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# Simple non-invasive measurement of rapid eye vibration

M.A. García-Pérez[a],*, E. Peli[b]

[a] *Departamento de Metodología, Facultad de Psicología, Universidad Complutense, Campus de Somosaguas, 28223 Madrid, Spain*
[b] *The Schepens Eye Research Institute, Harvard Medical School, 20 Staniford Street, Boston, MA 02114, USA*

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## Abstract

A simple, non-invasive method for the measurement of eye vibrations above 30 Hz is described. The method can be used in either laboratory or natural conditions, and is based on the cancellation of an illusion of motion that occurs when two nearby light sources flickering in counterphase above the flicker fusion limit are observed during eye vibration. In these conditions, the light sources appear to oscillate in space at a frequency equal to the difference between the vibration and flicker frequencies. The frequency of eye vibration can be determined by adjusting the flicker frequency until the illusion disappears (i.e., until the difference frequency becomes zero). The same set-up can also be used to determine the amplitude of eye vibration, by adjusting the spatial separation between the two light sources until the oscillation appears to be the result of their bouncing off each other upon contact. The reliability and sensitivity of this method are illustrated with data from three observers whose eyes were vibrated with a commercial massager applied onto their neck, and using three different settings for the speed of the massager.

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## 1. Introduction

Dynamic responses of the human body to vibration have been the subject of study for a long time, and the effect of whole-body vertical vibration on visual performance has also been studied [1–7]. In laboratory conditions subjects can be exposed to whole-body vibration with specified parameters and some times a comparison has been made between the effect of body vibration when the visual stimulus is static and the effect of stimulus vibration when the observer is static. Body vibration and stimulus vibration are nominally identical in these cases, but it is known that body posture, seating conditions, and anthropometrical characteristics of the subjects result in the

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*Corresponding author. Tel.: +34-913-943-061; fax: +34-913-943-189.
*E-mail addresses:* miguel@psi.ucm.es (M.A. García-Pérez), eli@vision.eri.harvard.edu (E. Peli).

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actual vibration of the head and eyes being different from its nominal level [8]. These variations result in individual differences in the actual vibration transmitted to the head and eyes [9]. Some studies have shown that stimulus vibration deteriorates vision more than the same magnitude of subject vibration at frequencies below 6 Hz [3,10], but the opposite occurs at higher frequencies [10]. These results suggest that body, head, and eye resonance alter the nominal parameters of subject vibration. A fair comparison of the effect of stimulus vibration with that of subject vibration could be made if the actual vibration of the eyes (when the subject vibrates) could be measured and its parameters applied to the stimulus (when the subject is static). Indeed, visual performance during whole-body vibration depends on the quality of the retinal image, which in turn depends only on how the eye vibrates regardless of the parameters of the vibration source. Note also that the use of accelerometers on bite bars to determine head vibration is insufficient for this purpose, because the eyes do not vibrate rigidly with the cranium.

Out of the laboratory, the human body is daily exposed to high-frequency (30–80 Hz) vibration that must also affect visual performance. The activities providing this vibration include most forms of transportation and the operation of some types of industrial machinery, and also such mundane tasks as the use of an electric toothbrush or other home appliances (e.g., massagers). A precise description of the vibration source is difficult to achieve but, again, measuring the vibration of the eyes in these circumstances is all that is needed to study their effects on visual performance and allow a comparison with results obtained in the laboratory.

Eye vibrations of high frequency and low amplitude are not easy to measure. Conventional equipment for the recording of eye movements at high spatial and temporal resolutions either involves invasive methods (scleral coils) or is cumbersome and requires head restraint (pupil tracking or Purkinje-image methods). These characteristics make eye trackers difficult to utilize along with other apparatuses in complex experimental settings. Lee and King [11] proposed a blur-cancellation method in which the subjects alter the vibration of the stimulus until it matches the vibration of the eye, a method based on the principle that when eye and stimulus vibrate synchronously the perception of blur caused by vibration will disappear. The applicability of this method is restricted to laboratory conditions in which the same source makes the stimulus and the subject vibrate, so that the frequency of vibration is known and only the amplitude and phase of the vibration of the eyes needs to be determined.

