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·Original Article·

Visual acuity evaluated by pattern-reversal visual-evoked potential is affected by check size/visual angle

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Abstract: Objective To systemically explore the range of visual angles that affect visual acuity, and to establish the relationship between the P1 component (peak latency ~100 ms) of the pattern-reversal visual-evoked potential (PRVEP) and the visual acuity at particular visual angles. **Methods** Two hundred and ten volunteers were divided into seven groups, according to visual acuity as assessed by the standard logarithmic visual acuity chart (SLD-II). For each group, the PRVEP components were elicited in response to visual angle presentations at 8°, 4°, 2°, 1°/60′, 30′, 15′, and 7.5′, in the white-black chess-board reversal mode with a contrast level of 100% at a frequency of 2 Hz. Visual stimuli were presented monocularly, and 200 presentations were averaged for each block of trials. The early and stable component P1 was recorded at the mid-line of the occipital region (Oz) and analyzed with SPSS 13.00. **Results** (1) Oz had the maximum P1 amplitude; there was no significant difference between genders or for interocular comparison in normal controls and subjects with optic myopia. (2) The P1 latency decreased slowly below 30′, then increased rapidly. The P1 amplitude initially increased with check size, and was maximal at ~1° and ~30′. (3) The P1 latency in the group with visual acuity ≤0.2 was significantly different at 8°, 15′ and 7.5′, while the amplitude differed at all visual angles, compared with the group with normal vision. Differences in P1 for the groups with 0.5 and 0.6 acuity were only present at visual angles <1°. (4) Regression analysis showed that the P1 latency and amplitude were associated with visual acuity over the full range of visual angles. There was a moderate correlation at visual angles <30′. Regression equations were calculated for the P1 components and visual acuity, based on visual angle. **Conclusion** (1) Visual angle should be taken into consideration when exploring the function of the visual pathway, especially visual acuity. A visual angle ~60′ might be appropriate when using PRVEP components to evaluate poor vision and to identify malingerers. (2) Increased P1 amplitude and decreased P1 latency were associated with increasing visual acuity, and the P1 components displayed a linear correlation with visual acuity, especially in the range of optimal visual angles. Visual acuity can be deduced from P1 based on visual angle.

Keywords: visual acuity; visual angle; pattern-reversal visual-evoked potential; check size; regression equation

1 Introduction

Visual-evoked potentials (VEPs) are used to evaluate visual pathway function from the retina to the primary occipital cortex. Since the first use of the white-black chessboard reversal pattern and the grating pattern to study vision and the revealing of tight correlations between components of the VEP and visual acuity[1,2], researchers have attempted to apply the technique to clinical evaluation and ophthalmological assessment[3-5]. Because of the method-

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ological advantages of VEPs (simple waveform, repeatability, and small inter-individual variation), increasing attention has been paid to the study of diseases involving visual problems, such as in the field of oculopathy (amblyopia[6,7], refractive errors, field defects, diseases of the optic nerve, glaucoma[8] and color blindness), in diseases with latent impairment of vision (multiple sclerosis[9], diabetes[10]), and in psychological dysfunctions (schizophrenia, dementia, epilepsy)[11-14]. So far only some changes in the early components (especially the P100) have been associated with certain diseases. Moreover, because the characteristics of VEP components depend on the type of visual stimulus[15], the findings can lead to confusion when different laboratories use different stimuli. Therefore, further studies are essential to re-evaluate the use of VEPs for estimating visual acuity in clinical practice and in objective forensic appraisal.

During the last three decades, increased emphasis has been laid on stimulus parameters such as check size, color, contrast change[16], luminance level, temporal frequency, and spatial frequency[17,18]. The characteristics of participants such as age, gender, and ocular dominance have also been considered[19]. Steele standardized VEPs using normal emmetropic subjects, and then applied the results to uncorrected myopic subjects to objectively determine visual acuity for the assessment of clinical outcomes, and the primary conclusion was that the VEP can distinguish between emmetropic and corrected myopic eyes[20]. Moreover, many studies have investigated check size/visual angle using the pattern-reversal VEP (PRVEP), and its relationship with visual acuity. Kurita-Tashima and colleagues measured the negative wave with peak latency ~75 ms (N75) and the positive wave with peak latency ~100 ms (P100) in the PRVEP, and revealed that the logarithm of the check size had significant inverse linear relationships with the latency and amplitude of N75, and a significant curvilinear relationship with P100 latency[21]. However, in this study and others[22,23], all the regression equations were calculated from subjects with normal vision or corrected myopia and induced refraction error; uncorrected myopic subjects were little studied. In addition, large visual angles have never been used for evaluating the effectiveness of P-VEP testing in normal vision.

