Dependence of the amplitude of fusional convergence movements on the velocity of the eliciting stimulus

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Foveal stimuli were used to elicit fusional convergence movements of the left eye in 5 subjects with normal binocular vision. The amplitude of fusional convergence was measured by recording eye position. The eyes were light adapted, and the stimulus to the left eye was driven at angular velocities ranging from 1/8 to 6 degrees per second. Although large individual differences were found in the maximum amplitude of fusional convergence, this maximum was elicited in all subjects with velocities of less than 1 degree per second. As the angular velocity of the stimulus increases, the amplitude of fusional convergence first rises abruptly and then descends. The range of approximately 10 to 1 between the lower and upper velocity values which give rise to 75 per cent maximum fusional convergence probably accounts for why the velocity of eliciting fusional convergence is not crucial in determining the clinical result.

The amplitude of fusional vergence movements* of the eyes is measured routinely during every thorough ophthalmological examination. It has long been observed clinically that the maximum amplitude of movement is qualitatively dependent on the velocity with which one attempts to elicit the movement. It is generally believed that if a prism of large dioptric power is suddenly applied to one eye, then the maximum amplitude of fusion movement will not be achieved. For this reason the amplitude is generally measured either by a prism of continuously variable strength, such as the Risley rotary prism, or by a method which increases the prism strength by discrete, relatively small, steps such as the Berens prism bar. Hofmann and Bielschowsky measured the amplitude of fusional movements in a haploscope. Bielschowsky, commenting on these experiments, states that fusional movements "develop very gradually." Thus, it would be anticipated that increasing the prism power too rapidly, whether by rotary prism, prism bar or haploscope, would result in a lowered measured amplitude of fusional vergence.

The present paper is concerned with the manner in which the amplitude of fusional convergence varies as the velocity of the stimulus eliciting such fusional vergence is altered.

In this investigation the fusion move-
Fig. 1. Targets subtend 6 minutes by 25 minutes of arc at the nodal point of the eye. The white central dot is fixated by the right eye.

Table I. Corrected visual acuity and value of spherical lens placed 3 cm. in front of eye in the apparatus

<table>
<thead>
<tr>
<th>Subject</th>
<th>O. D.</th>
<th>O. S.</th>
</tr>
</thead>
<tbody>
<tr>
<td>V. A.</td>
<td>Lens</td>
<td>V. A.</td>
</tr>
<tr>
<td>1</td>
<td>20/20</td>
<td>None</td>
</tr>
<tr>
<td>2</td>
<td>20/28</td>
<td>None</td>
</tr>
<tr>
<td>3</td>
<td>20/25</td>
<td>-8.00</td>
</tr>
<tr>
<td>4</td>
<td>20/17</td>
<td>-0.12</td>
</tr>
<tr>
<td>5</td>
<td>20/16</td>
<td>None</td>
</tr>
</tbody>
</table>

ment of convergence is elicited at angular velocities in the range of 1/8 degree of arc per second to 6 degrees of arc per second while the resulting eye movement is recorded.*

Apparatus and methods

The apparatus has been described previously in detail.8, 9

In a modified haploscope the right eye views a stationary stimulus via a front-surface mirror, while the left eye views a similar stimulus directly. The stimulus to the left eye is driven in an arc at various angular velocities.

By the use of suitably regulated light and voltage sources, a photomultiplier cell, amplification, and recorder, the position of the left eye is continuously known. A small, approximately rectangular, spot of light is focused on the boundary of the iris and the sclera. The amount of light nonspecularly reflected to the photocell is used as a measure of the position of the left eye. The observation distance for both eyes is 1.1 M.

Fig. 1 illustrates the type of target used to elicit fusional convergence of the left eye. The centers of both rectangles are fixated by the fovea of each eye. The right eye fixates the stationary white dot. Viewing the targets binocularly, the normal subject sees a horizontal black line and a single black rectangle with a central white dot. The rectangles subtend 6 minutes by 25 minutes of arc at the nodal point of the eye.*

Procedure

With the right eye near its primary position, the subject, who is light adapted, fixates the foveal target. Binocular vision is prevented when the left target is obscured by a blank, white card. The left eye now assumes its "position of rest" or "fusion free" position. It is at this "fusion free" position that the left target is revealed before the fusional convergence movement is elicited. With the right target held stationary, the left target is driven to the right at a previously selected rate.1

Subject 1 is a trained observer. The other 4 subjects are naive, paid observers. Spherical lenses are placed 3 cm. in front of the eye. Table I shows the visual acuity with correction, as well as the values of the lenses used in the apparatus.

