Stimulus Duration, Neural Adaptation, and Sweep Visual Evoked Potential Acuity Estimates

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PURPOSE. Results in several studies have suggested that the visual evoked potential (VEP) amplitude can vary with stimulus duration. The purpose of this study was to determine whether acuity estimates obtained by extrapolation of the sweep VEP are altered by this adaptation effect.

METHODS. Sweep VEP data were obtained from 16 healthy observers under binocular viewing conditions. Data were acquired with a commercially available VEP unit using standard electrode recording techniques. Three sweeps (high spatial frequencies, medium spatial frequencies, and low spatial frequencies) were run. The subjects’ visual acuity at the monitor distance was 6/6 for the high spatial frequency sweep. For the medium and low spatial frequency sweeps, the subjects were dioptrically blurred to 6/15 (medium spatial frequencies) or 6/30 (low spatial frequencies) at the monitor distance. Each sweep consisted of six spatial frequencies (contrast 80%; temporal frequency (TF) = 7.5 Hz; screen luminance = 100 candela [cd]/m²). For each spatial frequency, the stimulus duration was 8 seconds, partitioned into 1-second bins. A minimum of eight sweeps were obtained per subject. An acuity estimate was obtained for each second’s data by fitting a line to the high spatial frequencies (excluding noise) and extrapolating this line to the x-axis. With this technique, estimates could not be obtained for 29 of 384 possible acuities.

RESULTS. The sweep VEP acuities for the 16 subjects did not change significantly over the 8 seconds of data collection for the high, medium, or low spatial frequency sweep (repeated measures analysis of variance [ANOVA]: high, \( P = 0.25 \); medium, \( P = 0.50 \); low, \( P = 0.23 \)). In any given subject, there was a 1- to 2-octave range in acuity estimates over the 8 seconds of stimulus presentation (high, \( 1.23 \pm 0.417 \) octaves; medium, \( 1.41 \pm 0.593 \) octaves; low, \( 1.52 \pm 0.475 \) octaves; mean ± SD).

CONCLUSIONS. These results suggest that there is not a significant change in sweep VEP acuity estimates over an 8-second stimulus presentation. Thus, neural adaptation does not significantly affect the clinical use of the sweep VEP. (Invest Ophthalmol Vis Sci. 1998;39:2759–2768)

Neural adaptation can alter the amplitude of the visual evoked potential (VEP). This effect has been examined in humans1-4 and at the single-cell level in animals.5-19 Ho and Berkley5 examined the effect of 45-second adaptation periods on the VEP at a range of spatial frequencies (2-10 cycles per degree [cpd]). They observed that the peak amplitude for the evoked potential occurred 3 to 6 seconds after the stimulus onset. After the peak, the decline in amplitude was modeled with an exponential equation. The time constants for these equations ranged from 2.9 to 19 seconds, depending on the spatial frequency and contrast of the stimulus.

Peachey et al.2 examined adaptation of the VEP at five spatial frequencies (0.77, 1.55, 3.1, 6.2, and 12.4 cpd). They presented the stimulus for 20.34 seconds and examined the amplitude and phase of the steady state VEP over 2.26-second intervals after an initial 9.04-second adaptation period. For the low spatial frequencies (0.77 and 1.55 cpd), the response amplitude of the visual evoked potential did not change significantly. At 3.2 cpd, the response amplitude increased for 6 to 12 seconds and then stabilized. At 6.2 and 12.4 cpd, Peachey et al. showed that the maximum amplitude response occurred 3 to 4 seconds after the stimulus was presented. After this time, the amplitude decreased to as low as 38% of its maximum. They suggested that this may be the result of a contrast gain or contrast adaptation mechanism that has different response characteristics at different spatial frequencies.