The assessment of corrected vision mainly depends on self-reporting and it is difficult to obtain a precise and objective measure, especially for people who deliberately malinger and patients who are incapable of test-matching due to low intelligence or mental disorder. Therefore, studies of naked-eye vision or uncorrected myopia are important for forensic and clinical practice. Previous approaches showed that stimuli with a small check size/visual angle induce an oblique effect of the picture edge due to the picture-outline mechanism, and this phenomenon is common, especially in people with poor vision[24]. Enlarging the visual angle would eliminate the oblique effect, so we used a full range of check sizes to generate regression equations for estimating particular visual disorders, especially for Chinese people with poor vision.

Although many conventional methods for testing visual acuity are available, they are difficult to use with infants or the handicapped and for forensic purposes (e.g., in cases of ocular trauma, trauma mixed with ocular pathological or psychological dysfunctions, malingering, and exaggeration of amblyopia or even blindness)[25,26].

Based on the hypothesis that a large range of visual angles and different levels of visual acuity are basic requirements for the study of visual function, this preliminary study was carried out to explore the effect of visual angle, and to test the usefulness of the P1 component of the PRVEP as an objective index of visual acuity and the general status of vision. Subjects with normal vision and uncorrected myopia were studied, using a large range of visual angles and subsets of people with visual dysfunction were studied so as to generate a model for practical application. So, the study was designed to provide an objective assessment of visual acuity and to provide a means of obtaining evidence for the diagnosis and prognosis of visual function in clinical and forensic practice.

2 Subjects and methods

2.1 Participants Two hundred and ten subjects (105 males and 105 females; mean age 23 years, range 18–28)

with normal or myopic eyes took part in this study. They were students at Soochow University, China, and were recruited by advertisements. Their vision was measured with the standard logarithmic visual acuity chart (SLD-II). Based on monocular visiual acuity, they were divided into 0.1, 0.5 and 1.0 groups from poor vision to normality. Then 0.2, 0.4, 0.6 and 0.8 groups were added. Combining the two divisions, there were seven groups based on acuity, 0.1, 0.2, 0.4, 0.5, 0.6, 0.8 and 1.0. The best-corrected visual acuity of all subjects was not less than 1.0.

Subjects with disease of the central or peripheral nervous system, a history of prior head injury, alcoholism, mental retardation or significant psychiatric disorders, use of psychotropic drugs, disorders of the visual system, or monocular visual acuity <0.1 were excluded. The exclusion criteria were checked with SLD-II and a medical interview. After a complete description of the study to the subjects, written informed consent was obtained.

2.2 Stimuli The VEP was recorded with the vision monitor system of the Neuroscan Synamps (Scan 4.3) ERP recording system (Neuroscan Inc., USA), applying full-field pattern-reversal stimulation. The stimuli were delivered in seven blocks of white-black chessboards with different check sizes in a constant ratio sequence (8°, 4°, 2°, 1°, 30′, 15′, and 7.5′) (Fig. 1).

In the traditional approach to PRVEP testing, the low frequency of 2 Hz is used to elicit the P100 component and

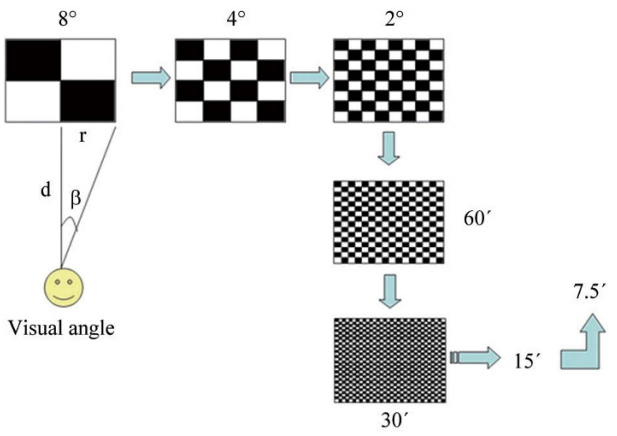

Fig. 1. Schematic of visual stimuli in which the reversal check size decreased in a constant-ratio sequence of visual angles.

