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Original article

Maturation of visual evoked potentials across adolescence

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Abstract

Adolescence represents the period of transition from childhood to adulthood and is characterized by significant changes in brain structure and function. We studied changes in the functional visual processing in the brain across adolescence. Visual evoked potentials (VEPs) to three types of pattern reversal checkerboard stimuli were measured in 90 adolescents (10–18 years) and 10 adults. Across adolescence, the N75 and P100 VEP peaks decreased in size while the N135 peak increased slightly in size. The latency of VEP peaks showed no reliable change across adolescence. The results suggest that even very basic visual sensory function continues to develop throughout adolescence. The results indicate significant changes in visual parvocellular and magnocellular pathways across adolescence.

Keywords: Visual evoked potentials; Adolescence; Pattern reversal; Checkerboard; Parvocellular pathways; Magnocellular pathways

1. Introduction

Adolescence is the period of life between childhood and adulthood. During this time, the brain undergoes substantial changes in both structure and function. The development of brain structure across adolescence has been studied extensively using imaging techniques [1–6]. In contrast, the development of brain function across adolescence has received relatively little attention. The aim of the current study is to better understand how the functional processing of visual information in the brain changes across adolescence.

Functional processing in the visual system can be studied using a non-invasive method called visual evoked potentials (VEPs). VEPs, which are thought to reflect functional processing throughout the entire visual pathway [7], represent the average pattern of electrical activity released by cells in the visual cortex in response to a visual stimulus. While numerous visual stimuli can be used to elicit VEPs – such as light flashes, moving visual stimuli, and colored stimuli – the "stimulus of choice" is the pattern reversal checkerboard because it produces the most reliable and robust VEP waveform [8].

As the name suggests, the pattern reversal checkerboard consists of black and white squares forming a checkerboard, and the checks alternate between black and white squares at a specific rate. With every reversal of color, cells in the visual cortex generate electrical responses that can be recorded by the scalp electrodes. Averaging the responses from a number of reversals will result in a VEP waveform as seen in Fig. 1.

In adults, a VEP waveform evoked in response to pattern reversal checkerboard stimuli typically consists of a negative peak at around 75 ms that is called the N75 (also named N1, N70 or N80). The N75 is followed by a positive peak at around 100 ms called the P100 (or P1 or P105), which in turn is followed by a negative peak at 135 ms called the N135 (N2 or N140). The neural generators of the N75 and P100 appear to be generated in the striate visual cortex, while generators of N135 may lie in the extra-striate part of the visual cortex [9–11].

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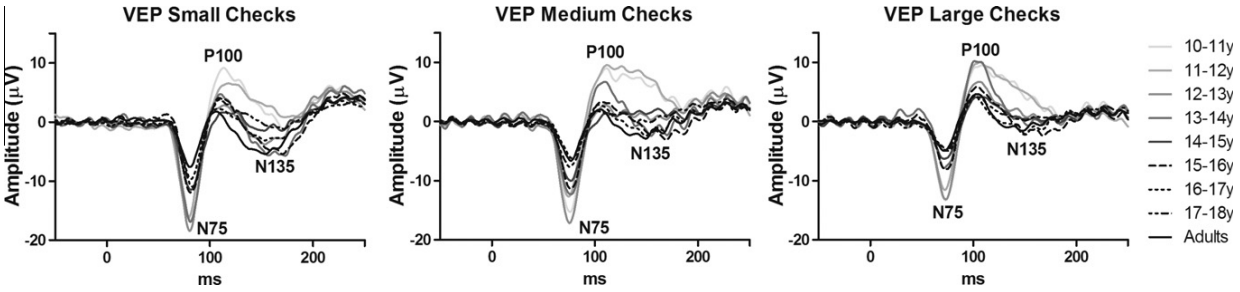

Fig. 1. Grand mean waveforms at Oz for all age groups to small, medium and large check sizes. The VEP peaks N75, P100 and N135 are identified.

The amplitude and the latency of pattern reversal VEP peaks are highly sensitive to stimulus presentation parameters such as luminance, contrast and the check size (i.e., spatial frequency) [12]. In the present study, the luminance and contrast parameters were kept constant under acceptable limits according to VEP standards [8], while the check size – or spatial frequency – was manipulated. Varying the check size is thought to stimulate different pathways of the visual system. The parvocellular pathway is thought to be activated by small check patterns less than 30′, which create high spatial frequencies. The magnocellular pathway is believed to be stimulated by check patterns greater than 30′, which create low spatial frequencies [13–15].

Table 1 summarizes the methods and outcomes of all the studies that have tested adolescents for pattern reversal checkerboard VEPs. Close inspection of this table reveals two facts. First, no study has tested the development of VEPs across adolescence per se. Instead, adolescents have been included in samples that also comprise children, adults, and elderly people. Second, there are mixed reports on how the N75 and P100 VEP peaks change across age. While most studies suggest that the N75 peaks decreases in size across adolescence to all sizes of checks [15–19], two studies report that there is no change in N75 amplitude across childhood and adolescence [20,21]. Similarly, while most studies found no change in N75 latency across age,

Table 1
Studies of the development of the pattern reversal visual evoked potential peaks across adolescence.

