The Latency of Saccades, Vergence, and Combined Eye Movements in Children and in Adults

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PURPOSE. To examine the latency of eye movements in three-dimensional space (saccade, vergence, and combined saccade–vergence) in children and adults.

METHODS. Fifteen normal children (4.5–12 years of age) and 15 normal adults (22–44 years of age) were tested. A standard paradigm was used to elicit pure lateral saccades at far and close viewing distance, pure vergence (convergence and divergence), and saccade combined with vergence movements. Horizontal eye movements from both eyes were recorded simultaneously by the oculometer, a photoelectric device.

RESULTS. The mean latency in saccades, vergence, and combined eye movements was longer in children than in adults; the variability of such latency values was also larger in children. There was a progressive decrease with age in mean latency. All latencies approached or reached adult levels at approximately 10 to 12 years of age. Latency of saccades at close viewing distance was shorter than that at far in both adults and children. Convergence latency was longer than divergence latency in adults and most of the children. Latency of components of combined movements was longer than that of corresponding pure movements. Children initiated combined movements by triggering the vergence component first, whereas adults did not show a dominant pattern. The percentage of synchronous start of the two components was significantly higher in adults.

CONCLUSIONS. Saccade- and vergence-triggering mechanisms are distinct and mature progressively and in parallel with age. The capacity for synchronization of the two components of combined eye movements develops more slowly and remains below adult level, even at the age of 12 years. (Invest Ophthalmol Vis Sci. 2002;43:2939–2949)

Saccades are the fast movements used to change fixation rapidly. They are conjugate movements—that is, the eyes move equally and in the same direction. In laboratory conditions, after a step change in target position, the adult human central nervous system responds with a saccade after a latency of approximately 200 to 250 ms. Several processes are believed to take place during the latency period, such as shift of visual attention to the new target, disengagement of oculomotor fixation, and computation of the metrics of the movement. Each of these processes involves activation of a large circuit of cortical areas, including the parietal cortex and the frontal lobe (for a review see Leigh and Zee5). Thus, latency of eye movements is a cognitive–physiological parameter. In the past few years, an increased number of studies have examined saccade latency in relation to cognitive development in children (e.g., Cohen and Ross6,7 Fischer et al.,4 Fukushima et al.,5 Munoz et al.,8 and Ross et al.10). These studies showed that latency of visually guided saccades in children are longer than in adults, and the latency shortens progressively with age. The eventual effect of the viewing distance on the latency of saccades is unknown in both children and adults. Many everyday activities, such as reading, take place at near, and it would be interesting to know whether saccade latencies are different. Perhaps the preparation state necessary to initiate a saccade depends on the distance at which the eyes verge.

Vergence eye movements are necessary to change fixation from a far to a close target, or vice versa. These movements are disconjugate (in opposite direction in the two eyes) and are executed slowly.1 In contrast, latency of vergence eye movements is short (approximately 160–180 ms) in normal adults—shorter than saccade latency (see review by Schor and Ciufreda15). However, these latencies are based on results in a few studies only and on a limited number of subjects. In addition, the few existing studies examining difference in latency between convergence and divergence have provided contradictory results. Krishnan et al.9 found longer latency for convergence than divergence, with the latter showing greater variability. In contrast, Semmlow and Wetzel10 and Hung et al.11 found a shorter latency for convergence than for divergence, with relatively small variability among subjects. The difference between convergence and divergence latencies was on the order of 20 ms in both studies. To our knowledge, there are no studies on latency of vergence eye movements in children or the eventual difference in latency between convergence and divergence.

The natural movements made in looking successfully at different objects in three-dimensional (3-D) space normally involve components of both vergence and saccades. Several studies have suggested that the two oculomotor subsystems, that of saccades and that of vergence, exhibit markedly contrasting dynamic characteristics, such as speed and duration—for example, saccades are fast, high-velocity movements, whereas vergence is slow. In contrast, vergence during combined movements is faster and can resemble saccades more, presumably because of an acceleration of the vergence by the saccade (see Erkelsens et al.,12 Colliewijn et al.,13 Chaturvedi and Van Gisbergen,15 and Hung16). Our interest in the present study was in the latency of combined eye movements. Combined eye movements in adults have been found to have longer latency than pure eye movements. This is, however, based again on a single report (see Takagi et al.17), in which only three subjects were studied, and needs further support. Com-
bined movements bring general important questions to cognitive neuroscience concerning the parallel sensory processing of direction and depth information and the control of the saccade and vergence oculomotor subsystems.