is considered the best for assessing visual acuity[27]. This frequency was used in our study, with a mean luminance of 50 cd/m^2, contrast at 100%, and at a distance of 1 m. Each experimental block consisted of 200 trials with 2-min rest between blocks. The sequence of eye tested was randomized and matched among subjects. Checks subtending from 8° to 7.5′ were delivered so as to obtain a replicate trial for each size. The average of the two trials was used for statistical analysis.

2.3 Procedures All subjects sat comfortably in a dimly-lit, sound-attenuated and electrically shielded room, a distance of 1 m from a 17″ computer monitor. Each participant wore a Quikcap 32-channel EEG recording cap with the 10-20 international system, which was connected to the recording system. The monitor was controlled by the stimulation software (Neuroscan) that ran on a PC which also tagged the EEG acquisition. EEG activity was recorded with bilateral mastoids as reference (A1 and A2), and a ground electrode on the forehead. Vertical and horizontal electro-oculograms were recorded to control for motor artifacts, with electrode contact impedance <5 kΩ. Blinks and vertical eye movements were recorded with electrodes above and below the left eye. Horizontal eye movements were monitored from electrodes at the left and right outer canthi. Sweep time was 250 ms (–50 and +200 ms peristimulus) and the amplifier band-pass filter was DC to 30 Hz. Subjects were requested to focus on the central point and avoid blinking and eye movements during the trials. An eye patch was used to cover either eye for monocular testing.

After asking the subjects to focus on the red cross at the center of the screen and making a baseline EEG recording for 3 min, the stimuli were presented in sequence, and a series of EEGs were obtained. The VEPs were extracted by offline analysis. The averaging epochs was 250 ms, from 50 ms before the stimulus to 200 ms after the stimulus. Computerized artifact rejection was performed prior to averaging (<5% of trials were rejected).

P1 component recognition was based on polarity and latency. After ~100 ms, the first major positive peak occurring between 100 and 130 ms was elicited, following a

negative response at 55–95 ms. The time from the stimulus onset to the peak of the P1 wave was defined as the P1 latency. The amplitude from the baseline to the peak was designated as absolute P1 amplitude.

2.4 Statistical analysis P1 latency and amplitude were treated as dependent variables, and within-subject factors, stimulus check size, electrode position, visual acuity and gender were independent variables. Statistical analysis was performed with SPSS 13.0. To compare means, one-way ANOVA followed by *post hoc* test and independent-samples *t*-test were used, and linear and curve estimation models were used for regression analysis.

3 Results

3.1 Features of the PRVEP and distribution of recording site, gender and binocular difference The P1 component of the PRVEP was recorded from Oz, O1 and O2 according to the international standard 10-20 electrode-linkage system. The Oz site showed the maximum P1 amplitude (Fig. 2).

All components of the PRVEP were analyzed at Oz.