Fluctuations in the response amplitude may have a significant impact on the clinical use of the sweep VEP. The sweep VEP technique was initially introduced as a means of rapidly assessing visual function.16-24 Given the results showing VEP amplitude changes depending on the duration of stimulus presentation, extrapolation of acuity using the sweep VEP may depend significantly on the length of stimulus presentation and on the start of data acquisition after stimulus onset. Current sweep VEP programs only present each spatial frequency for 1 or 2 seconds and thus may not obtain the maximum response at higher spatial frequencies, thereby underestimating acuity. Currently, some investigators are lengthening the stimulus duration to minimize the effect of adaptation on the sweep VEP responses.25 However, lengthening the stimulus presentation...
The sweep VEP is used to estimate visual acuity in people in whom other kinds of tests are difficult or impossible to use. In general, a significant percentage of patients tested with sweep VEPs have decreased visual acuity. To determine the visual acuity of these subjects requires that each sweep include a wide range of spatial frequencies, which leads to prolongation of the testing period, or a sweep consisting of low to moderate spatial frequencies must be used. Stimulus duration may affect acuity estimates differently with high and low spatial frequency sweeps, because neural adaptation has different effects across the spatial frequency spectrum. Thus, the accuracy of acuity estimates from sweep VEPs may differ, depending on the true acuity of the observer and the particular spatial frequencies tested.

The purpose of this study was to determine whether the stimulus duration affects the final visual acuity obtained with the sweep VEP. To accomplish this, we measured sweep VEPs for discrete intervals over an 8-second stimulus period with the subject's best visual correction. In addition, the subjects were dioptrically blurred to 6/15 and to 6/30, with the spatial frequencies in the sweep adjusted accordingly to determine the acuity. Thus, we were able to determine whether differential neural adaptation across the spatial frequency spectrum significantly affects acuity assessment for a range of visual acuities. A portion of these data was presented previously.

**METHODS**

**Subjects**

Sixteen healthy subjects (age range, 23–40 years; mean 28.6 ± 5.29 years; mean ± SD) took part in this study. All had vision correctable to 6/6 or better. None of the subjects had ocular or systemic disease. All subjects provided informed consent for...
the project, and the research followed the tenets set forth in the Declaration of Helsinki.

**Stimulus**

The stimulus was a horizontally oriented sine wave grating that swept up the spatial frequency spectrum. Three spatial frequency sweeps were used (high: 8.0, 10.0, 13.0, 16.0, 20.0, and 26.6 cpd; medium: 4.0, 5.0, 6.5, 8.0, 10.0, and 13.0 cpd; low: 2.0, 2.5, 3.0, 4.0, 5.0, and 6.5 cpd). The contrast was 80% and the temporal reversal rate (square wave) was 7.5 Hz. The screen luminance was 100 cd/m.² The stimulus screen (19° wide × 14.5° high) was viewed binocularly at 1 m. Each spatial frequency was presented for 8 seconds. Thus, a single sweep lasted 48 seconds (8 seconds × 6 spatial frequencies). An 8-second stimulus duration was chosen because previous studies indicated that the greatest visual evoked potential amplitude occurred within this interval. Sweeps were repeated until the confidence intervals for the data were no longer decreasing (typically, eight or more sweeps per subject). The intersweep interval varied from subject to subject, depending on the fatigue level of the participant.

The high spatial frequency sweep was run with the subject's distance correction when needed. The medium spatial frequency sweep was run with the subject dioptrically blurred (+1.75 ± 0.418 diopters [D]; mean ± SD) to 6/15 at the screen distance, and the low spatial frequency sweep was run with the subject dioptrically blurred (+2.58 ± 0.445 D, mean ± SD) to 6/30 at the screen distance. The Bailey Lovie LogMar chart was used to determine visual acuity.

**Recording Technique**

Data were acquired with an Enfant 4010 system (Neuroscientific, Farmingdale, NY). The recording electrode (Ag/AgCl) was placed 2 cm above the inion on the midline. The reference and ground electrodes were placed on the earlobes. The signal was amplified 10,000×, band-pass filtered (0.5-100 Hz), and digitized at 300 Hz with 12-bit resolution. The active electrode impedance was maintained below 10 kΩ (mean, 5.8 ± 2.39 kΩ; mean ± SD).