	References	Age range (years) Age groups (years) N	Mode	Stimuli	N75		P100		N135	
					Amplitude	Latency	Amplitude	Latency	Amplitude	Latency
1	[27]	13–82 NA	Binocular	12′ checks				I		
		125		48′ checks				I		
2	[19]	6–59 2 (6–20; 21–59) 137	Binocular	70′ checks	D	=	D	=		
3	[24]	6–87 NA 181	Binocular	50′ checks			D			
4	[16,17]	4–95 NA 286	Monocular	50′ checks	D	I	D	D	=	=
5	[21]	5–14 5 (5–6; 7–8; 9–10; 11–12; 13–14) 100	Binocular	70′ checks	=	=	=	=		
6	[20]	1 month–19y NA 141	Binocular	50′ checks	=	=	=	=		
7	[18]	6–80 6 (6–10; 11–15; 16–20; 21–80) 406	Binocular	30′ checks	D	=	D	D		
8	[26]	4–42 3(4–12; 13–19; 20–42) 54	Binocular	16′ checks				D		
9	[23]	2–26 4 (2–6; 6–14; 14–18; 18–26) 38	Binocular	Sinusoidal gratings			D	=		
10	[25]	7–18 1 50	Binocular	50′ checks			=	D		
11	[15]	6–18	Binocular	7.5′ checks	D	=	D	D		D
		2 (6–11;12–18)		15′ checks	D	=	D	D		D
		82		30′ checks	D	=	D	D		=
				60′ checks	D	=	D	D		=
12	[22]	6–60	Binocular	10′ checks			D	D		
		7 (6–10; 11–15; 16–20; 21–30; 3 elderly groups		20′ checks			D	D		
		70		40′ checks			D	D		
13	Current study	10–25	Binocular	15′ checks	D	=	D	=	I	=
		9 (1 year interval)		30′ checks	D	=	D	=	I	=
		100		50′ checks	D	=	D	=	I	=

Note. D = Decreased; I = Increased, = No change, NA– not available.

one study [16], reported that the N75 got later to large checks with age.

A similar pattern of results exists for the P100: Most studies have reported a decrease in the size of P100 with age [15,16,18,19,22–24]. However, there are a few which reports that the VEP P100 peak does not change with age [20,21,25]. In terms of latency, most studies report a decrease in P100 latency across adolescence [15,16,18,22,24–26]. However, a few studies report no change in P100 latency with age [19–21,23], and one study even found that the P100 increased in latency with age [27].

There is a surprising dearth of data on the development of the VEP N135 peak across adolescence. Unfortunately, the existing data is mixed. One study reported that the N135 remained unchanged in amplitude and latency from childhood until 30 years-of-age for large checks [16]. However, the latency of the N135 VEP peak got early with age for small checks, but did not change for large checks [15].

Given (1) the mixed findings of previous studies that have examined the development of the VEP peaks across age, (2) the absence of any study of the development of these peaks across adolescence alone, and (3) the need for more information about how visual functional processing develops in adolescence, the aim of the current study was to determine how VEP peaks change across adolescence. To achieve this aim, we elicited VEPs in eight groups of adolescents (10–18 years), as well as a reference group of adults, using small, medium, and large checks in pattern reversal checkerboards. Past studies typically measured the development of VEPs to large checks, rather than small and medium checks. It would seem advantageous to test VEPs to checks of different sizes since they are thought to stimulate different visual pathways channels (parvocellular and magnocellular). In addition, we took measurements of all three VEP peaks: N75, P100, and N135. Only two previous studies have examined the maturation of all peaks of VEPs in a single experiment with the same participants [15,16]. Unfortunately, the later study used only large checks, and presented stimuli to only one eye (monocular stimulation). This is less ecologically valid than binocular stimulation, and introduces asymmetry in the topographical differences in the neuronal fields [28]. The former study did use checks of different sizes. However, it averaged the data across adolescence (12–18 years) which would have obscured any changes within adolescence.

2. Methods

2.1. Ethics

The methods used in the present study were approved by the Human Ethics Committee at the University. Informed consent was obtained from participants as well as their parents.

2.2. Subjects

Data was collected from 100 subjects (40 females), aged 10–25 years, who were divided into nine age groups. Eight groups comprised adolescents: 10–11 years ($N = 14$), 11–12 years ($N = 10$), 12–13 years ($N = 14$), 13–14 years ($N = 12$), 14–15 years ($N = 10$), 15–16 years ($N = 11$), 16–17 years ($N = 9$), 17–18 years ($N = 10$). The ninth group comprised adults, whose VEPs were presumed to be mature (22–25 years; $N = 10$). All subjects had either normal visual acuity (20/20) or corrected vision with glasses or lenses. All subjects had non-verbal IQ in at least average range as assessed by the Matrices subtest of the Kaufman Brief Intelligence test [29]. Subjects reported no history of visual, psychological, physiological, or learning problems.

2.3. Experimental stimuli

The VEPs were recorded in response to binocular stimulation of patterned black and white checkerboard stimuli reversing at 2-Hz with three difference check sizes of 15′ (small), 30′ (medium) and 50′ (large) projected on the computer screen. The visual angles subtended at the eye of the subject were .25°, .50° and .83° for small, medium and large checks, respectively. The mean luminance of pattern was 60.71 cd/m^2 with a luminance of 9.02 and 112.4 cd/m^2 for black and white checks, respectively and the background luminance was kept constant for all the subjects. The Michelson contrast of the pattern was 85.14% with a total field size of 23°. The above-mentioned stimulus parameters were in accord with the visual evoked potentials standard [8]. There were 200 reversals of the stimuli of each size and every reversal was coded as '1'. The order of presentation of small, medium and large checkerboards was counter balanced, and subjects were given an adequate break between each condition.

2.4. Recording the electroencephalogram (EEG)

Subjects were seated in a comfortable chair placed 1 m from the computer screen where the checkerboard was projected. The subjects were asked to fix their gaze at a red cross placed in the center of the checkerboard. The Neuroscan system (4.3), and sintered Ag–AgCl electrodes that were sewn into an electrode cap (Quik Cap) according to the 10-10 system, were used to measure each subject's EEG at 30 scalp sites: Fz, Fp1, Fp2, F3, F4, FC3, FC4, FT7, FT8, F7, F8, C3, C4, CP3, CP4, Cz, Pz, FCz, O2, O1, Oz, P3, P4, P7, P8, T7, T8, TP7, TP8, M2. The left mastoid (M1) served as online reference. The vertical eye movements (VEOG)

were measured with electrodes placed above and below the left eye. The horizontal eye movements (HEOG) were recorded using electrodes placed on the outer canthi of each eye. The ground electrode was positioned between FPz and Fz. This online EEG was sampled at 1000-Hz with an online bandpass filter from .05 to 100-Hz. The raw EEG data was stored for offline analysis.

