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RESEARCH NOTE

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Sigma smooth pursuit eye tracking: constant *k* values revisited

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Abstract Effective sigma tracking, i.e., apparent movement perception when slow eye movements are made across a stationary repetitive pattern under stroboscopic illumination, has been shown to be a function of the distance between sequential stimuli (P_s) and the flash frequency (f_s). The relationship between these factors and eye velocity (V_e) has been formally specified as $V_e = k\, P_s\, f_s$ [deg s^{-1}], where it has been argued that the value of k, which defines the rate limit for eye velocity, is normally 1, or exceptionally 2 or 3. However, theoretically the limitations on the maximum value for k are the maximum optimal pursuit speed for eye tracking (V_{max}) and the minimum values which P_s and f_s can assume while preserving target discrimination, and since the values for V_{max} are known to lie well beyond 20 deg/s and those for P_s and f_s well below 0.3 deg and 10 Hz respectively, it should be possible to demonstrate empirically that k can assume integer values considerably larger than the indicated maximum of 3. To test this prediction, three subjects performed seven series of five EOG-monitored trials producing sigma-pursuit, with values of k ranging from 1 to 7. All subjects evidenced smooth pursuit eye tracking for every condition and reported experiencing sigma-type apparent motion in 95% of the trials. The results confirm theoretical expectations and unequivocally demonstrate that sigma tracking can be readily effected under conditions where k significantly exceeds the maximal values previously reported, in conformity with theory.

Keywords Smooth pursuit eye tracking · Efference copy · Sigma movement

Introduction

Behrens and Grüsser (1979) described and formalized the sigma paradigm (σ-paradigm) as follows:

Stationary periodic visual patterns (row of equally spaced dots or black-white stripes) of the period P_s illuminated stroboscopically with a flash frequency f_s induce an apparent movement perception (σ-movement) when slow eye movements are performed across the periodic pattern. The movement appears in the direction of the eye movements when the angular speed V_e of the eyes corresponds to the following condition:

$$V_e = k\, P_s\, f_s \text{ [deg s}^{-1}\text{]} \qquad (1)$$

(p. 317).

Behrens and Grüsser's (1979) Eq. 1 has become the standard reference for defining σ-velocities (Behrens and Grüsser 1979; Collewijn et al. 1981; Curio and Grüsser 1985; Grüsser 1986). The issue which motivates the present note is the statement made by Behrens and Grüsser regarding the value range of the factor k representing the rate limit in the formula, namely that: "K is a constant and equals 1 (or exceptionally 2 or 3)" (p. 317). Although this statement reflects the results obtained in their experiment, we contend that within the range of values P_s and f_s can assume that will preserve target discrimination, the only limitation on the maximum value of the integer k is the maximum optimal smooth pursuit speed for eye tracking, i.e., approximately 40 deg/s (subsequently referred to as V_{max}). Formally expressed, $k_{max} = V_{max}\, P_s^{-1}\, f_s^{-1}$. Schalén (1980) showed that, up to speeds of about 40 deg/s, the maximum velocity gain of smooth pursuit (i.e., maximum velocity of smooth pursuit / target velocity) is close to 1, and the total tracking consists mostly of smooth pursuit eye movements. Superimposed saccades of more than 10 deg, however, start occurring signifi-