**Data Analysis and Acuity Extrapolation**

The sweep VEP data for one subject are shown in Figure 1. The top graphs display the response amplitude of the second harmonic (discrete Fourier transform) of the sweep VEP for each second of data collected for all six spatial frequencies. The bottom figures display the corresponding phase values. The data for seconds 1 through 4 are in the left graphs and for seconds 5 through 8 are in the right graphs. The error bars are the 95% confidence intervals. For the sake of clarity, error bars are not shown for all the data.

The data were determined to be noise if either the 95% confidence intervals for the sweep VEP amplitude data overlapped with zero, or the 95% confidence intervals for phase were greater than 90°. The value of 90° was chosen after inspection of the data. The average confidence interval range for the data at the peak spatial frequency (the spatial frequency with the greatest amplitude response) for 10 of the subjects was 43.5° ± 24.6° (mean ± SD). Thus, the mean plus two SDs is approximately 90°. Both criteria were met by most of the data that were determined to be noise. The data in Figure 1, exceeded the criteria for the 26.6-cpd data. None of the data collected at the lower spatial frequencies were considered to be noise for this subject.

Acuities were determined by fitting a line to the high spatial frequency data that were above noise (Fig. 2). The spatial frequency is plotted on the horizontal axes, and the response amplitude on the vertical axes. The two ways in which the acuities were determined are shown. In the top graph, the linear fit included data between the peak spatial frequency (8.0 cpd) and the highest spatial frequency above noise (20.0 cpd). The linear fit was extrapolated to the x-axis (zero amplitude) for the resolution or visual acuity estimate (24.78 cpd or 6/7.3). If there were no data points between the peak spatial frequency and the noise level, the acuity was taken.

**Figure 2.** Visual acuity extrapolation. **Top:** the acuity extrapolation for subject 4 using data from second 8. The high spatial frequency data were fit with a line that was extrapolated to the x-axis for the acuity (24.78 cpd or 6/7.2). See the Methods section for further details of the fit. **Bottom:** if a line could not be fit to the data, the resolution was taken as the highest spatial frequency that produced data above the noise level (20.0 cpd or 6/9).
as the peak spatial frequency (Fig. 2, bottom graph). By using this technique, acuities could not be determined for 29 of 384 possible estimates (16 subjects × 8 seconds of data × 3 acuity levels = 384). The majority of the undetermined acuity estimates (24 of 29) were from two subjects with low VEP amplitudes.

RESULTS

A plot of the acuity estimates for the high spatial frequency sweep is shown in Figure 3. On the horizontal axis, time is plotted in seconds; on the vertical axis, acuity is plotted in cycles per degree. The small squares represent the data from individual subjects, and the large squares are the group means with their respective SDs. At time 0, the LogMar acuities are given. The plot displays the sweep VEP acuity estimates for each second (i.e., seconds 1, 2, 3). The sweep VEP acuity estimates are unaffected by the stimulus duration (repeated measures ANOVA: \( P = 0.25; F = 1.33 \)).

The LogMar acuities are significantly higher than the sweep VEP acuities (repeated measures ANOVA; \( P < 0.00005; F = 211.41 \)). The LogMar mean acuity in the subjects was 40.2 cpd (6/4.5; range, 27.4-57.2 cpd [6/6.6-6/3.2]). The difference between the highest and lowest sweep VEP acuities in individual subjects had a 1- to 2-octave range across the 8 seconds of stimulus presentation (Table 1). The acuity range in all the subjects was 1.25 ± 0.417 octaves (mean ± SD). The average range of sweep VEP acuity in all the subjects was 6/6-6/13.5. The difference between LogMar and sweep VEP acuity can be explained by the choice of spatial frequencies in the high spatial frequency sweep. The highest spatial frequency presented was 26.6 cpd. Because all the subjects had approximately 6/6 (30 cpd) visual acuity or better, the sweep VEP acuity estimates were likely to underestimate the subject's actual acuity. This highlights the importance of carefully choosing the spatial frequencies in the sweep to bracket the acuity of the subject.

