI difference (AV-(A + V)) was measured consistently on the P2 effect (occurring between the P2 and N2 components) in 8-10y, 15-17y, and 18-30y over the fronto-central area using a cluster-based permutation. The MSI difference was detectable, but did not reach statistical significance in the 3–12m, 2-4y, 5-7y, and 11-14y groups. The later MSI latency measured in infants follows the developmental pattern of unisensory ERP (Lippé 2007, Lippé 2009). Higher interindividual variabilities in younger groups (as shown in Fig. 3 and on the cluster-based permutations Fig. 2) might account for the amplitude difference not reaching significance after multiple comparisons. While other studies have shown evidence of multisensory integration in infants, for instance using illusory percepts of audio-visual speech, these also tend to be weaker and more inconsistent compared to the adult responses (Tremblay, C. et al., 2007, Rosenblum et al., 1995). Furthermore, a growing body of longitudinal neuroimaging research has demonstrated that early adolescence is a time of continuous brain growth and change, challenging long-held assumptions that the brain has primarily finished maturing at puberty (Johnson et al., 2009). Similar to the younger groups, our results in the 11–14 year-old adolescents could reflect the high inter-individual variability in MSI development. Nonetheless, our results corroborate previous studies using AV paradigms in children ranging from 6 years old to early adulthood, suggesting that the capacity to integrate AV information continues to develop well into childhood and does not reach its full developmental maturity until late adolescence (Barutchu et al., 2010, 2009; Downing et al., 2014; Gori et al., 2012; Nardini et al., 2016).

Although MSI was not significant in younger groups (from 3 months to 7 years old), this does not mean that the younger brain cannot process multisensory integration. While no explicit task was required from our participants, how neuronal activity related to MSI may be associated with maturation differences in attentional capacity remains an open question (Konrad, 2005; Posner and Rothbart, 1998). From 6 to 12 months, infants have better voluntary control over their visual fixations and show brief looks at basic AV stimuli (Courage et al., 2006). Beyond that age, the anterior attention system, including areas of the prefrontal cortex, becomes increasingly influential in the voluntary selection and maintenance of attention (Posner and Petersen, 1990) and may play a role in the ability to interpret information from multiple sources. The immaturity in attentional processes might thus explain the lack of consistency in AV integration observed at young ages. A limited sample of participants in the present study and a wide age range undoubtedly weakened our sensitivity to measure MSI effects, especially since in young children brains develop rapidly. Nevertheless, our data set allowed us to observe the maturation of the MSI process and confirm its presence in older groups. Future research should integrate behavioral and electrophysiological measures in studies examining the pediatric population's attention to multisensory stimuli.

ANOVA results of the MSI integration revealed a strong indicator of age-related effect at the P2 effect latency but no differences related to the sex of the participant. This difference in latency could be explained by the development of the auditory and visual systems (Ruhnau et al., 2011). From 3 months to 7 years old, the difference between AV and SumAV showed a significant delay in latency of the P2 effect compared to 18-30y. In contrast, no significant difference was found in the 8-10y, 11-14y, and 15-17y compared to 18-30y, suggesting that P2 effect already gained some maturity at 8-to-10 years of age.

4.2. Audiovisual, auditory, and visual brain processing across ages

Early sensory N1 and P2 spatiotemporal distributions in this study revealed distinct bimodal AV stimuli developmental patterns. In particular, infants and children from 3 months to 7 years old exhibited immature AV processing in the right temporo-parietal regions. In contrast, children from 8 to 10 years old showed the emergence of bimodal AV processing in the frontal region. Later on, mature AV profiles similar to those of adults in the fronto-central areas were found in 11 to 17 years old.

Multisensory processing depends on the structural and functional maturation of the unisensory senses (Lippé et al., 2009). While all senses begin to develop in utero, they have different rates of neuroanatomical maturation and functional development during infancy and childhood (Lippé et al., 2007). Our results for auditory ERPs are consistent with previous research showing the emergence of a mature N1 topographical distribution in the fronto-central areas in young adolescents (11–14 years old), eventually reaching a mature pattern like those of adults around late adolescence (15–17 years old) (Litovsky, 2015). Compared to the adult N1 fronto-central pattern, toddlers and children from 2 to 10 years old showed onset of N1 auditory in the lateral central, centro-parietal, and temporo-parietal regions with a predominance in the left hemisphere. N1 amplitude was predominant at fronto-central sites in adults and temporal sites in children from 4-8 years old (Bruneau et al., 1997). Finally, infants from 3 to 12 months exhibited an immature N1 auditory distribution in central, parietal, centro-parietal, and fronto-temporal regions. In line with other ERP studies, our results showed a decrease in latency and an increase in N1 and P2 amplitude with age

(Lippé et al., 2007).