2.5. Creating the VEPs

The raw EEG data was visually inspected for obvious artifacts, which were blocked from further analysis. The eye-blink artifacts were removed from the recording using standard ocular artifact removing algorithm [30]. Then the EEG data was re-referenced to the right mastoid with the two mastoids mathematically linked. The EEG activity was bandpass filtered (1-Hz high-pass and 100-Hz low-pass; 12 dB per octave roll off) and then divided into 300-ms epochs with a 50-ms pre-stimulus baseline interval, which was used for the baseline correction. All the epochs with a voltage change exceeding ± 100 μV were removed from the analyses. All epochs generated by a reversal (coded '1') were averaged together to produce a pattern-reversal VEP in response to three difference sizes of the checks.

2.6. Measuring the VEPs

The scalp site 'Oz' was used to represent the binocular pattern reversal VEPs as suggested by the standards and previous studies [8,18]. Fig. 1 illustrates the waveforms from Oz in response to three different check sizes for each age group. The first negative peak and the first positive peak in a subject's averaged waveform to all the check sizes were labeled as N75 and P100, respectively. The subsequent negative peak was taken as N135 in the waveform recorded at Oz. The N75, P100 and N135 peaks fell between 65–85, 95–125 and 125–160 ms, respectively, for all sizes of the checks. The amplitude was measured from baseline-to-peak at the largest point in the time window of the peaks.

2.7. Analyzing the VEPs

The amplitude and the latency data of the VEPs to all three sizes of the checks were first tested for normality and to see whether the data violated the assumption of homogeneity of variance. Results of Kolmogorov–Smrinov tests for normality revealed that the amplitude and latency measures of N75, P100 and N135 in the 9 age groups for the three sizes of check did not deviate from the normal distribution in 91% of the datasets (9 groups $\times$ 3 peaks $\times$ 2 measures $\times$ 3 check sizes $= 162$ datasets). Levene's tests of homogeneity revealed that the amplitude and latency measures of the VEP peaks of the groups did not violate the assumption of homogeneity in 80% of the comparisons (3 peaks $\times$ 2 measures $\times$ 3 conditions $= 18$ comparisons). Parametric tests are robust to such mild violations of normality and variance [31]. Thus, we used parametric tests (ANOVAs and Pearson r correlations coefficients) to assess the effect of age and check size on peak amplitude and latencies of VEPs.

Mixed ANOVAs were used to analyze the data at the group level. The within-subject factor was check size (3 levels: small, medium, and large) and the between-subjects factor was age-group (9 levels: 10–11, 11–12, 12–13, 13–14, 14–15, 15–16, 16–17, 17–18, 22–25 years). If the assumption of sphericity was violated, the Greenhouse–Geisser correction was used. If a significant main effect of check size was found, pairwise comparisons (with Bonferroni corrections) were used to compare the results between three check sizes. If a significant interaction between age and check size was found, post-hoc one-way ANOVAs were used to examine the age effects for each check size separately.

Pearson's correlation coefficients (r) were used to analyze the data at the individual level to determine the strength of the relationships between age and the size and latency of the three VEP peaks at Oz. We considered $r = .10$ as a weak relationship, $r = .30$ as a moderate relationship, and $r = .50$ as a strong relationship [31,32]. We also calculated linear regression statistics to determine if there was a statistically significant change in slope (β) across age groups.

To avoid reporting ambiguous results, an effect of age was only considered reliable if it met three criteria. First, the age effect had to be statistically significant in the group data, as determined by the between-subject factors (age-groups) result of a mixed ANOVA. Second, the age effect had to be statistically significant in the individual data, as determined by Pearson's correlation coefficient (r). Third, the age effect had to be at least moderate in size in the individual data (i.e., Pearson's r had to be at least .3). Further, an interaction between age and check size was only considered reliable if (1) there was a significant interaction in the group data, (2) the post-hoc ANOVAs showed a significant age effect for two of the checks at most, and (3) the age effect had to be at least moderate in size and statistically significant for two checks at the most.

For the group and individual analyses and pairwise comparisons, we used a p value of $<.05$ to determine if an effect was statistically significant. Since the slope statistics corresponded directly with the Pearson r statistics, we did not use the slope statistics as a criterion for reliability as slope will be a close derivative of Pearson r. However, the slope values (β) are shown with the Pearson r values in the relevant figures.

3. Results

Fig. 1 illustrates the waveforms at Oz for small checks (a), medium checks (b) and large checks (c) for each age group. Fig. 2 compares the mean amplitude and latency values across three sizes of checks and a summary of pairwise comparisons between the checks is also shown in each graph. Fig. 3 compares the mean values of N75, P100 and N135 for each age group for small medium and large check sizes. Figs. 4–6 illustrate the strength of the relationship between individuals' age and their N75, P100, and N135 amplitude and latency measures at Oz for small, medium and large sized checks. These figures include the statistics for Pearson's r and slope (β). Table 2 summarizes the outcomes for the group data (the primary ANOVAs) and for the individual data (Pearson's r). Tables 3–5 show group means and standard deviations for N75, P100, and N135 amplitude and latency values for small, medium and large checks, respectively. For ease of understanding, the statistical values in the tables will not be restated in the results sections below.

3.1. N75 Amplitude

The mixed ANOVA on the group data for the amplitude of N75 revealed significant main effects of age and check size, but no significant interaction between the two. These effects occurred because N75 amplitude decreased with increasing size of checks (small > medium > large; see Fig. 2a) and there was a decrease in N75 with age (see Fig. 3). This finding was supported by the individual data, which showed moderate and significant relationships (as indexed by Pearson's r) between individuals' age and amplitude of N75 for small and medium checks, and a strong significant relationship for large checks (see Fig. 4). According to our criteria for reliability, this meant that N75 showed a reliable decrease in amplitude across adolescence for all three sizes of checks.