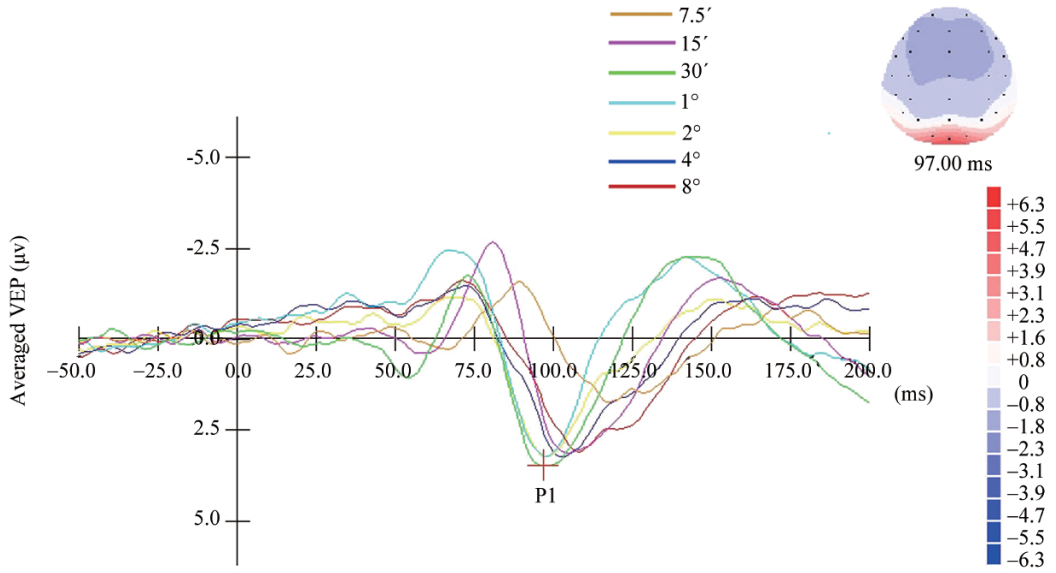

Fig. 2. Averaged global PRVEP and topographic mapping showed a maximum P1 amplitude at the mid-line region, Oz. Maximum P1 amplitude and minimum latency occurred at 1° and 30′ (n = 30).

No difference (*post hoc* test, n = 30, P >0.05) was found in the N1 peaks. In contrast, the P1 latency and amplitude showed significant differences between different check sizes (*post hoc* test, n = 30, P <0.01). The latency tended to shorten first and then increased with decreasing visual angle (Fig. 3).

The P1 values showed no significant difference between genders (*t*-test, n = 15, P >0.05) (Table 1). All subjects were right-handed. Interocular comparison of P1 in subjects with 0.1, 0.5 and 1.0 acuity showed a non-significant tendency for a shorter latency and higher amplitude for the right eye (*t*-test, n = 15, P >0.05).

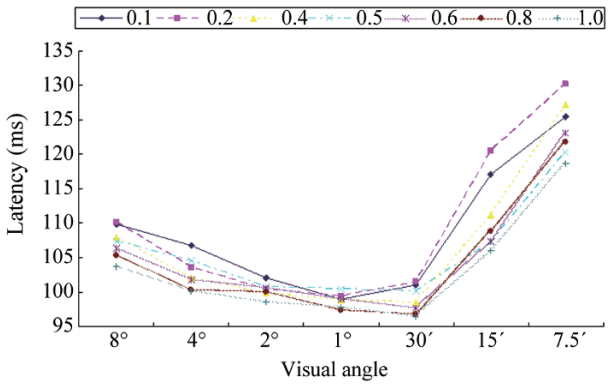

Fig. 3. P1 latency *versus* visual angle for subjects with different visual acuity levels.

Table 1. Comparison of P1 at visual angles 4°, 1° and 15′ between genders and with visual acuity of 0.1, 0.5 and 1.0 (mean ± SD, n = 15, P >0.05)

Visual acuity	Check size	P1 latency (ms)				P1 amplitude (μV)			
		Male	Female	t	P	Male	Female	t	P
0.1	4°	106.47 ± 10.51	107.07 ± 12.94	–0.139	0.890	3.80 ± 2.00	4.24 ± 2.41	–0.546	0.589
	1°	98.87 ± 5.79	101.33 ± 12.78	–0.681	0.504	4.65 ± 2.63	4.27 ± 2.60	0.393	0.697
	15′	115.60 ± 10.69	119.53 ± 6.55	–1.215	0.234	3.50 ± 1.63	3.54 ± 3.03	–0.036	0.972
0.5	4°	107.07 ± 10.86	102.07 ± 8.58	1.399	0.173	4.28 ± 2.53	4.36 ± 1.89	–0.108	0.915
	1°	100.07 ± 5.42	100.93 ± 4.45	–0.479	0.636	4.85 ± 2.60	4.85 ± 2.44	0.006	0.995
	15′	109.60 ± 9.83	104.87 ± 7.19	1.506	0.143	4.62 ± 2.19	5.10 ± 2.70	–0.532	0.599
1.0	4°	104.47 ± 7.46	100.60 ± 10.57	1.158	0.257	4.37 ± 1.75	4.80 ± 1.94	–0.628	0.535
	1°	100.80 ± 7.39	96.40 ± 3.85	2.045	0.054	5.63 ± 1.32	6.26 ± 2.21	–0.947	0.352
	15′	106.80 ± 10.71	103.60 ± 6.40	0.994	0.329	5.42 ± 2.49	5.99 ± 2.46	–0.637	0.529

3.2 Features of the PRVEP responding to check size/visual angle The P1 latency decreased slowly below 30′, then increased rapidly in subjects especially with relatively high acuity (0.6, 0.8 and 1.0) (Fig. 3). The P1 latency differed among all the check sizes (*post hoc* test, n = 30, P <0.01).