The first main goal of the present study was to investigate the difference in latency between children and adults, not only for saccades but also for vergence eye movements. The second was to study the effect of viewing distance on the latency of saccades in both children and adults. The third was to investigate further the difference in latency between convergence and divergence in children versus adults. The fourth was to investigate latencies of combined movements relative to those of corresponding pure movements in both children and adults.

METHODS

Subjects

Fifteen children and 15 adults participated in the present experiment. The children’s ages ranged from 4.5 to 12 years (mean, 7.7 ± 2.7), and the adult’s ages ranged from 22 to 44 years (mean, 29.6 ± 7.1). All children had normal vision and none of them wore spectacles. Adult subjects were emmetropes, except S1 who was a myope (−2.5 D in both eyes) and performed the experiment without his glasses (limitation imposed by our recording apparatus). No subjects showed visual, neurologic, or psychiatric disorders or received medication. All subjects had normal motility and normal ocular alignment. Binocular vision was assessed with the TNO test of stereoaucuity. All individual scores were normal, 60 minutes of arc or better. The investigation adhered to the tenets of the Declaration of Helsinki and was approved by the institutional human experimentation committee. Informed consent was obtained from adults and the children’s parents after the nature of the procedure had been explained.

The experimental task was explained to the subjects and to the children’s parents before the experiments. Subjects were requested to move their eyes to the LEDs as soon as possible after the target appearance, but not before. The very young children (4.5–7 years) were held by the father or mother to keep them calm and focused on the experimental task. When their attention was noted to shift, they were encouraged to concentrate on the task, (e.g., jumping light targets). There were breaks between blocks of trials to maintain alertness. When they complained of fatigue, the experiment was stopped and was attempted on another day.

Eye-Movement Recording

A computer directed the visual stimulation. Data collection was directed by REX software (provided online at http://www.tchain.com by Timothy C. Hain, Northwestern University Medical School, Chicago, IL), which was developed for real-time experiments and run on a computer. Horizontal movements from both eyes were recorded simultaneously with a photoelectric device, the Dr. Bouis oculometer (Karlsruhe, Germany). This system has a resolution of 1 to 5 minutes of arc and a linear range of ±20°. There is no obstruction of the visual field with this recording system (see Bach et al.18). Eye-position signals were digitized with a 12-bit analog-to-digital converter, and each channel was sampled at 500 Hz.

Visual Display

The visual display used consisted of LEDs placed at two isovergence circles: one at 20 cm from the subject, and the other at 150 cm. On the near circle, three LEDs were used: one at the center and two at 20°. The required mean vergence angle for fixating any of these three LEDs was 17°. On the far circle, five LEDs were placed: one at the center, two at ±10°, and two at ±20°. Fixation on any of these LEDs required a vergence angle of 2.5°.

Oculomotor Procedure

In a dark room, the subject was seated in an adapted chair with a head and chin support. The subject viewed binocularly and faced the 3-D visual display of the LEDs. The distance between the subject and the far isovergence surface was 20 cm. The visual display of the LEDs was placed at eye level to avoid vertical eye movements.

Calibration Task. The subject made a sequence of saccades to an LED target jumping from 0° to ±10° or 0° ± 20° at the far isovergence surface. During each of these trials, the target remained at each location for 2 seconds. The subject was instructed to fixate the LED as accurately as possible. The LED presentation was sufficiently long to allow accurate and stable fixation. The calibration factors were extracted from these recordings.

Main Oculomotor Task: Saccade–Vergence Combined Movements. Each trial started with the lighting of a fixation LED at the center of one of the circles (far or close). After a 2.5-second fixation period the central LED was turned off and a target-LED appeared for 2 seconds. When the target-LED was on the center of the other circle, it called for a pure vergence eye movement, along the median plane. When it was at the same circle, it called for a pure saccade (leftward or rightward); and, when it was lateral and on the other circle, the required eye movement was a combined saccade and vergence eye movement (see Fig. 1). Note that our use of saccades, both at close and at far distance allowed us to maintain the randomness of direction and depth in all trials. All target LEDs for saccades were at 20°. All targets along the median plane required a change in ocular vergence of 15°. Similarly, combined movements required a saccade of 20° and a vergence of 15°. In each block, the three types of eye movements were interleaved randomly. Each block contained 24 trials: four saccades at far, four saccades at close, four convergences, four divergences, four combined convergent movements, and four combined divergent movements. For most of the subjects (children or adults), four blocks were run, separated by a rest of few minutes. Calibrations were repeated at the beginning of each block.