3.2. N75 Latency

The mixed ANOVA on the N75 latency data of the group showed a significant main effect of check size but no main effect of age group or an interaction between the two. The significant main effect of check size occurred because the latency of N75 became shorter with increasing size of checks (small > medium > large; see Fig. 2b). The lack of effect of age was supported by weak relationships between individuals' age and N75 latency for all three checks (see Fig. 4). Thus, there were differences in N75 latency between the three check sizes, but no shifts in N75 latency across adolescence.

3.3. P100 Amplitude

The mixed ANOVA on the group data for the amplitude of P100 revealed a significant main effect of both check size and age group, but no interaction between

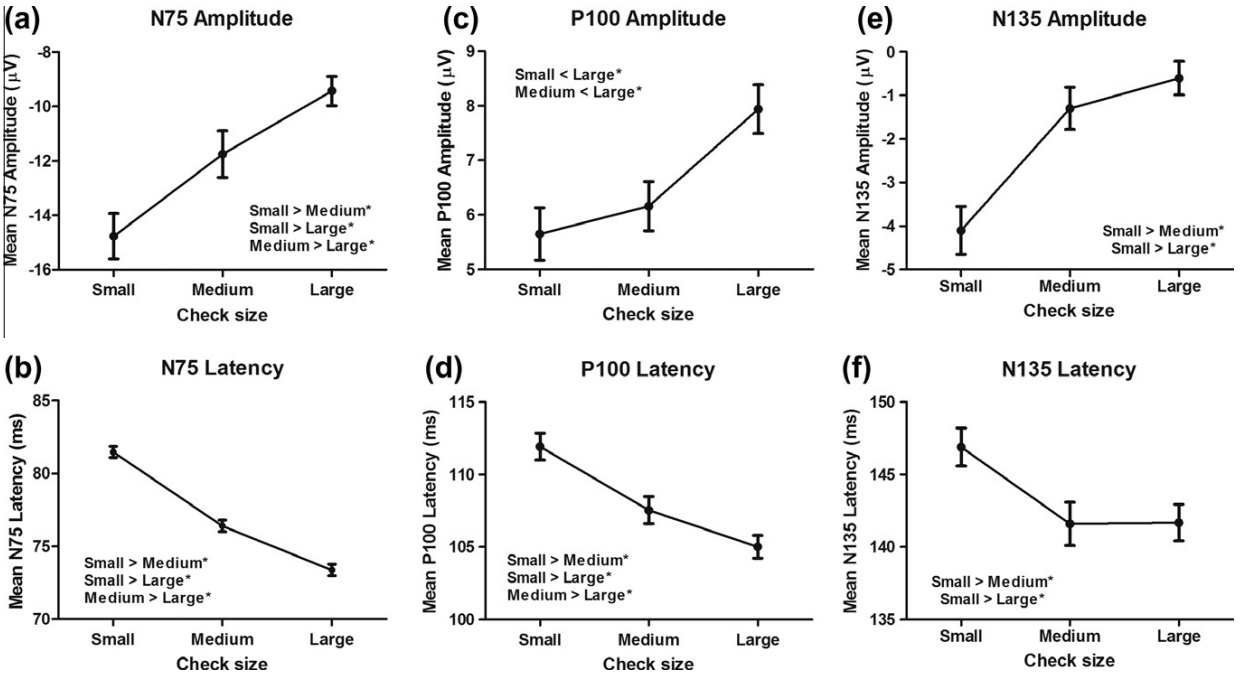

Fig. 2. The differences between check sizes for N75, P100 and N135 peak amplitudes and latencies. The standard error for mean is also shown for each check size.

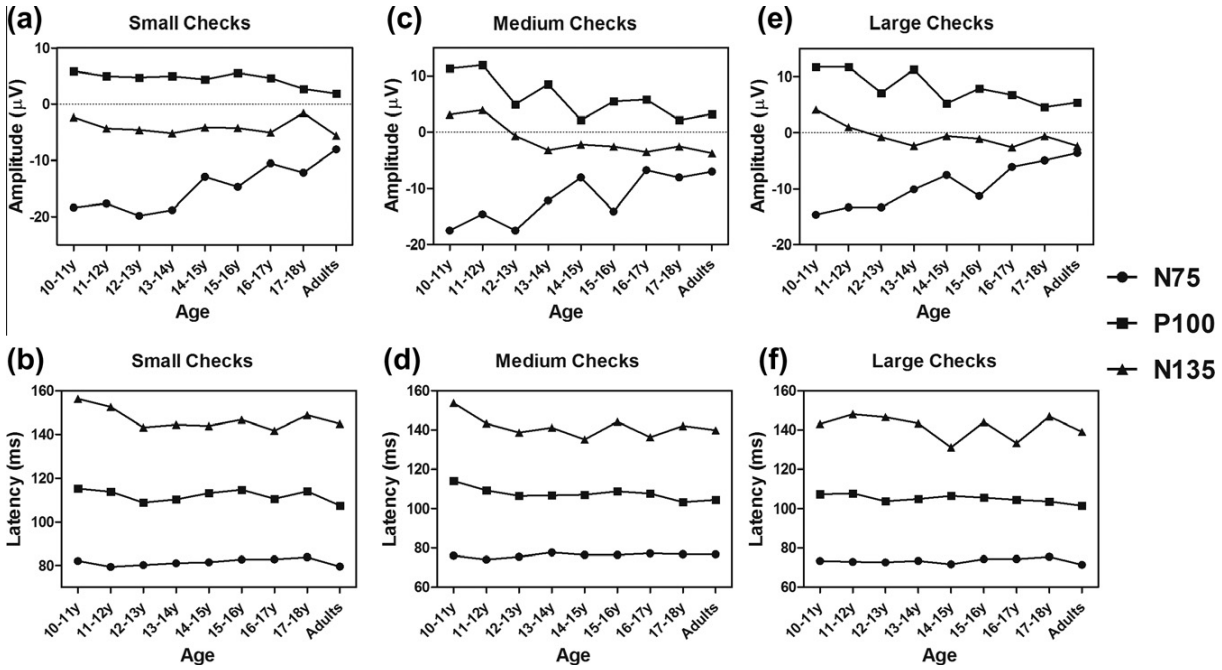

Fig. 3. Mean peak amplitude and latency values for the VEP peaks at Oz for small medium and large sized checks.

the two. These effects occurred because the amplitude of P100 to medium and small checks was smaller than large checks (see Fig. 2c). The main effect of age occurred because of a significant decrease in amplitude of P100 across age (see Fig. 3). This was supported by moderate and significant relationships between individuals' age and their P100 amplitude for all three checks (see Fig. 5). Thus, the P100 amplitude showed a reliable decrease across adolescence for the three checks.