Anti-parallel to the P1 latency, the P1 amplitude initially increased with check size, and was maximal at 1° and 30′.

3.3 Features of the PRVEP responding to visual acuity P1 latency tended to decrease and P1 amplitude tended to increase with increasing visual acuity at a particular visual angle. Compared with the normal vision group, P1 latency in the group with acuity ≤0.2 showed significant differences at 8°, 15′ and 7.5′, while the groups with 0.5 and 0.6 showed significant differences at the smaller check sizes of of 15′and 7.5′ (Fig. 4).

Comparing the P1 amplitude in the lower acuity group with normal subjects, significant differences occurred at all visual angles (*post hoc* test, n = 30, P <0.05). In the 0.5 and 0.6 groups, significant differences in amplitude only occurred from 1° to 7.5′ (Fig. 5).

3.4 Linear-regression equations for visual acuity Regression analysis of the relationship between the P1 components and visual angle was used to derive equations. Except for the P1 latency at 2° and 1°, all P1 components had a linear relationship with visual acuity at the angles studied.

Linear, logarithmic and quadratic regressions were all used to compare the relationship of the P1 components with visual acuity based on different visual angles. The re-

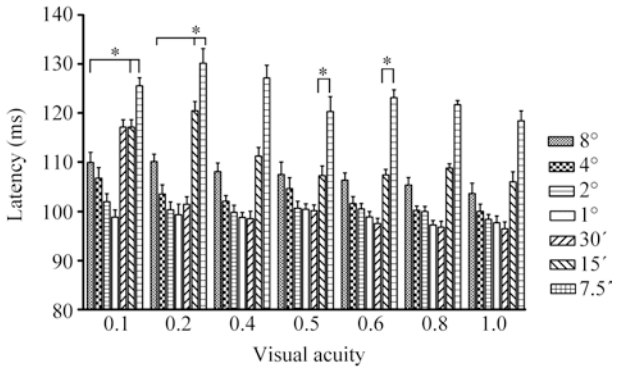

Fig. 4. P1 latency *versus* visual acuity at different visual angles (n = 30, *P < 0.05).

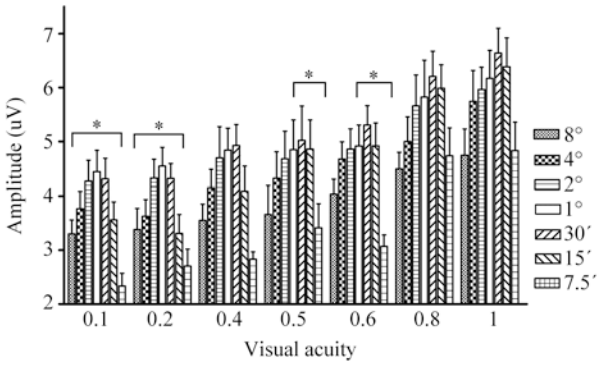

Fig. 5. P1 amplitude versus visual acuity at different visual angles. n = 30, *P <0.05.

sults showed that the linear tendency (latency: $F = 33.145$, $R^2 = 0.253$; amplitude: $F = 33.754$, $R^2 = 0.256$) showed a better fit (Fig. 6). The linear regressions for P1 latency and amplitude corresponding to different levels of visual acuity at particular visual angles are listed in Table 2.