The goal of this paper is to describe a simple non-invasive method for the measurement of high-frequency (above 30 Hz) eye vibrations, a method based on a cancellation strategy that is widely applicable in either laboratory or natural conditions. The method is based on an illusion of motion that occurs when a display that flickers beyond the critical fusion frequency (about 30 Hz; see Levinson [12]) is observed under mechanical vibration of the eyes [13]. The method allows measuring both the frequency and the amplitude of eye vibration, and its rationale is described next.

Fig. 1 illustrates the principle underlying the illusory perception of motion described by Peli and García-Pérez [13] when the eyes vibrate while looking at two nearby point sources that are flickering in counterphase above the critical fusion frequency. With still eyes, the lowpass temporal characteristic of the visual system [12] filters out the flicker at each retinal location, and the light sources are perceived as static and continuous: each light source is flickered onto a single retinal location (Fig. 1a, left) and temporal lowpass filtering produces the perception of two continuously illuminated dots that are static on the retina (Fig. 1a, right; see the appendix for

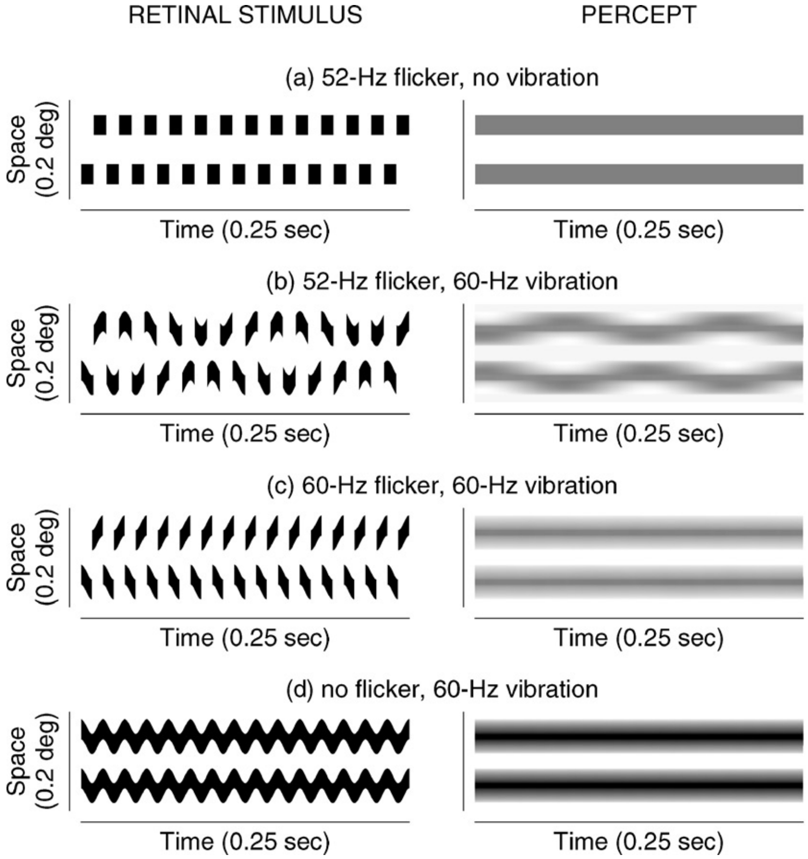

Fig. 1. Effects of stimulus flicker and sinusoidal eye vibration on the perceived appearance of two nearby point stimuli. Light ON is represented as darkness in the left panels. (a) Light sources flicker in square-wave counterphase at 52 Hz and the eyes are static. (b) Light sources flicker at 52 Hz and the eyes vibrate at 60 Hz. (c) The eyes vibrate at the same frequency (60 Hz) as the lights flicker. (d) The lights do not flicker and the eyes vibrate at 60 Hz.

computational details). Yet, when the eye vibrates, these flickering lights are effectively swept over the retina continuously and, if the frequency of the vibration differs from the flicker frequency (Fig. 1b, left), the same temporal lowpass filtering results in the apparent relative distance between the light sources varying as a function of time, which causes the illusion by giving the impression of relative motion (Fig. 1b, right). On the other hand, eye vibration at the same frequency (or an integer multiple) of the flickering light results in each light source undergoing the same exact sweep on the retina during its ON phase, resulting in the perception of blurred images that maintain a constant spatial separation over time (Fig. 1c). In these conditions, the relative phases between flicker and vibration affect the spread of the perceived blur, but in any case the perceived image is that of two static dots. Finally, eye vibration in the absence of flicker merely results in blurred images (Fig. 1d) without any illusory motion.