3.4. P100 Latency

As for N75 latency, the mixed ANOVA on the group data for the latency of P100 revealed a significant main effect of check size but no effect of age group. This significant effect occurred because P100 latency decreased with increasing size of checks, although the difference between the checks was small (see Fig. 2d). The relationship between individuals' age and latency of P100 was significant but weak for small, medium, and large checks (see Fig. 5). Hence, according to our criteria, the latency of P100 did not show any reliable change across adolescence.

3.5. N135 Amplitude

The mixed ANOVAs on the group data for the amplitude of N135 showed a significant main effect of both check size and age group but no significant interaction between the two. These effects occurred because the N135 was larger to small checks than medium and large checks, with no difference between latter two (see Fig. 2e). The main effect of age was due to an increase in N135 amplitude across age (see Fig. 3). This effect was supported by moderate and significant relationships between N135 amplitude and individuals' age for medium and large checks (see Fig. 6). For small checks, the relationship was weak. However, it is possible that large and decreasing P100 amplitude might have influenced the baseline-to-peak amplitude of N135. Hence to explore this possibility further, peak-to-peak measurement amplitude of N135 was carried out. Similar to baseline-to-peak N135, the mixed ANOVA on the group data of peak-to-peak N135 amplitude revealed significant main effects of check size (N135 was larger to small checks than medium but similar two large) and age group (mild increase in N135 amplitude) but no interaction between the two. However, at the individual level the relationship between peak-to-peak N135 and age for all the checks were weak. According to our criteria for a reliable change across adolescence, peak-to-peak N135 amplitude didn't show any reliable change across adolescence.

3.6. N135 Latency

The mixed ANOVA showed significant main effects of check size and age group on the latency of N135. The effects occurred because the N135 was later for small checks than medium and large checks, which did not differ from each other (see Fig. 2f). The main effect of age occurred due to the decrease in N135 latency with

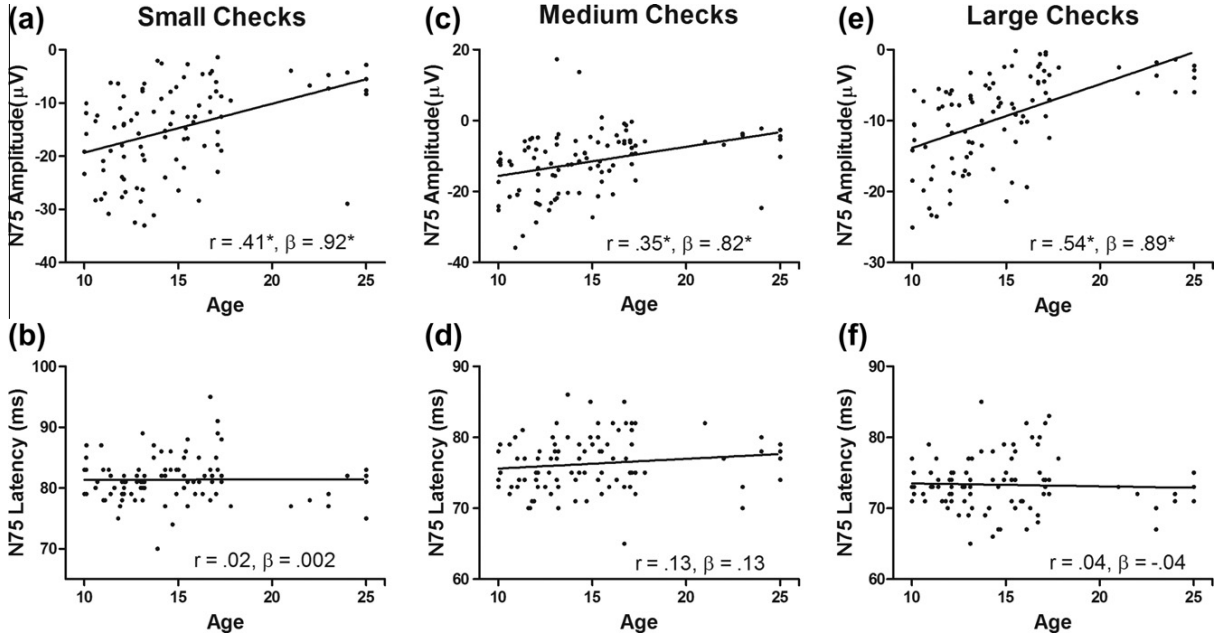

Fig. 4. The relationship between individuals' age and their peak amplitude and peak latency of N75 for three check sizes at Oz.