A plot of the acuity estimates for the medium spatial frequency sweep is shown in Figure 4. The figure format is the same as that of Figure 3. The sweep VEP acuity estimates did not change significantly with stimulus duration (repeated measures ANOVA; \( P = 0.50; F = 0.91 \)). In addition, the LogMar acuity was not significantly different from any of the sweep VEP acuities (repeated measures ANOVA; \( P = 0.25; F = 1.41 \)). The range of sweep VEP acuity estimates in individual subjects was 1.41 ± 0.593 octaves (mean ± SD). The mean LogMar acuity was 11.5 cpd (6/15.7), and the range of sweep VEP

![VEP ANOVA, \( P = 0.25 \)](image-url)
VEP estimate of acuity was affected by neural adaptation for the first 8 seconds of stimulus presentation (Fig. 3). Altering the visual acuity with plus-diopter lenses and testing with lower spatial frequencies had no effect on this observation (Figs. 4, 5). Thus, the stimulus duration, regardless of the spatial frequency components of the sweep, did not significantly alter the final acuity obtained with sweep VEPs.

The data presented by Ho and Berkley\textsuperscript{1} suggest that neural adaptation should significantly affect the acuity estimate with the sweep VEP. Furthermore, according to Peachey et al.,\textsuperscript{2} the greatest effect should be in high spatial frequency sweeps, because this is when the greatest adaptation or alteration in VEP amplitudes occur. Our results do not support this contention.

There are several reasons why our visual acuity estimates from the sweep VEP data are not affected by stimulus duration. First, Ho and Berkley\textsuperscript{1} examined four subjects, and Peachey et al.\textsuperscript{2} examined three. With a small sample size, the data can be skewed by the choice of subjects or by a single unusual subject. For example, in Figure 5 from Peachey et al.,\textsuperscript{2} there is a considerable range of adaptation across subjects. One subject shows little if any adaptation, whereas another subject shows considerable range of adaptation across subjects. One subject displays the greatest visual acuity in the first few seconds after stimulus onset, whereas another subject displays the greatest visual acuity after the first 8 seconds. Thus, the stimulus duration had no effect on the visual acuity estimates obtained with sweep VEPs.

Similar observations were made in our data. Table 1 provides the visual acuity (in cycles per degree) for the first 8 individual seconds of the high spatial frequency sweep VEP in all the subjects. Although the average for the entire duration did not change across the 8 seconds, there was considerable variability among the subjects. For example, subjects 2, 3, 6, 7, 9, 10, and 14 displayed the greatest visual acuity in the first few seconds.

### Table 1. Sweep VEP Acuity Estimates for the 8 Seconds of Stimulus Duration with the High Spatial Frequency Sweep

<table>
<thead>
<tr>
<th>Subject</th>
<th>LogMar Acuity</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
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<td>10.00</td>
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<td>23.20</td>
<td>16.10</td>
<td>15.60</td>
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<td>28.60</td>
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<td>26.60</td>
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<td>8.00</td>
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<td>21.60</td>
<td>13.00</td>
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<td>± 7.72</td>
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<td>± 9.38</td>
<td>± 9.10</td>
<td>± 8.59</td>
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| VEP acuity is shown in cycles per degree. LogMar acuity is shown for comparison. The range of acuity across the 8 seconds was 1.23 ± 0.417 octaves (mean ± SD).
| —, Times when acuity could not be determined (see the Methods Section). VEP, visual evoked potential. |
Acuity estimates for the 16 subjects with the medium spatial frequency sweep. Estimates are provided for data from each second (i.e., seconds 1, 2, 3, and so on). The mean (large squares) and SD (error bars) for each second are also shown. An analysis of variance did not indicate a significant difference for sweep visual evoked potential (VEP) acuity across the different seconds \( (P = 0.50; F = 0.91) \). An ANOVA did not indicate a significant difference between LogMar visual acuities (VA) and sweep VEP acuity \( (P = 0.25; F = 1.41) \). Small squares, data from individual subjects.