4 Discussion

With regard to the relationship between visual acuity and visual stimulus size, some reports show that an increase in P1 amplitude occurs within visual angles 10′ to 30′, while it decreases at other angles. A recent study implied that 15′ or 60′ might be optimal for estimating visual acuity[34]. The different results among studies might reflect the selective conflicting of the testing coefficient and age-differences between the test groups. Moreover, some reports found a curvilinear relationship between the P1 amplitude and check size/visual angle[20,35]. The peak amplitude of P1 wave was elicited at 30′ in the visual acuity groups studied[35]. A similar curvilinear tendency with slow enhancement and rapid decline was also found in our study. However, two peak values were found at 60′ and 30′, rather than the one peak in the previous finding[35]. In addition, we also found relationships of both P1 amplitude and P1 latency with visual angle, which might be attributed to the wide-range of visual acuities. The curvilinear relationship of P1 latency is supported by the study of Kurita-Tashima[36], which showed the latency peak was at 35′.

Based on the above, we supposed that the optimal visual angle might differ for individuals with different visual acuity. For the visual acuity <0.2 group, the maximum P1

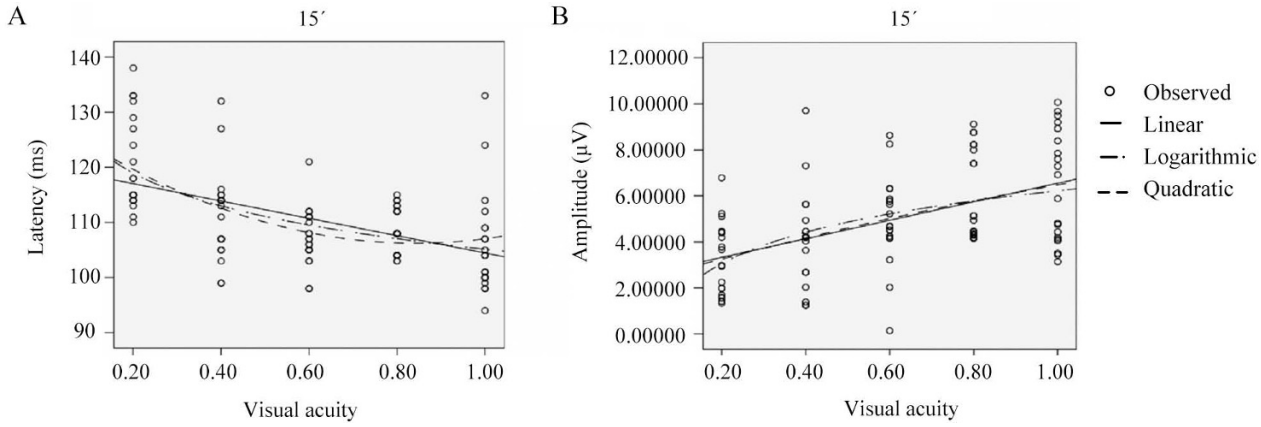

Fig. 6. Relationships of P1 latency (A) and amplitude (B) with visual acuity ($n = 30$).

Table 2. Linear regressions for visual acuity and P1 latency or P1 amplitude at different visual angles ($n = 30$, *$P > 0.05$)

Visual angle	Equation	|R|	F	P value
8°	$Y_1 = -7.065X_1 + 110.84$	0.207	7.661	0.006
	$Y_2 = 1.643X_2 + 3.040$	0.272	13.643	0.000
4°	$Y_1 = -7.166X_1 + 106.626$	0.223	8.967	0.003
	$Y_2 = 2.143X_2 + 3.385$	0.315	18.862	0.000
2°	$Y_1 = -3.021X_1 + 101.917$	0.122	2.585	0.110*
	$Y_2 = 1.876X_2 + 3.963$	0.247	11.142	0.001
1°	$Y_1 = -1.476X_1 + 99.567$	0.063	0.671	0.414*
	$Y_2 = 1.860X_2 + 4.113$	0.236	10.116	0.002
30′	$Y_1 = -5.704X_1 + 101.869$	0.246	11.028	0.001
	$Y_2 = 2.641X_2 + 3.900$	0.347	23.386	0.000
15′	$Y_1 = -14.639X_1 + 118.42$	0.454	44.450	0.000
	$Y_2 = 3.424X_2 + 3.014$	0.442	41.620	0.000
7.5′	$Y_1 = -9.156X_1 + 127.995$	0.246	11.056	0.001
	$Y_2 = 2.848X_2 + 1.969$	0.451	43.616	0.000

X_1 and X_2, visual acuity corresponding to the P_1 latency and P_1 amplitude; Y_1 and Y_2, P_1 latency and amplitude, respectively.

amplitude occurred at 60′and 30′, whereas one peak at 30′ was found in the other groups. These phenomena could be explained by pattern-contour mechanisms[37]. Since the pattern edge blurs at smaller check sizes, a rapid decrement of P1 amplitude and prolongation of P1 latency occurred in the vision 0.1 and 0.2 groups, reflecting the fact that with poorer acuity, a larger visual angle is needed to distinguish the details of the visual stimulus.