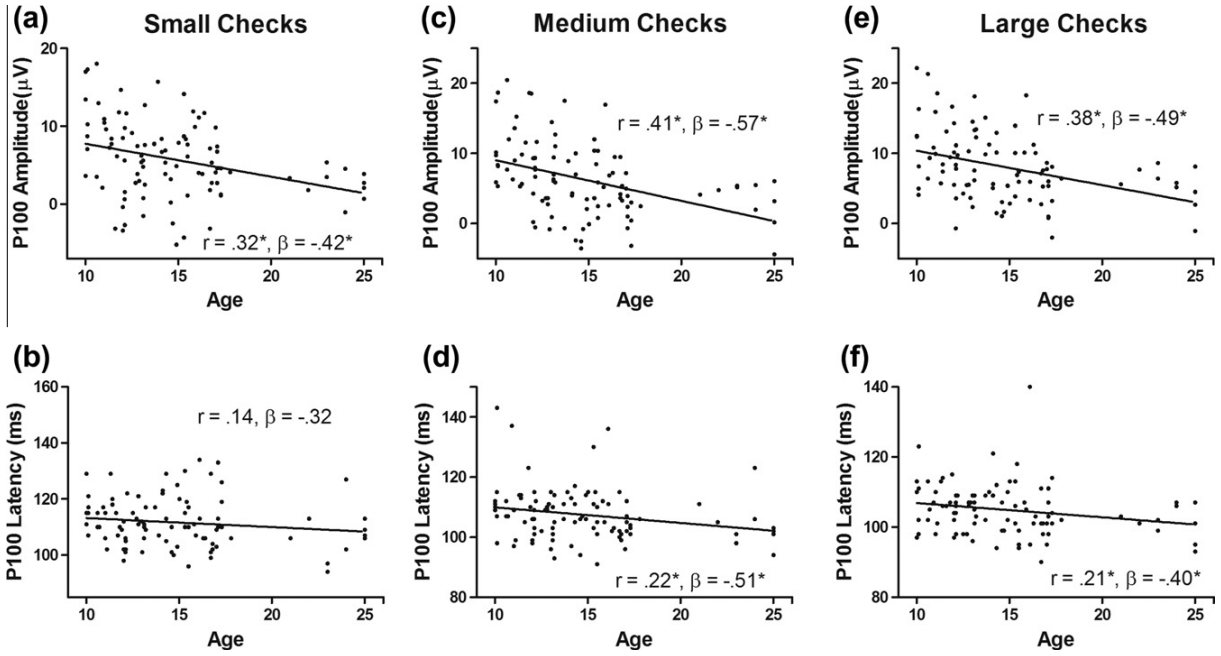

Fig. 5. The relationship between individuals' age and their peak amplitude and peak latency of P100 for three check sizes at Oz.

age. However, this effect was not fully supported by the individual data: The relationship between individuals' age and N135 latency was non-significant and weak for medium checks, and weak but significant for small and large checks (see Fig. 6). Thus, according to our criteria, the latency of N135 did not show any reliable change across adolescence.

4. Discussion

The aim of the current study was to better understand how VEPs develop across adolescence. To achieve this aim, we presented checkerboard stimuli with small, medium and large sized checks to both eyes to evoke N75, P100 and N135 VEP peaks in eight groups of adoles-

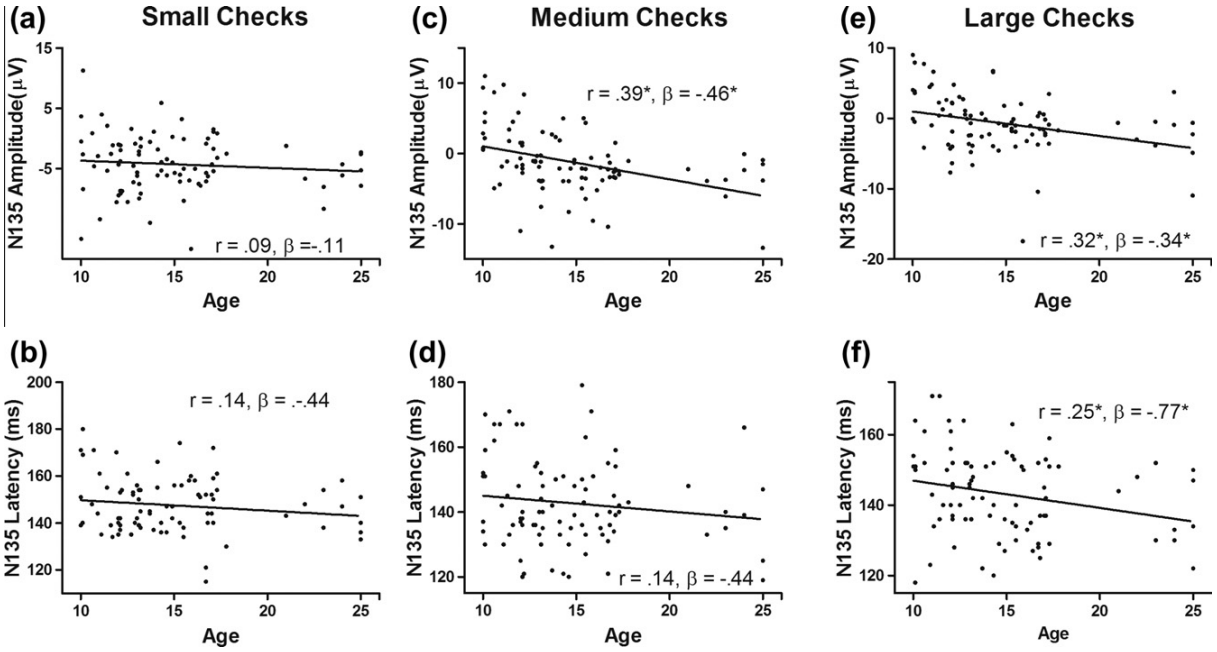

Fig. 6. The relationship between individuals' age and their peak amplitude and peak latency of N135 for three check sizes at Oz.

Table 2
ANOVA and Pearson *r* results for N75, P100 and N135 amplitude and latency measures for the three check sizes.

Peaks	Check size	Amplitude				Latency			
		Checks	Age	Age × checks	Pearson's *r*	Checks	Age	Age × checks	Pearson's *r*
N75	Small	28.49†	4.76†	ns	.41*	24.66†	ns	ns	.02
	Medium	S > M > L	D		.35*	S > M > L			.13
	Large				.54**				.04
P100	Small	9.77†	8.72†	ns	.32*	27.89†	ns	ns	.14
	Medium	S = M < L	D		.41*	S > M > L			.22
	Large				.38*				.21
N135	Small	20.22†	3.25†	ns	.09	7.23†	ns	ns	.14
	Medium	S > M = L	I		.39*	S > M = L			.14
	Large				.32*				.25

Note. S = Small checks, M = Medium checks, L = Large checks, D = Decreased, I = Increased.
† Significant at $p < .05$.
* Moderate relationship.
** Strong relationship, ns – not significant.