Second, adaptation effects may not be great enough to alter the sweep VEP acuity estimate significantly. In this study, single-point estimates of acuity were made in 188 (49% of 384) cases, in which there were no data points between the peak VEP and the noise level (Fig. 2, bottom). In all these cases, variations in amplitude caused by adaptation would have no effect on the acuity estimate (unless a relevant amplitude was sufficiently altered to exceed or decline below noise level). Thus, adaptation would have little effect on these acuity estimates.

The acuity estimates that were based on extrapolated lines showed considerable variability, typically 1 to 2 octaves across the 8 seconds. This variability may have been simple intrasubject VEP amplitude variability or it may have resulted, at least in part, from VEP adaptation. Because no systematic differences between seconds were found, any contributions to this variability that were based on adaptation were either not large enough to be detectable or were in different directions in different subjects. Peachey et al.\(^2\) illustrated that adaptation effects in the first 8 seconds are typically less than 1 \( \mu \text{V} \). This small change in amplitude with stimulus duration may not be enough to affect the acuity estimates significantly. For example, our subject 9 had a sweep VEP acuity of 25.8 cpd for the first second of data for the high spatial frequency sweep (Table 1). By altering the amplitude of the responses only 1 \( \mu \text{V} \), the lowest resolution that was obtained was 22.7 cpd. Compared with the range of acuities across the 8 seconds of stimulus duration for this subject (25.8 - 40.1 cpd), a change from 25.8 cpd to 22.7 cpd was small. Thus, even if all subjects displayed a similar adaptation profile, this adaptation effect would only change acuity estimates by a small amount and may not be statistically detectable.

**Adaptation across Spatial Frequencies**

A control experiment was performed to examine the effect on response amplitude of the spatial frequency location in the sweep. Because the entire sweep was 48 seconds and most of...
the spatial frequencies in the sweep were within 2 octaves of one another, prior stimulation at one spatial frequency may have affected the response amplitude measured at a subsequent spatial frequency. To examine this possibility, another spatial frequency sweep was performed on 10 of the subjects. The spatial frequencies in this sweep were 5, 6, 8, 10, 20, and 26.6 cpd. All other stimulus conditions were similar to the high spatial frequency sweep. The data collected at 8 cpd were compared with the data for 8 cpd from the high spatial frequency sweep (spatial frequencies of 8, 10, 13, 16, 20, and 26.6 cpd). In the high spatial frequency sweep, the 8 cpd data had no prior adapting stimulus, whereas, in the adaptation sweep, the 8-cpd stimulus was preceded by two other stimuli (total presentation time of 16 seconds, 8 seconds at 5 cpd and 8 seconds at 6 cpd). The amplitudes of the response at 8 cpd for each second of data were then compared for the two sweeps. The mean and SD (in all 10 subjects) for the adaptation sweep for each second (in microvolts) was 3.38 ± 2.10, 3.19 ± 2.60, 2.76 ± 2.15, 2.52 ± 2.06, 2.56 ± 1.99, 2.50 ± 1.80, 2.50 ± 1.82, and 2.65 ± 2.03 (seconds 1-8), and for the high spatial frequency sweep (in microvolts) it was 2.48 ± 0.95, 3.05 ± 2.18, 3.19 ± 2.62, 3.13 ± 3.21, 3.02 ± 3.13, 3.07 ± 2.79, 3.01 ± 2.71, and 2.93 ± 2.18. An ANOVA did not find a significant difference between the two sets of data (P = 0.69 for the high spatial frequency sweep versus the adaptation sweep), across the 8 seconds of data for the two sweeps (P = 0.61), or for the interaction of time by sweep (P = 0.17). Even though post hoc testing was not warranted, we performed a t-test and a Wilcoxon paired-sample rank test on the different seconds for the two sets of data. There was no significant difference between data for the two sweeps in any second in either test (all P > 0.10). Thus, prior adaptation to other spatial frequencies in the sweep did not affect the response amplitude for subsequent spatial frequencies.