Data Analysis

Calibration factors for each eye were extracted from the saccades recorded in the calibration task. A linear function was used to fit the calibration data. From the two individual calibrated eye position signals, we derived the vergence signal, left eye - right eye, and the conjugate signal (left eye + right eye)/2. Fig. 2 shows an example of pure saccade (A), pure convergence (B), combined convergent movement (C), and combined divergent movement (D). For each type of movement, the saccadic or conjugate component and the vergence or disconjugate component is shown. The onset of a pure saccade or of the saccadic component of the combined movements was defined as the time when eye velocity exceeded 5% of saccadic peak velocity. The offset when eye velocity dropped below 10°/sec. The onset and the
offset of the vergence signals (for pure vergence movement and for the vergence component of the combined movements) were defined as the time point when the eye velocity exceeded or dropped below 5°/sec. The placement of the markers by the computer was verified by one of the investigators scrutinizing saccade and vergence components on the screen. Eye movements in the wrong direction, movements with latency less than 100 ms or more than 1000 ms or movements contaminated by blinks were rejected. These criteria are standard and have been used by others (see Fukushima et al.5 and Munoz et al.6). In younger children (<8 years), results of approximately 20% of the trials were rejected, and in older children and adults, 6% of trials were rejected, according to these criteria. Analysis of variance (ANOVA) was performed to analyze the difference in latency between any two different types of eye movements in the adult and child groups. For measures expressed in the percentages, ANOVA was applied after normalizing the percentages with the formula: \( y = 2 \arcsin(\sqrt{p}) \), where \( p \) is the percentage (see initiation of combined movements in the Results section). Because the variance of latency in the children was greater than in the adults, the nonparametric Kruskal-Wallis test was used to compare the difference in latency between adults and children. We also used the Bravais-Pearson test to examine the correlation coefficient between the mean latency and its variability.

FIGURE 2. Typical recordings of the three types of eye movements studied. Recordings from child IS, 10 years old. The saccade signal is obtained by averaging the position signal at the two eyes: (LE + RE)/2; the vergence signal is the difference between the two signals (LE - RE). The target LED appeared at time 0. Arrows: onset of each movement; dotted lines: location of the target. For combined movements, the lateral eccentricity and the depth or vergence component of the target are indicated. Note that the pure saccade is accompanied by a transient disconjugacy of convergence and divergence (A). A small saccade component occurs during the pure convergence (B). The vergence component of the combined convergent movement starts before the saccade (C). The vergence component of the combined divergent movement starts after the saccade (D).
RESULTS

In our results, for all types of eye movements there was a positive correlation between the latency and the variability of its length. The correlation coefficient ($r$, Bravais-Pearson test) between mean latency and the SD for the different types of eye movements ranged between 0.57 and 0.93 in the children and between 0.53 and 0.84 in the adults. All these values were statistically significant at $P < 0.05$. The correlation coefficients applied to all subjects (children and adults) for the different types of eye movements were also significant ($r = 0.68 - 0.93$, all $P < 0.05$). Furthermore, the SD of latency was, on average, 32% of the mean in the children, whereas in the adults, it was only 19%. In the following sections, we present in detail the results on mean latency. The results on variability will also be shortly presented and discussed.

Pure Movements

Saccade Versus Vergence. Figure 3 presents the individual and the group mean latencies together with SEs for pure saccades and pure vergence in children (A) and adults (B). Leftward and rightward saccades at far or at close. Vergence includes pure convergence and divergence along the median plane. Vertical bars: SE. Group means are based on 15 subjects. Statistically significant difference in latency between saccade and vergence.

Viewing Distance. Further analysis examined the effect of viewing distance on the latency of pure saccades and pure vergence. Figure 4 shows the latency for saccade at far (150 cm) and at close (20 cm) viewing in children (A) and adults (B). In most of the subjects (except one child and four adults), the latency for saccades at close was shorter than that for saccade at far. ANOVA with subjects as the random factor and far versus close as the fixed factor revealed that such a difference was significant in both the children ($F_{1,14} = 6.58, P < 0.05$, Fig. 4A) and adults ($F_{1,14} = 6.70, P < 0.05$, Fig. 4B). Thus, saccade latency was shorter at close distance by approximately 20 ms in both children and adults.