Then, when the eyes vibrate at an unknown rate, the frequency of vibration can be determined by adjusting the counterphase flicker frequency of two nearby light sources so as to reach the situation depicted in Fig. 1c, where the amount of blur may vary depending on the relative phases of flicker and vibration but the two light sources will appear static. The flicker frequency at which the illusory motion is cancelled is indeed the frequency at which the eyes are vibrating.

Note also that the stimulus set-up illustrated in Fig. 1a can be used to determine the amplitude of the vibration. In the right panel of Fig. 1b, the illusory oscillatory paths of either light source do not overlap in space because the spatial separation of the two light sources is larger than the amplitude of the oscillation of either source on the retina. If the actual spatial separation of the light sources could be varied, the perception would vary from that of two oscillating dots whose paths are separated (when the separation between the light sources is similar or larger than that depicted in the left panel of Fig. 1a) to that of two oscillating dots whose paths intersect (for separations sufficiently smaller). Then, the amplitude of the vibration can be determined by adjusting the actual separation between the light sources so that they appear to just touch each other as they move along their oscillatory path.

## 2. Materials and methods

### 2.1. Visual stimulus

The stimulus consisted of two sharp-edged, circular LEDs (each 4.5 mm in diameter) mounted on a precision slider that allowed varying the distance between the LEDs continuously in the range 1–32 mm. The slider could be positioned at any orientation on the frontal plane of the observer, and included a nonius scale that permitted accurate distance measurement (to 0.1 mm) of the actual edge-to-edge separation of the LEDs. The LEDs were made to flicker in square-wave counterphase through custom-made circuitry driven by a 4011A waveform generator (BK Precision, Placentia, CA) to produce the stimulus shown in the left panel of Fig. 1a.

### 2.2. Mechanical vibration of the eyes

Head vibration was produced with the help of a commercial percussion massager (HoMedics Inc., Commerce Township, MI) that allows variable speeds. Three different speed settings were actually used in the experiments, which correspond to stand-alone vibrations with fundamental frequencies of approximately 38, 49, and 63 Hz, as measured with a stroboscope. (The reported values correspond to the strongest component of the periodic pattern of percussion; these measurements indeed revealed that the vibration of the massager contained other components.) The weight and dual pivoting heads of the massager are well suited for producing steady head vibration when the massager is held resting against the subject's neck without applying any additional pressure. That this head vibration is transmitted to the eyes was informally determined by checking for the perception of illusory motion in a counterphase flickering display. This massager was chosen instead of the electric toothbrush that first revealed this phenomenon [13] because the vibration of the latter (and, as a result, the vibration transmitted to the eyes) is much more affected by slight variations in location on the upper jaw and in pressure against it.

Because mere contact with the body alters the frequency and amplitude of the vibration of the massager as compared to the stand-alone condition, without proper calibration and monitoring this apparatus is not capable of producing head vibration with prescribed parameters. Yet, this characteristic is not an obstacle for the purpose here because the goal is not to determine the relationship between the vibration of the source and the vibration of the eyes, but rather to check the sensitivity and reliability of the method for determining the vibration of the eyes.

### 2.3. Procedure

The room was dimly lit so as to obtain maximal contrast between the LEDs and the gap between them. Subjects sat at the appropriate viewing distance (see below) and were instructed as to how to hold the massager without applying any pressure that might alter the vibration transmitted to the head throughout the session. Subjects were trained in this task before the experiment started, and they were also asked to find a reproducible posture such that image blur occurred almost only vertically as judged by the appearance of a single LED. Viewing was monocular with each subject's dominant eye.

A session consisted of 8 or 10 trials. At the beginning of each trial the separation between the LEDs was fixed at 20–30 mm and flicker was set at a noticeable low frequency (1–3 Hz). The subject increased the flicker frequency up to the fusion level and then further until a strong (illusory) motion perception occurred. At this point, the subject indicated the amplitude of the perceived motion by having the experimenter slowly reduce the distance between the LEDs until they appeared to the subject to be bouncing off upon contact with each other. When this distance had been recorded, the subject further increased the flicker frequency for the apparent motion progressively to slow down and until it disappeared. (This adjustment is indeed extremely easy to carry out because exceeding the cancellation frequency brings the LEDs back into apparent motion.) This cancellation flicker frequency was read off of the digital display of the waveform generator, which was hidden from view of the subject.