**Visual Acuity Assessment with Sweep VEPs**

One of the main uses of the sweep VEP is to determine visual acuity quickly in otherwise nonresponsive patients. Acuities determined with the pattern VEP have a good correlation with acuities measured psychophysically; however, the procedure is slow. Because of the time required to measure acuity with pattern VEPs, it is not clinically feasible in all patients. Acuity measurements with the sweep VEP can be made in significantly less time and can subsequently be used in patients with short attention spans.

The correlation between sweep VEP acuity and psychophysical measurements of acuity have been determined in healthy subjects and in patients with amblyopia. In healthy subjects, the correlation between sweep VEP acuity...
and Snellen acuity has been examined by blurring the individual with spectacle lenses. Katsumi et al. used the same equipment and methods as in this study. They found that with a small amount of blur (visual acuities better than 20/40 or 6/12 and blur less than +1.0 D), the sweep VEP acuities were equal to or slightly poorer than the Snellen acuities. With blur of approximately +1.50 D (acuities of approximately 20/70 or 6/21), the sweep VEP acuities were better than the Snellen acuities. The correlation between LogMar acuity and sweep VEP acuity in our subjects is displayed in Figure 7. The LogMar acuity (in cycles per degree) is plotted on the horizontal axis, and the sweep VEP acuity (in cycles per degree) is plotted on the vertical axis. The best fit line with the 95% confidence interval is shown. Similar to the observation in Katsumi et al., when the acuities are good (approximately 6/6 or 30 cpd), the sweep VEP acuity is equal to or poorer than the LogMar acuity. In our data, the LogMar and the sweep VEP acuities (acuity from the first second of the VEP) can be compared by determining the difference in octaves between the two. For the 15 subjects whose data were available for the high spatial frequency sweep, the difference was 1.08 ± 0.288 octaves. Katsumi et al. had a difference of 0.642 octaves. Thus, for the high spatial frequency sweep, the LogMar acuity was significantly better than the sweep VEP acuity. This may have occurred...
because the highest spatial frequency we presented was 26.6 cpd, but the highest spatial frequency presented by Katsumi et al. was 30.356 cpd. Thus, either still higher spatial frequencies should be included in the sweep to get an accurate acuity or there may be other factors (e.g., the number of spatial frequencies included in the sweep) that result in this underestimate of acuity by sweep VEPs.

Unlike the findings of Katsumi et al., we did not find a difference between sweep VEP acuity and LogMar acuity when the acuities were between 6/15 and 6/30. The repeated measures ANOVA indicated that there was no difference between the two acuities in this LogMar acuity range. In addition, the difference in octaves for the LogMar and the sweep VEP acuity for the first second of data were 0.29 ± 0.705 octaves for the medium spatial frequency sweep and 0.18 ± 0.812 octaves for the low spatial frequency sweep. Katsumi et al. found a difference of −0.688 octaves with +2.00 D of blur (similar to our 6/15 level) and a difference of −0.979 octaves with +3.00 D of blur (similar to our 6/30 level). Thus, their results indicate that the sweep VEP estimates of acuity are higher than the Snellen estimates of acuity. We may not have found a difference because the spatial frequencies in our sweeps were adjusted to bracket the subject’s LogMar acuity. This results in a greater number of stimuli in the spatial frequency range of interest, which gives a better linear fit and acuity estimate for the data; and the number of subjects used in our study was greater than that in Katsumi et al. Katsumi et al. show a plot (their Fig. 4) of the difference in octaves between the sweep VEP and Snellen acuity for the six subjects examined. For levels of blur between +1.50 D and +2.50 D (similar to that which we used), the acuity differences range from none to approximately 1.25 octaves in the six subjects. Thus, the plot in their Figure 4 indicates that there is considerable subject variability. Increasing the population size may result in less of a group difference between sweep VEP and Snellen acuities.

**Conclusions**

In conclusion, the change that has been observed in the amplitude of the VEP with continued stimulus presentation does not affect the sweep VEP acuity estimate. In addition, this observation was confirmed with a range of spatial frequencies and acuity levels. This indicates that the sweep VEP stimulus duration could be maintained at a minimum (1–2 seconds per spatial frequency), to optimize the benefit of obtaining rapid acuity assessments in people with poor attention spans.

**References**