Table 3
The N75 mean peak amplitude (μV) and latency (ms) data for all age groups recorded at Oz for small, medium and large checks.

Age	Check size					
	Small		Medium		Large	
	Amplitude	Latency	Amplitude	Latency	Amplitude	Latency
10–11y	−18.35(7.88)	82.09(3.11)	−17.51(8.28)	76.09(2.94)	−14.60(6.17)	73.45(2.54)
11–12y	−17.62(8.73)	79.44(2.78)	−14.57(9.37)	74.22(3.56)	−13.33(7.19)	73.00(2.17)
12–13y	−19.81(7.11)	80.21(1.57)	−17.51(7.40)	75.50(2.24)	−13.34(5.17)	72.78(1.76)
13–14y	−18.79(10.45)	81.09(4.98)	−12.16(11.41)	77.81(3.89)	−10.08(4.55)	73.54(5.52)
14–15y	−12.88(6.52)	81.50(3.80)	−8.06(8.78)	76.50(4.27)	−7.52(4.18)	71.80(4.56)
15–16y	−14.67(7.94)	82.75(3.53)	−14.13(8.02	77.50(3.77)	−11.29(6.56)	74.37(3.46)
16–17y	−10.52(8.18)	82.88(4.98)	−6.75(6.31)	77.33(6.10)	−6.08(5.74)	74.44(5.98)
17–18y	−12.15(6.63)	83.80(4.46)	−8.05(4.40)	76.90(3.75)	−4.96(3.83)	75.50(3.95)
Adults	−8.03(7.56)	79.60(2.75)	−6.99(6.61)	76.39(3.77)	−3.65(1.81)	71.50(2.12)

Table 4
The P100 mean peak amplitude (μV) and latency (ms) data for all age groups recorded at Oz for small, medium and large checks.

Age	Check size					
	Small		Medium		Large	
	Amplitude	Latency	Amplitude	Latency	Amplitude	Latency
10–11y	10.35(5.84)	115.18(6.07)	11.30(5.22)	114.18(13.51)	11.69(6.12)	107.36(7.65)
11–12y	8.62(4.96)	113.77(8.12)	11.93(4.98)	109.33(8.07)	11.7(4.54)	107.77(5.82)
12–13y	4.09(4.73)	108.71(7.55)	4.93(3.91)	106.42(5.15)	7.09(3.89)	103.71(4.33)
13–14y	6.14(4.92)	110.27(5.23)	8.51(5.44)	106.81(6.66)	11.27(4.51)	104.90(4.36)
14–15y	3.17(4.37)	113.1010.88)	2.15(4.46)	107.00(7.27)	5.18(3.84)	106.50(8.01)
15–16y	6.19(5.53)	114.62(9.85)	5.44(4.49)	108.87(11.69)	7.86(4.77)	105.50(8.91)
16–17y	4.95(4.62)	110.44(12.64)	5.80(2.61)	107.66(11.89)	6.72(2.78)	104.44(14.50)
17–18y	4.63(2.72)	113.90(9.36)	2.15(2.94)	103.20(4.87)	4.53(3.61)	103.60(5.73)
Adults	2.67(1.88)	107.40(9.25)	3.20(3.22)	104.40(7.97)	5.36(2.87)	101.40(4.76)

Table 5
The N135 mean peak amplitude (μV) and latency (ms) data for all age groups recorded at Oz for small, medium and large checks.

Age	Check size					
	Small		Medium		Large	
	Amplitude	Latency	Amplitude	Latency	Amplitude	Latency
10–11y	−2.31(8.81)	156.28(16.75)	3.12(6.20)	153.71(15.20)	4.06(3.59)	143.00(15.51)
11–12y	−4.29(6.85)	152.50(13.26)	3.90(3.90)	143.33(15.01)	−.97(3.46)	148.00(15.58)
12–13y	−4.55(3.75)	143.15(7.17)	−.71(4.17)	138.69(13.47)	−.79(3.76)	146.53(10.78)
13–14y	−5.15(4.75)	144.45(6.47)	−3.24(4.51)	141.18(9.64)	−2.38(2.29)	143.36(8.29)
14–15y	−4.10(2.20)	143.85(6.30)	−2.21(4.02)	135.14(12.18)	−.58(3.80)	131.14(6.91)
15–16y	−4.23(4.94)	146.66(15.42)	−2.58(4.00)	144.16(18.48)	−1.08(1.96)	144.00(10.78)
16–17y	−5.04(2.98)	141.62(15.64)	−3.57(3.16)	136.25(9.60)	−2.63(3.51)	133.25(8.63)
17–18y	−1.56(2.41)	148.75(10.31)	−2.57(.74)	142.00(5.85)	−.60(1.91)	146.87(7.93)
Adults	−5.60(3.15)	144.80(8.17)	−3.79(3.78)	139.90(13.24)	−2.39(3.82)	139.00(10.39)

cents aged from 10 to 18, and a reference group of adults aged from 22 to 25. The amplitude and latency of the VEP peaks were measured at Oz. We analyzed the development of these measures at the group level (i.e., between groups) and at the individual level (across individuals with different ages). Below we use the results to make conclusions about how each of the VEP peaks change across adolescence, the clinical applications of pattern reversal VEPs, and recommendations for future research.

4.1. The development of the N75 across adolescence

The results of the current study are summarized in Table 1 for comparison with previous development studies of VEPs. The latency of the N75 VEP peak showed no change across adolescence in response to any check size. This concurs with the results of a number of previous studies outlined in Table 1 [15,18,20,21].

In contrast, the peak amplitude of N75 decreased reliably across adolescence, which is consistent with many previous studies [15,16,18,19]. The significant reduction the amplitude of N75 suggests that the neural generators of the N75 in striate visual cortex – a possible generator of N75 – continue to develop across adolescence. The results also showed that the N75 was bigger for small checks than large-sized checks, but that the size of the N75 changed at the same rate across adolescence for all check sizes. This suggests significant changes in both parvocellular and magnocellular visual pathways across adolescence.