Luminance changes of pictorial stimuli might further contribute to amplitude attenuation and latency extension[33]. Lower amplitude and longer latency might be due to stimulation of the peripheral retina where rods predominate[38], with sensitivity to subdued light but weak visual acuity. The results suggested that the mechanism of visual processing at lower levels of visual acuity might be inherent and differ from those in normal vision. Meanwhile, the results also provided evidence that the study of visual angle combined with visual acuity is needed to appraise visual processing. Our results also indicated that check size has a stronger effect on the P1 component than visual acuity which might be because visual angle and margin perception of a pictorial stimulus are basic prerequisites for visual processing. However, further studies are needed to clarify the mechanism.

Previous study showed that the early and late phases of the P1 component are respectively localized to the dorsal extrastriate cortex of the middle occipital gyrus and ventral extrastriate cortex of the fusiform gyrus[39]. Some reports showed that the amplitude of the P1 component is a sensitive sign of early pathology in the visual system[41], whereas P1 amplitude is affected by stimulus parameters, the physiological state of the subject, and the degree of attention during testing. Therefore, it would be serious to evaluate the visual function only by the reduction of P1 amplitude without pathological changes of neurons. In contrast, most previous studies revealed that P1 latency has less inter-individual variation than P1 amplitude[42], so particular emphasis was laid on the contribution of P1 latency to visual acuity, however, the major variability and the relative blunt modulation of P1 deduced by the traditional ways might limit its further application[21]. Kharauzov reported a strong logarithmic relationship between the threshold spatial frequency and visual acuity, allowing automated calculation of visual acuity from the electrophysiological data[43]. Besides the difference of the visual stimulus from our study, Kharauzov's study neglected the effect of visual angle. Using the full range of check sizes in the equal-ratio sequence, we established the relationships between P1 components and visual acuity based on different visual angles. This could provide a primary database to improve and standardize the mode of PRVEP testing for objective assessment of visual acuity.

Although an abnormal PRVEP only reflects damage in the visual pathway (from eye to visual cortex), it cannot effectively be used to locate the site of a visual disorder. In this study, we aimed to objectively evaluate the degree of the visual acuity neglecting the site of the visual defect. Since eye-movement is monitored, the PRVEP is objective and reliable for assessing visual acuity, and thus valuable for forensic practice. It was reported that suspected voluntary suppression of the VEP could be modified by using a large check size or stimulus field and binocular stimulation[44], and this study also suggested that a larger check size/visual angle plays an important role in assessing function in the visual pathway, especially with a serious disorder of visual acuity. Based on our study, optimal visual angles could be selected for the examination of different levels of visual dysfunction. Moreover, the precise assessment of visual acuity can be undertaken using the P1 component of the PRVEP. The results ae independent of subjects' responses and therefore provide an objective assessment of visual acuity for forensic purposes. Finally, further study of visual acuity with larger sample sizes and subdivision into age groups would improve the equations, and make this method more effective and convenient for estimating the status of visual dysfunction.

5 Conclusion

The P1 component of the PRVEP can be used to evaluate optic function and objectively assess visual acuity. Our study suggested that visual angle is essential for exploring the status and dysfunctions of the visual pathway,

especially visual acuity.

Both the amplitude and latency of the P1 component of the PRVEP showed a curvilinear relationship with check size/visual angle. The peak P1 latency and amplitude occurred ~60′for acuity <0.2, whereas 30′ was the optimal stimulus for the other groups. Large visual angles around 60′/1°might be used to generate PRVEP components for evaluating poor vision and identifying malingerers. Further, P1 amplitude tended to increase and P1 latency to decrease with increasing visual acuity. The P1 components displayed linear correlations with visual acuity, especially in the range from 60′ to 15′.

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