Separate sessions were run for each of the three speed settings at each of two viewing distances (2 and 4 m). The order of sessions was random for each subject. Each session took 4–6 min to complete. The eye movement recordings described in Section 2.4 were obtained at a later time in a different laboratory.

### 2.4. Eye movement recordings

Eye movements were recorded while the subjects were fixating a point target and applying the massager. Rotational eye movements were recorded with a Dual-Purkinje-Image version 6.3 eye tracker (Fourward Technologies, Inc., Buena Vista, VA) [14]. Because this apparatus requires head restraint and substantially limits the mobility of the observer whose eye movements are being recorded, the subjects could not use the massager as they did during the experiments with the cancellation technique. Instead, an experimenter applied the massager onto the subject's neck with some pressure in order to counter the dampening caused by the head-restraint system. A reasonable match with the vibrations elicited in the cancellation experiments was sought by having the counterphase flickering display within the subject's field of view, but eye vibration mostly in the vertical direction (again as judged by the subject's perception of blur) could not always be obtained within the physical limitations of posture imposed by the eye tracker. Under these circumstances, it is very unlikely that the frequency and amplitude of eye vibration as determined from the eye movement recordings match the frequency and amplitude determined with our cancellation technique. Then, these recordings cannot provide an objective test of the validity of the cancellation method, but they are useful for ascertaining that the massager indeed provides different eye vibration patterns at different speed settings. On the other hand, use of the cancellation method in this setting (i.e., with head restraint) proved unfeasible because of the large effect of variations in the pressure applied by the experimenter, which could not be reliably reproduced.

The analog eye-position signal was sampled at 1000 Hz and stored for off-line analysis. Two or three segments of 5 s of data were separately collected, each beginning when the subject indicated perception of illusory motion in the flickering display. Separate sets of recordings were taken with the massager operating at each of the three speeds described in Section 2.2.

### *2.5. Subjects*

Three observers took part in the experiment, who signed informed consent forms that were approved by the Institutional Review Board in compliance with NIH guidelines and regulations.

## 3. Results

### *3.1. Temporal frequency of eye vibration*

Fig. 2 shows the frequency at which illusory motion was cancelled for each subject in each condition. The frequency of eye vibration measured with our cancellation method does not differ much from the frequency at which the massager vibrates in the stand-alone condition, although some minor differences can be observed. These minimal differences can reasonably be attributed to the effect of contact between the massager and the body (measurements with a stroboscope indicated that the fundamental stand-alone frequency of vibration varied upon contact with the body, and also varied minimally over time but sufficiently so as to hinder a precise measurement) and possibly also to anthropometrical characteristics (such as individual differences in transmissibility of non-fundamental frequencies in the actual vibration of the massager). In any case, the results were consistently reproducible for each subject in each condition: standard errors

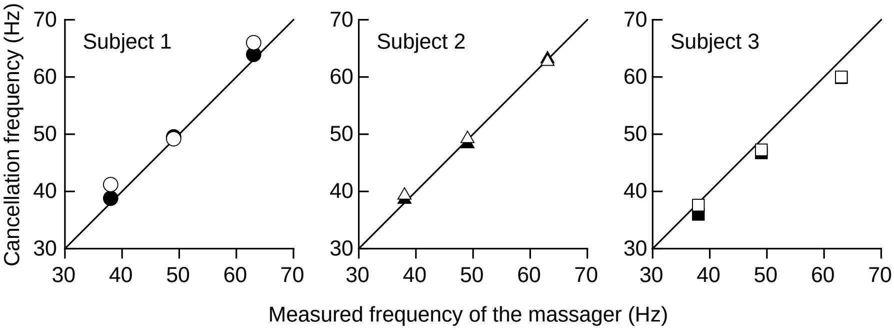

Fig. 2. Temporal frequency of eye vibration, as a function of the actual stand-alone frequency of vibration of the massager. Data collected at viewing distances of 2 and 4 m are, respectively, represented with open and solid symbols.

of the mean across trials in each session (which were taken without any major postural change) were always below 0.6 Hz and usually below 0.25 Hz.