In preliminary experimentation a range of velocities is tested on each subject and then 5 discrete velocities are chosen to elicit the range of the phenomenon for each subject. A total of 10 observations at each velocity is obtained on each subject.

In each experimental session, a series of five records is taken on one subject. There is at least a 5 minute rest between each record, and a minimal rest of half an hour between each series. A series of increasing velocities is alternated with one of decreasing velocities. A maximum of two series per day is taken on any one subject.

Two calibrations are taken on each record, one before and one after the stimulus to the left eye is presented. The method of converting millimeters of pen excursion to degrees of eye movement is substantially similar to that previously reported.8 A base line is determined by averaging 5 points at time intervals of 0.04 second. These points are read just before the start of the target drive. The maximum fusional convergence is taken as the highest point above the base line just

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*These speeds are considerably greater than those at which vertical fusion movements are elicited. Ellerbrock8 found that the amplitude of vertical fusion movements was diminished by velocities as low as 0.5 degree per second.

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9Since Subject 3 was unable to see the small white fixation dot clearly, he was presented with rectangles subtending 25 by 50 minutes of arc with a correspondingly larger white fixation dot.

10Under these conditions there is little or no movement of the right eye.11
Fusional convergence movements

Fig. 2. Top, record of the left eye position as the left foveal target is driven at 1 degree per second. The arrow on the right indicates the maximum fusional convergence, and the negative slope indicates that the eye is returning to its “position of rest.” Note that blinking, during the early course of the movement, has not interrupted the subsequently smooth fusional movement. Bottom, record of the left eye position as the left foveal target is driven at 6 degrees per second. The Y-axis scale is about five times greater than that in the top record.

Fig. 3. Circles represent the means of ten observations. The height between each pair of bars represents two standard errors of the associated mean. Smooth curves represent \( \theta = \alpha v^b e^{\alpha v} \) fitted by the method of least squares.
Fig. 4. Circles represent the means of ten observations. The height between each pair of bars represents two standard errors of the associated mean. Smooth curves represent \( \theta = a v^b e^{-kv} \) fitted by the method of least squares.

A record was discarded if a head shift caused a significant difference between the two calibrations. A record was also discarded if immediately following a blink, the eye abandoned the fusional convergence movement and returned toward its "position of rest." This chiefly occurs on records taken at very low velocities. Hence, the amplitude of fusional vergence taken at these low rates may be overestimated.

The upper chart in Fig. 2 shows a typical record for Subject 1. The left target is driven at 1 degree per second. The arrow on the left indicates the start of the target drive. The arrow on the right indicates the maximum fusional convergence. The subsequent negative slope indicates the return of the left eye toward its "position of rest." It may be seen that blinking during the early course of the fusional convergence movement has no apparent effect on the resumption of binocular vision.

The lower chart in Fig. 2 shows the relatively small amplitude of fusional convergence elicited on the same subject when the left foveal target is driven at 6 degrees per second. For this subject the average fusional convergence elicited at this angular velocity is 2.5 degrees.

Results and comment

The circles in Figs. 3 and 4 indicate the average maximum fusional convergence as a function of the velocity of the eliciting stimulus. The smooth curves were fitted to the data by the method of least squares to the semiempirical function

\[ \theta = a v^b e^{-kv} \]  

where \( \theta \) is in degrees, \( v \) is the angular velocity of the stimulus in degrees per second, and \( a, b, \) and \( k \) are parameters. \( \theta \) is maximal when \( v \) equals \( b/k \).

Figs. 3 and 4 show that there are large individual differences in the amount of fusional convergence which can be elicited even when the optimum velocity of stimulus is used for each individual. That such individual differences occur, when approximately the same velocity of stimulus is used for each individual, has long been observed clinically.

The velocity which elicits the maximum fusional convergence also varies from one subject to another. In Table II the value of \( v \) for which \( \theta \) is maximal is given in column \( b/k \). This is seen to be 0.83 degree per second for Subject 1 and 0.17 degree per second for Subject 5, a range of more than 4 to 1. It thus appears, that as with conjugate pursuit movements, there are
individuals who are "velocity resistant" and those who are "velocity susceptible". A "velocity susceptible" individual will have a relatively large value of the k parameter.