There is a continuous decrease in metabolic activity (glucose consumption) across adolescence [33,34], as well as significant changes in gonadal steroid levels between 14 and 17 years [35]. Paired with these findings, the current outcomes suggest that metabolic and hormonal changes during adolescence alter the neurotransmitter activity in the neurons of visual pathways which in turn may stimulate the development of both the magnocellular and parvocellular pathways.

4.2. The development of the P100 across adolescence

Like the N75 VEP peak, the size of the P100 peak reduced with age across adolescence, which supports numerous previous results [15–19,22]. In addition, the P100 was larger to large check sizes than small and medium check sizes, which did not differ from each other. There was no interaction between age and check size, so the P100 reduced in size for all check sizes. Consid-

ered together, these outcomes join the N75 data in suggesting that metabolic and hormonal changes during adolescence might stimulate the development of both the magnocellular and parvocellular pathways in the striate visual cortex.

According to our three-point criteria for a reliable change across adolescence, P100 latency did not show any reliable change across adolescence. This supports the findings of some previous studies [19–21], but not others that report decreases in P100 latency across age [15–18,22,25,26]. One explanation for the contrary findings is our three point criteria for reliable change across adolescence: Though the group data did not show any significant change in P100 latency, the individual data showed a significant yet weak decrease in P100 latency across latency for medium and large sized checks. Some of the fore-mentioned studies have reported weak-to-moderate yet significant decreases in P100 latency with age [18,22,25]. These shifts may not have been considered reliable in the current study.

4.3. The development of the N135 across adolescence

The outcomes for the N135 VEP peak were similar in most ways to the N75 and P100 peaks. First, there was no change in N135 latency with age, which supports the earlier findings [15–17]. Second, the size of the N135 shifted with age. However, instead of decreasing with age, as was the case for the N75 and P100, the N135 increased in size with age. This does not support the findings of the only other study that looked at the development of the N135 VEP peak, which found that this peak did not shift in size across age [16]. However, that study looked at the development of the N135 across the entire life span (4–95 years) rather than just adolescence, so the contradictory findings are perhaps unsurprising. Third, the N135 was larger to small checks than medium and large checks, but there was no interaction between check size and age. Thus, the N135 increased in size across adolescence for all check sizes. It is noteworthy that, the effect of decreasing P100 amplitude with age might have carried over to N135 amplitude resulting in its increase across adolescence. In order to avoid ambiguity in this result, we looked at the development of peak-to-peak N135 amplitude and found no reliable shift across adolescence. Thus it is possible that the increasing N135 baseline-to-peak amplitude was influenced by preceding P100 peak. These outcomes might suggest that, the changes may be absent or minimal in the parvocellular and magnocellular pathways of the extra-striate part of visual cortex – which is presumed generator of N135.

4.4. Clinical applications of pattern reversal VEPs

VEPs recorded in response to pattern reversal checkerboards produce highly reliable and robust waveforms [8]. Hence, they have become the main stay for clinical testing of visual pathways in the last few decades. VEPs can provide diagnostic information regarding the functional integrity of the visual system. For example, manipulating stimulus parameters can evaluate of different segments of visual pathways (e.g., different spatial frequencies will stimulate the magnocellular and parvocellular pathways) [13]. Thus, VEPs are used to diagnose a variety of impairments in children, such as occipital epilepsies, developmental co-ordination disorders, and disorders of optic nerve [36–38]. It would be useful to do the same in adolescents. Since we know that VEPs change significantly across adolescence, fine-grained norms will be needed. The VEPs for the small, medium, and large checks in the present study could be used as a preliminary norm set for investigating suspected visual impairments in adolescents.

4.5. Recommendations for future research

There are at least three limitations of the current study that might be addressed in future research. First, although this study tested a large number of listeners, they were divided into a number of 1-year age-bands. There were 9–14 subjects in each group which proved to be enough to detect significant effects across adolescence in line with previous studies. However, future studies should recruit more subjects for each age group to increase the reliability of statistical effects. This is particularly important for the N135 since so few studies have looked at the development of this VEP peak across age.

Second, due to time limitations, this study used a cross-sectional design. Future studies would do well to investigate the development of VEPs across adolescence would be to measure the VEPs of a large group of children every year from the age of 10–18 years. This would minimize any between-age variance that relates to differences between individuals, and hence increase between-age variance genuinely related to an increase in age.

Third, the current study is only one of three studies that have measured the development of VEPs to pattern reversal with small, medium, and large checks. This was done with other stimulus parameters – luminance and contrast – kept constant. Different types of stimulus (e.g., light flashes, stimuli with faster reversal rates, pattern-onset stimuli) and different stimulus parameters (e.g., changes in contrast, colored checks, half-field and full-field stimulation) can be used to stimulate different sections of the visual pathways as it is generally accepted that human visual system consists of multiple pathways which process different information [12,13]. For example, pattern onset stimuli may stimulate chromatic visual pathways and pattern-reversal achromatic. Moreover, half field stimulation may stimulate optic nerve, chiasmal and post-chiasmal areas of visual pathways and full-field stimulation will stimulate central ret-

inal and postretinal function [9,25]. Thus, future studies are needed to develop norms for VEPs that index function at different levels of visual processing system in the brain.

5. Summary

The aim of the present study was to understand how VEPs develop across adolescence. We measured the VEP N75, P100 and N135 peaks to pattern reversal checkerboard stimuli with small, medium and large sized checks in 90 children and adolescents aged 10–18 years, as well as 10 adults. Across adolescence, for all the sizes of checks, baseline-to-peak amplitudes of N75 and P100 peaks decreased in size, and the N135 increased in size which might be influenced by preceding peak. In contrast, the latency of these peaks showed no reliable change with age. These shifts suggest changes in underlying neural generators of the VEP peaks in the parvocellular and magnocellular pathways of the striate and extra-striate visual cortex.

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