### *3.2. Amplitude of eye vibration*

Fig. 3 shows the amplitude of eye vibration for each subject in each condition, as measured by the present method. These amplitudes were computed from the edge-to-edge distance between LEDs at the moment the subjects indicated apparent bouncing, using the relation

$$\alpha = 2\tan^{-1}\left(\frac{d_1}{2d_2}\right),$$

where $\alpha$ is the angular amplitude (in degrees of visual angle), $d_1$ is the measured edge-to-edge distance between the LEDs (in mm), and $d_2$ is the viewing distance (also in mm). Because the eye vibrates rotationally [15] nearly around its optical nodal point and our viewing distance is comparatively large, the angular amplitude of vibration should be unaffected by variations in viewing distance, all else being equal. The data in Fig. 3 indeed show small but significant variations with viewing distance (compare solid and open symbols at any given abscissa). Yet, the form of these variations is not systematic, neither across nor within subjects: solid symbols (for measurements at a viewing distance of 4 m) are not always above (or always below) open symbols (for measurements at a viewing distance of 2 m).

The unruly form of these variations suggests that they are due to actual inter-session variations in the vibration transmitted to the eyes: each of the data points in Fig. 3 was obtained in a different session, with inter-session intervals of variable length which resulted in changes of posture and relocation of the massager. On the other hand, the different trials within each session (in which the massager was applied without interruption and without postural changes) resulted in highly similar amplitude measurements as revealed by the small standard errors (always below 0.4 min of arc, and usually below 0.2 min of arc). The small intra-session variability argues in favor of the reliability of the method, and the inter-session variability—conceivably reflecting actual variations in the vibration of the eyes—argues in favor of its sensitivity to detect small variations in amplitude of vibration. This latter point is further corroborated by the report of Subject 2, who indicated that he applied the massager with additional pressure in the high-speed

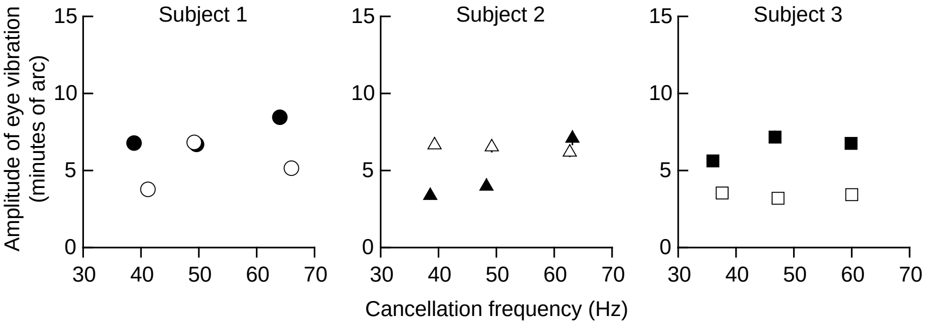

Fig. 3. Amplitude of eye vibration, as a function of the frequency of vibration. Data collected at viewing distances of 2 and 4 m are respectively represented with open and solid symbols.

condition at 4 m because otherwise he could not comfortably judge the point of apparent bouncing of the LEDs. His data in this condition (rightmost solid triangle in the middle panel of Fig. 3) reflect this fact in the form of a much larger amplitude of vibration than measured at lower speeds of the massager from the same viewing distance.

### 3.3. Frequency and amplitude determined by eye movement recordings

Sample recordings from two subjects at each of the three speeds of the massager are shown in Fig. 4, which illustrate that individual differences in the frequency of eye vibration are small compared to the much larger differences caused by the actual speed setting of the massager. For both subjects, the pattern of eye vibration is highly periodic and has a larger amplitude in the