The auditory P2 (sometimes called P1 in infants) was defined as a large positive peak occurring between 100 and 300 ms after the presentation of an auditory stimulus (Campbell et al., 2011). For consistency, we identified this component as the auditory P2 in all age groups. A modulation in amplitude and latency has been reported on the auditory P2 following congruent and incongruent audiovisual stimulation in adults as well as in infants, although a modulation in amplitude alone has been more often reported (Brandwein et al., 2011, Hyde et al., 2011, Knowland et al., 2014, Reynold, 2013). Nonetheless, the decrease in latency of the P2 effect in the MSI might reflect a more efficient processing of the auditory stimulus in both children and adults. This has been suggested in the case of audiovisual speech processing where auditory information presented simultaneously with a visual cue was more efficiently processed through the auditory system (Pilling, 2009, Van Wassenhove et al., 2005, Knowland et al., 2014). For instance, in 5-month-old infants, events with redundant sensory information were associated with enhanced neural response and more efficient stimulus processing compared to when the same stimulus was presented without multisensory redundancy (Reynold, 2013). Knowland et al. 2014 measured a decreased latency of the P2 component in adults and children when speech signals were presented along with visual cues. They suggested that latency modulation might be characteristic of the predictive process of both content (especially in the case of audiovisual speech processing such as the McGurk effect) and timing of the auditory signal. Even when using non-speech stimuli, presenting visual cues congruent to auditory stimuli might result in a timing prediction (when it should occur) of the auditory stimuli and a more efficient stimulus processing (Viswanathan and Jansen, 2010). Furthermore, the modulation of the P2 effect using AV stimuli is consistent with studies showing the sources of the P2 component originating in the posterior superior temporal regions (Liebenthal, 2010). This region is part of a network involved in audiovisual integration and multisensory attention modulation (Tang, et al., 2016) as well as audiovisual speech processing (Campbell, 2007).

The expected visual P1 and N2 waveforms were found in the occipital regions with a much larger amplitude in the younger age groups (3 months to 10 years) than those of the older groups (11 years to adulthood). This is consistent with prior reports showing that the visual P1 and N2 amplitudes decreased across development. These findings are likely caused by structural and functional changes from 10-year-olds to adulthood consistent with increases in brain white matter volume during these periods (Brandwein et al., 2011; Hileman et al., 2011; Kuefner et al., 2010; Lippé et al., 2009). Our results also showed the presence of a P1b component in older age groups from 11 years old to adulthood. It is possible that P1b reflects changes in the presentation of the visual stimulus by older participants when a uniform gray mask was used as the resetting stimulus following the checkerboard. The older groups might be more aware of visual stimulus changes than the younger groups. This effect could represent the maturation of the visual Magnocellular pathway sensitive to motion in low contrast stimulus (Tremblay et al., 2014). However, as compared to the baseline, P1b reached significance only for the 11-14y group, remained nonsignificant for 15-17y, and a statistical tendency was found in the 18-30y group. It is unclear whether individual variability in morphological patterns of P1b is indicative of visual perception of stimulus changes among older groups. Another possible explanation for the absence of P1b in younger groups is possibly due to a larger and higher P1, which could enclose P1b. Nevertheless, our results showed a broader and higher P1 in young children suggesting the immaturity of their visual network.