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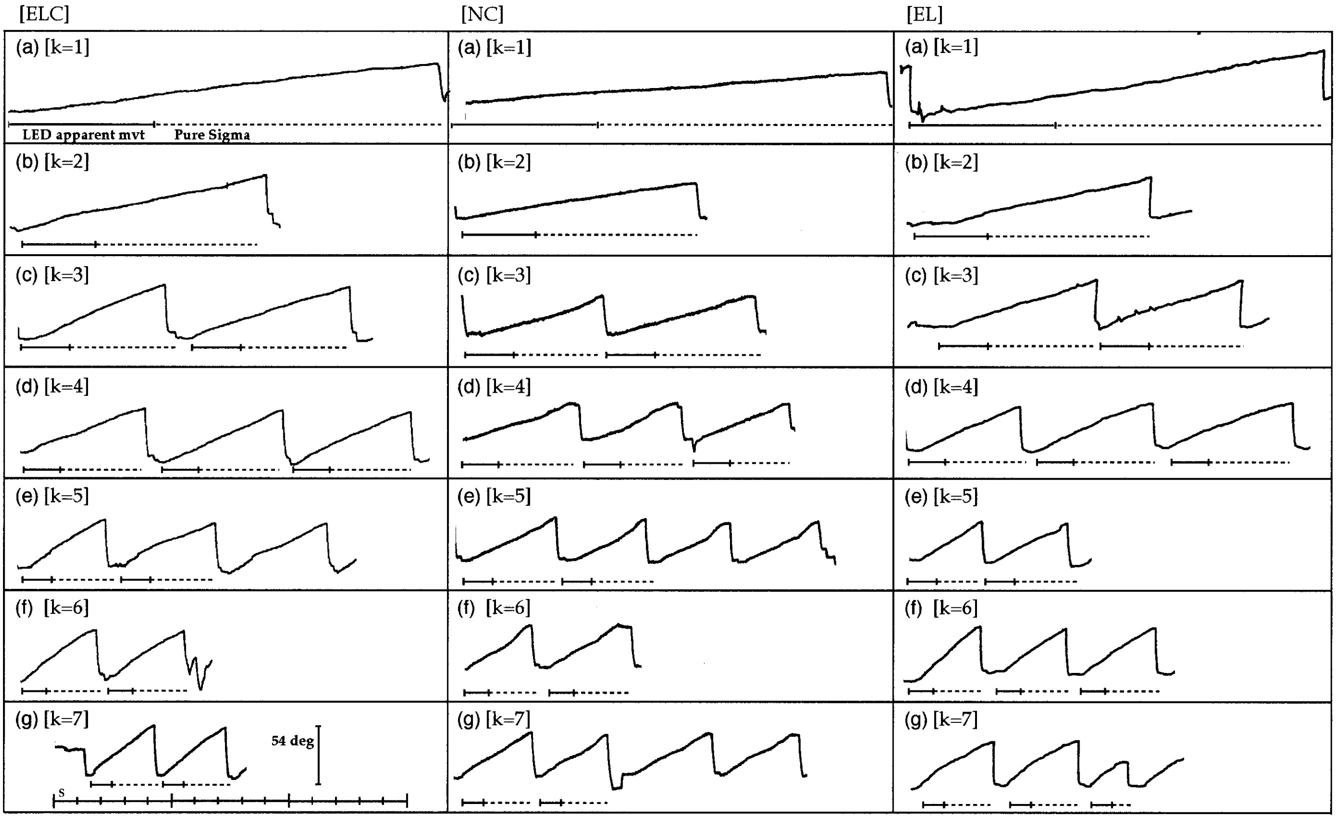

Fig. 1 Sample EOG recordings of horizontal eye movements made while subjects ELC, NC, and EL were performing sigma-eye-tracking from left to right over a horizontal row of 200 dots, under a 10-Hz stroboscopic illumination, and using β apparent motion (of LEDs occupying the center of the first 64 dots) as initiating stimulus. In conditions *(a)–(g)*, the β apparent motion was set, respectively, at speeds of 2.9 (k=1), 5.8 (k=2), 8.7 (k=3), 11.6 (k=4), 14.5 (k=5), 17.4 (k=6), and 20.3 (k=7) deg/s

cantly more frequently at velocities greater than 30 deg/s. Therefore, with very conservative values of 20 deg/s for V_{max}, 0.3 deg for P_s and 10 Hz for f_s it should be possible to demonstrate that k can assume integer values considerably larger than the indicated maximum of 3. The purpose of this report is to provide empirical data in support of this argument.