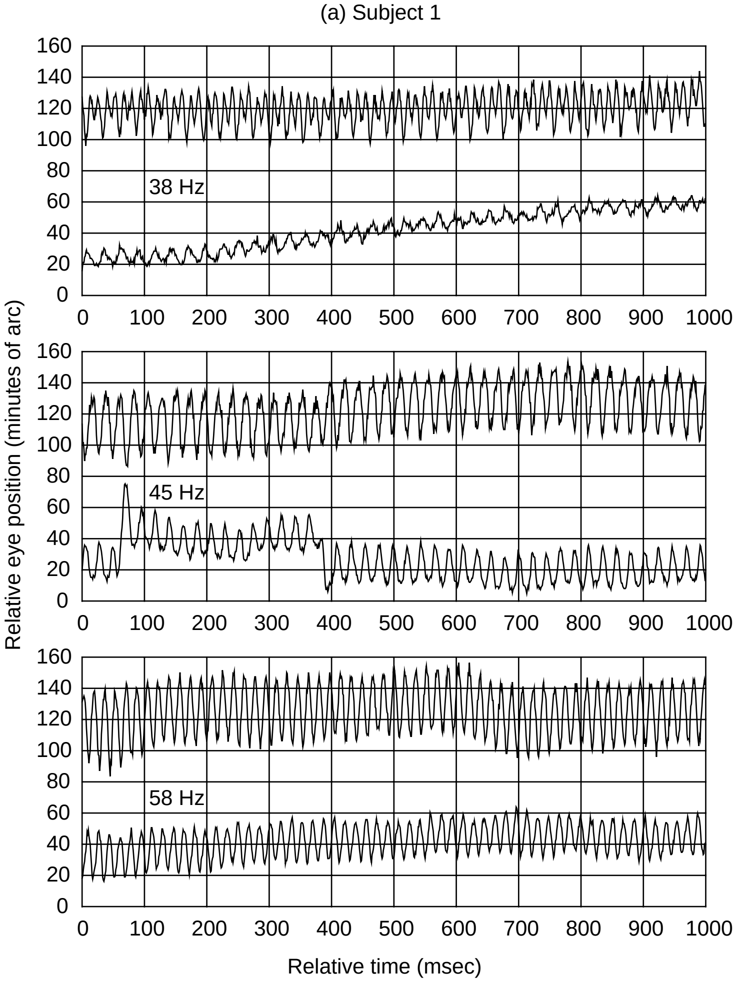

Fig. 4. Sample vertical (top trace in each panel) and horizontal (bottom trace) components of eye vibration, as measured with a Purkinje-image eye tracker. Top to bottom, the panels display recordings taken with the massager set at the lower, middle, and higher speeds.

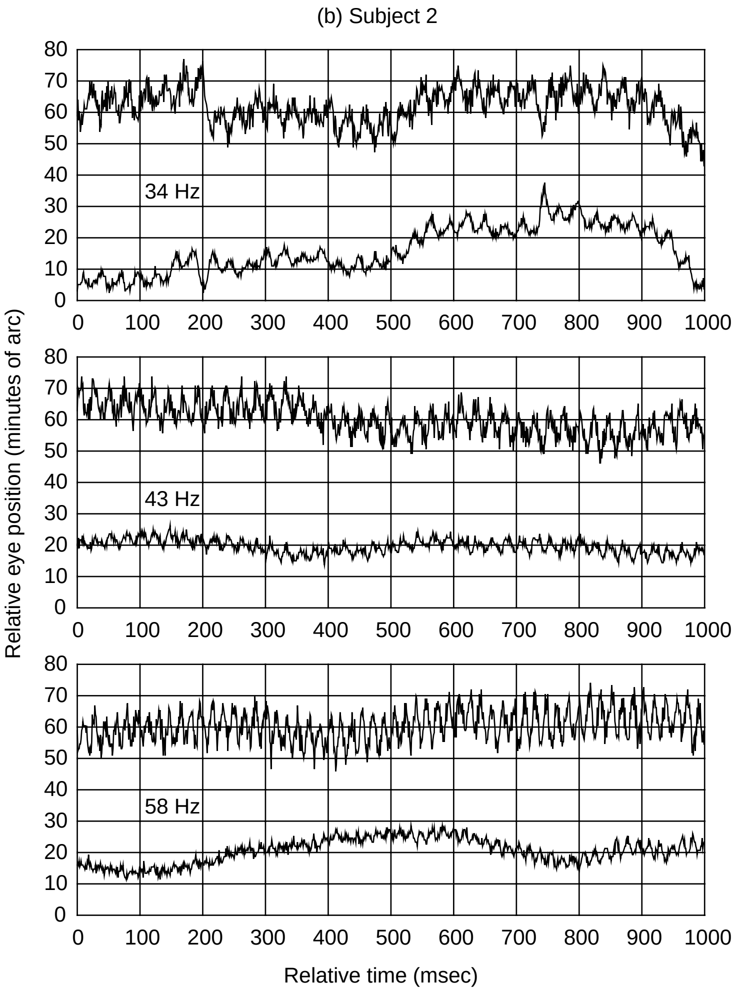

Fig. 4 (*continued*).

vertical direction (top traces in each panel) than in the horizontal direction, and this vibration rides on top of a low-frequency carrier reflecting eye drift caused by unstable fixation.