Table II also shows the angular velocities at which the fusional convergence has decreased to 75 per cent of its maximum value. Here again a range of individual differences of 4 to 1 may be seen, but in ordinary clinical practice the value of 0.6 degree per second or 1 prism diopter per second is probably not commonly exceeded which accounts for the clinical efficiency of the method as far as comparing individuals is concerned. The range of approximately 10 to 1 between the lower and upper v values which gives rise to 75 per cent maximum fusional convergence accounts for the fact that the velocity of eliciting fusional convergence is not crucial in determining the clinical result. It appears that the maximum fusional convergence is achieved with all subjects with velocities of less than 1 degree per second. This value is to be contrasted with velocities of 500 degrees per second obtainable with conjugate deviation, and 20 degrees per second obtainable by means of the accommodation, convergence, miosis synkinesis.

Discussion

It can be seen that the maximum amplitude of fusional convergence first increases with the velocity of the stimulus and then decreases. This is true for every subject. The fusional convergence appears to approach zero as the velocity of the stimulus becomes large.

It seems likely that changes in fusional convergence usually compensate for relatively small and slowly developing changes in the tonus of the extraocular muscles, or changes elsewhere in the system for binocular fixation. The experimental data presented here indicate that the fusional vergence mechanism is quite adequate to compensate for such slow changes.

With voluntary movements, the eye can achieve velocities as high as 500 degrees per second for large movements, and the average speed for small movements may be taken as between 100 degrees per second and 200 degrees per second, while the maximum rate for fusional movements is only about 6 degrees per second. The explanation of this difference may be given by Verhoeff, who says, "In the ocular muscles there are certain fibers that much more closely resemble smooth muscle than do the others." It seems to me probable that duction is carried out by means of these fibers, for the relative slowness, limited range and persistence of duction are characteristic of smooth muscle.

The fusional vergence mechanism does not appreciably compensate for stimulus motions at relatively slow rates such as 6 degrees per second. Within 0.2 second the stimulus to the left eye will have moved 1.2 degrees from the fovea. The fusional convergence power declines rapidly as the stimulus to fusion is presented to more and more peripheral retinal regions. Hence, the stimulus may have "escaped" from the control of the fusional vergence mechanism. This situation differs in at least two ways from the well-known "jump" acquisition of fusional vergence when a prism is suddenly introduced before one eye. In

<table>
<thead>
<tr>
<th>Subject</th>
<th>a</th>
<th>b</th>
<th>k</th>
<th>b/k</th>
<th>Maximum θ (in degrees)</th>
<th>Range of v values for 75% maximum θ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.85</td>
<td>0.34</td>
<td>0.41</td>
<td>0.83</td>
<td>12.57</td>
<td>0.16 to 2.41</td>
</tr>
<tr>
<td>2</td>
<td>21.81</td>
<td>0.24</td>
<td>0.58</td>
<td>0.42</td>
<td>13.81</td>
<td>0.05 to 1.43</td>
</tr>
<tr>
<td>3</td>
<td>32.64</td>
<td>0.58</td>
<td>1.14</td>
<td>0.51</td>
<td>12.36</td>
<td>0.15 to 1.19</td>
</tr>
<tr>
<td>4</td>
<td>8.85</td>
<td>0.32</td>
<td>1.32</td>
<td>0.24</td>
<td>4.10</td>
<td>0.04 to 0.72</td>
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<td>0.23</td>
<td>1.34</td>
<td>0.17</td>
<td>6.24</td>
<td>0.02 to 0.60</td>
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</table>
the present experiments the disparateness is gradually introduced, and there is a fixation dot before the right eye which prevents the preliminary conjugate saccadic movement described by Alpern.21 "... because of the slow speed . . . decreasing velocity, and involuntary nature of this type of corrective movement, it appears that the innervation arises from the space-representation region and the eyes are controlled by retinal feedback."22 In the present experiments the eye is subjected to a unit-velocity step stimulus. Here too, there must be cortical innervation and exteroceptive feedback.

The hypothesis has been advanced that "the ocular movements of fixation and pursuit are controlled to a substantial extent by parametric feedback from the extraocular muscles."22-24 It appears likely that the fusional vergence movements are mediated by exteroceptive feedback.

REFERENCES