Materials and methods

Three healthy male subjects (aged 18, 22 and 47 years) with normal or corrected to normal vision participated in this investigation. All were familiar with sigma pursuit. Following the application of electrodes for eye movement (EOG) recordings (silver-silver chloride electrodes placed near the outer canthus of each eye and above and below one eye), subjects were seated facing the center of a rectangular white board 1 m away with their heads immobilized by means of a chin rest/bite bar. The board subtended visual angles of 54×35 deg (1.015×0.64 m) and presented a horizontal row of 200 dots [each 0.14 deg (2.5 mm) diameter] 0.29 deg apart (5 mm). The board was curved to maintain the stimulus dot pattern at a uniform distance (1 m) from the observer. A light emitting diode (LED) was positioned in the center of each of the first 64 dots in the row (approximately the first third of the row). The EOG signals were dc-coupled (Princeton Applied Research Model 113 preamplifier) and recorded on paper (Grass Model 78D polygraph) and magnetic tape (Hewlett-Packard 8868A recorder) for offline analysis.

Since the object of these studies was to convincingly demonstrate that k_{max} values greater than 3 were not exceptional, V_{max}, P_s and f_s values which yielded k_{max} values up to 7 were studied (i.e., V_{max} of 20 deg/s, and P_s and f_s values of 0.3 deg and 10 Hz, respectively, yielding a k_{max} of 7=(20 degs/s×0.3 deg^{-1}×10 Hz^{-1}).

After verifying normal tracking ability by having subjects track the β apparent motion of the brief successive flashes of the LEDs (set at 50 ms intervals), subjects were asked to perform seven series of sigma pursuit (five trials/series) by tracking the row of dots from left to right using the LED-based β apparent motion as the initiating stimulus. The flash rate for dot illumination was set at 10 Hz throughout the experiment. What varied from one series to the next was the rate of the initiating LED-based β apparent motion. For the first series of five trials, the LED-based β apparent motion was set at 10 LEDs flashing in succession per second; for the second series it was set at 20 LEDs flashing in succession per second, i.e., twice the basic critical speed; in the third series β apparent motion was set at 3 times the critical speed (30 LEDs flashing in succession per second); and so on until the seventh series of trials where the LED-based β apparent motion was set at 7 times the basic critical speed.

Results

From the first series (k=1, basic critical speed) to the seventh (k=7, 7 times the basic critical speed), the recorded smooth pursuit eye tracking speeds varied from approximately 3 deg/s to 24 deg/s. All three subjects evidenced smooth pursuit eye tracking for every condition (Fig. 1) and reported experiencing sigma-type apparent motion of the row of dots in 95% of the trials (100/105).

Discussion

The results unequivocally demonstrate that sigma tracking can be readily and reliably effected under conditions where the value of k significantly exceeds the indicated maximal values previously reported, i.e., 2 or 3 (Behrens and Grüsser 1979). The demonstration that sigma tracking convincingly occurs under these conditions supports the theoretical prediction that the upper limit for the constant k is determined by the maximum eye-velocity for smooth pursuit tracking and the minimum values which P_s and f_s can assume while preserving target discrimination. These findings suggest further that by using theoretically based combinations of V_{max}, P_s and f_s values, sigma tracking at k_{max} values greater than the maximum tested in this study can be obtained.

References

Behrens F, Grüsser OJ (1979) Smooth pursuit eye movements and optokinetic nystagmus elicited by intermittently illuminated stationary patterns. Exp Brain Res 37:317–336

Collewijn H, Curio G, Grüsser OJ (1981) Interaction of the vestibulo-ocular reflex and sigma-optokinetic nystagmus in man. In: Fuchs, Becker (eds) Progress in oculomotor research. Elsevier, North Holland, pp 567–576

Curio G, Grüsser OJ (1985) Visual-vestibular interaction studied with stroboscopically illuminated visual patterns. Exp Brain Res 58:294–304

Grüsser OJ (1986) The effect of gaze motor signals and spatially directed attention on eye movements and visual perception. Progr Brain Res 64:391–404

Schalén L (1980) Quantification of tracking eye movements in normal subjects. Acta Otolaryngol 90:404–413