The actual frequency of vibration (determined by simply counting the cycles along each trace) is indicated in each panel of Fig. 4. These measured frequencies are generally lower than those determined with the cancellation method (compare with the values reported in Fig. 2), but this may simply reflect the different circumstances in either case: reproducible self-application of the massager without head restraint (in the cancellation method) versus application by the experimenter with head restraint and a different seating condition (in these measurements).

On the other hand, the (vertical) amplitudes of eye vibration are larger here (compare with the values reported in Fig. 3). Again, these differences may reasonably be attributed to the different circumstances under which either type of measurement was carried out: for these recordings, the experimenter had to apply the massager with some pressure in order to counter the dampening caused by the head-restraint system, whereas for the measurements in Fig. 3 the subjects self-applied the massager by simply letting it rest against their neck. Because of the different conditions involved, the recordings in Fig. 4 are not meant to provide an objective validation of the cancellation method but simply to illustrate that the massager induces eye vibration and not just head vibration, and that the frequency of eye vibration varies with the speed of the massager.

## 4. Conclusion

The cancellation method described here seems powerful for determining the frequency and amplitude of eye vibrations above 30 Hz, although the massager that was used to illustrate the workings of the method is not a good source for producing eye vibrations with specified parameters. Under the conditions of the measurements, data gathered in the same session (i.e., without postural changes) had little variability, whereas data gathered in different sessions (which involved postural changes and relocation of the massager) had more variability. This evidence of reliability and sensitivity seems to indicate that the method can provide accurate measurements of the frequency and amplitude of the eye vibration produced by vibration sources whose parameters can be accurately set and maintained within and across sessions. In addition, these measurements can be used to determine the relationship between eye vibration and head vibration as measured with accelerometers on bite bars, or between eye vibration and the parameters of the vibration source.

The reliability and sensitivity of the method along with its simplicity and wide applicability allows a more precise study of the effects of vibration upon visual performance by helping to determine the actual frequency and amplitude of eye vibrations, which may differ from the nominal values of these parameters when eye vibration is indirectly induced by whole-body vibration.

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## Appendix

The spatiotemporal output $g$ in the right panels of Fig. 1 was obtained from the input $f$ in the corresponding left panel through temporal convolution with the temporal impulse response (TIR)

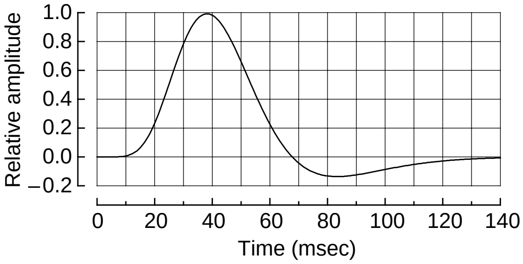

Fig. A.1. Shape of the TIR used to obtain the spatiotemporal output in the right panels of Fig. 1.

$h$ of the visual system, i.e.,

$$g(x,t)=\int_{-\infty}^{t} f(x,\tau)h(t-\tau)\,\mathrm{d}\tau.$$

A TIR similar to that in Ref. [16] was used, namely,

$$h(t)=\begin{cases}\dfrac{a(t/\tau_1)^{n_1-1}\exp(-t/\tau_1)}{\tau_1(n_1-1)!}-\dfrac{b(t/\tau_2)^{n_2-1}\exp(-t/\tau_2)}{\tau_2(n_2-1)!} & \text{if} \quad t>0,\\ 0 & \text{otherwise}\end{cases}$$

with $n_1 = 9$, $n_2 = 10$, $a = 1$, $b = 0.4$, $\tau_1 = 5\,\mathrm{ms}$ and $\tau_2 = 7\,\mathrm{ms}$ (see Fig. A.1). The convolution was carried out numerically by storing the visual input shown in the given left panel of Fig. 1 in a $300 \times 1000$ (row × column) array which thus samples space every 2.4 s of arc and samples time every 0.25 ms. To eliminate boundary effects, the input array was extended with a further 560 columns on the left which stored the stimulus as it would have been over the 140 ms preceding the time segment shown in the left panels of Fig. 1.

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