ERP morphology variation during development is linked to progressive myelination's physiological processes, synaptic density changes, and metabolic activity in the cortical and subcortical auditory and visual systems. These changes are decade-long, lasting through early and late childhood (Kozma et al., 2001; S. Lippé et al., 2009; Moore and Linthicum, 2007). Both auditory and visual sensory systems have different developmental timelines, and the level of visual (Atkinson, 2002; Ellemberg et al., 2003; Kovács et al., 1999; Kozma et al., 2001; Sayeur et al., 2015) and auditory (Draganova et al., 2005; Kuhl, 2000) processing complexity develops as a function of age and is expressed by more stable and accurate behavioral performance. Similar to the visual ERPs, the audiovisual ERPs are adult-like in young adolescents from 11-14 years old, while auditory ERPs reach adult-like maturity a few years later, around 15–17 years old. As the early development of AV integration may depend on the continued crossmodal calibration of A and V sensory systems required during development, it has been argued that the senses are not equal. In particular, the superiority of vision in providing information about the spatial environment tends to dominate over other modalities (Ernst, 2008). Similarly, our results (visual and audiovisual functions reaching maturity around 11–14 years old, while auditory function maturing later around 15–17 years old) suggest that visual function might improve bimodal AV processing (Spence et al., 2001). Taken together, the maturation of unisensory systems and their responsiveness could shape and be interconnected with the maturation of multisensory neuroanatomical structures and pathways. The prolonged course of the multisensory development may depend on incomplete myelination of white matter pathways (Cappe et al., 2009) and differences in the maturation of cortical and subcortical structures and networks underlying the ability to integrate multisensory information (Driver and Noesselt, 2008).

The N1, P1, and N2 components are generally related to low-level perception and are considered the processing of sensory aspects of experience (Kappenman and Luck, 2011). As expected, the timing and topography of N1-P2-N2 complex (referred as the N1, P1, N2 by Kappenman and Luck, 2011) varied with respect to age, but not sexes (see Fig. 4,5,6), reflecting the complex maturation underlying how the brain processes basic auditory and visual stimuli in both boys and girls (Brandwein et al., 2011; Ruhnau et al., 2011). While our results showed that P2 amplitude in AV was significantly higher in the 5-7y group compared to 3–12m and 2-4y groups, no differences were found between the older groups (8 to 30 years) and the younger groups (3 months to 4 years), suggesting that the period from 5 to 7 years is a transitional age for AV processing.

4.3. *Methodological consideration*

A limited sample of participants in the present study and a wide age range undoubtedly weakened our sensitivity to measure smaller MSI effects in young children whose brain develops rapidly. While the signal-to-noise ratio in the young groups was relatively low, sensitivity calculations performed in G*power (Faul et al., 2007) revealed that our sample allowed us to detect medium to large-size effects across sex and age groups. Although our results demonstrate sufficient statistical power to predict outcomes for the present study, there was high inter-individual variability in the component morphologies among participants of the same age group. In future studies, more participants should be included in each age group as well as narrower age ranges per group should help to examine in greater detail AV maturation trends.

5. Conclusions

Sensory experiences throughout infancy, childhood, and adolescence are important determinants in the development of the brain. While anatomical and physiological animal studies have demonstrated the importance of multisensory exposure in acquiring MSI capacities (Wallace and Stein, 2007), prenatal and postnatal exposure to environmental stimulation may impact the child's development and functional state of MSI. Our results showed variability in the peak latency and amplitude of the ERP components and topographic distributions across age groups, with MSI development being a long and gradual process starting in early childhood and reaching full maturity in late adolescence. Overall, our findings revealed distinct patterns for AV processing across development

and suggested that the maturity of bimodal AV processing develops in parallel with unisensory systems.

Significance statement

Although unisensory development is well studied, little is known about the multisensory mechanism during infancy. Our study is the first to characterize the development of sensory audiovisual mechanisms from 3 months old to adulthood. We demonstrate evidence of distinct patterns for AV events across development and suggest that the maturity of bimodal AV processing develops in parallel with unisensory systems.

CRediT authorship contribution statement

Phetsamone Vannasing: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Emmanuelle Dionne-Dostie:** Writing – original draft, Investigation, Formal analysis, Data curation. **Julie Tremblay:** Writing – review & editing, Visualization, Software, Methodology, Formal analysis. **Natacha Paquette:** Writing – review & editing, Supervision. **Olivier Collignon:** Writing – review & editing, Funding acquisition, Conceptualization. **Anne Gallagher:** Writing – review & editing, Supervision, Resources, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bandc.2024.106180.

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