For vergence movements (Fig. 5), the far–close viewing distance aspect corresponded to the comparison of conver-
Latency of Saccades, Vergence, and Combined Eye Movements

Combined Eye Movements

Latency of Combined Movements

The question addressed was to what extent the latencies of saccade and vergence components of combined movements are longer than those of corresponding pure movements. There is some evidence for such prolongation in the results of the study of three adults reported by Takagi et al., but the consistency of such prolongation in the adult population is not known, nor is it known whether it also exists in children.

Similar to the results for pure eye movements, latencies of both components of combined eye movements were longer in the children than in the adults (nonparametric Kruskal-Wallis test $H = 5.89 - 13.47$; all comparisons were significant at $P < 0.05$).

Because the latency of saccades depends on the viewing distance (saccades at close have a shorter latency than saccades at far), we compared saccadic components of combined movements with pure saccades starting from the same initial position (i.e., saccades at far, and saccadic components of combined divergent movements were compared with pure saccades at close). In addition, vergence components of combined movements were also compared with the corresponding pure vergence movements. In the children, the saccade component of combined convergent movements showed longer latency than pure saccades at far ($F_{1,14} = 6.0$, $P < 0.05$, see Fig. 6A), whereas the latency of the convergence component was not significantly longer than that of pure convergence ($F_{1,14} = 1.84$, $P = 0.20$, see Fig. 6B). For combined divergent movements, the latency of the saccade component was not significantly longer than that of pure saccades at close ($F_{1,14} = 2.2$, $P = 0.16$, see Fig. 6C). The latency of the divergence component was significantly longer than the latency of pure divergence ($F_{1,14} = 4.52$, $P < 0.05$, see Fig. 6D). Thus, in children, one of the two components of the combined movements had significantly longer latency than the corresponding type of pure eye movements, and there was a tendency for a similar prolongation for the other component. In the adults (see Fig. 7), all components of combined eye movements had significantly longer latencies than the corresponding pure movements ($F_{1,14} = 10.64$, $P < 0.01$ for saccadic components of the combined convergent movements; $F_{1,14} = 9.49$, $P < 0.01$ for convergence components; $F_{1,14} = 17.7$, $P < 0.01$ for saccadic components of the combined divergent movements; $F_{1,14} = 14.75$, $P < 0.01$ for divergence components).

It should be noted that nonparametric Kruskal-Wallis test applied to adults’ versus children’s data for saccades, vergence, and all combined movements on the 5Ds instead of the means, also confirmed a significant effect of the type of subjects (children versus adults for saccades: $H = 15.04$, $P < 0.01$; vergence: $H = 9.04$, $P < 0.01$; saccadic components of combined convergent movements: $H = 13.17$, $P < 0.01$; saccadic components of combined divergent movements: $H = 6.3$, $P < 0.01$; convergence components: $H = 13.47$, $P < 0.01$; and divergence components: $H = 10.07$, $P < 0.01$). A summary of the results of latency comparisons for different types of eye movements in adults and children is shown in Table 1.

Initiation of Saccade and Vergence Components for Combined Eye Movements

There is still controversy regarding the mechanism generating rapid and combined eye movements. According to Zee et al. and Mays and Gamlin, combined eye movements are produced by parallel control of saccade and vergence oculomotor subsystems interacting non-linearly and coupled by the omnipause neurons. In contrast, in Zhou and King concluded that rapid combined eye movements could be saccades in direction and in depth controlled individually for each eye. This issue is fundamental for understanding the organization of the visual and oculomotor (bincular and monocular) systems. In the present study, we approach this question by analyzing the latency of combined eye movements. The rationale is the following: As explained in the Methods section, from the individual eye position signals, we derived two signals—the conjugate signal and the disconjugate signal—which could be produced by two interacting, but distinct oculomotor subsystems: the saccade and the vergence.
Evidence for asynchrony in the initiation of the two components argues in favor of such a theoretical framework. Most important, comparison between children and adults could help in the understanding of the role of learning and experience in the ability to synchronize multiple motor commands.

Three different types of initiation were observed: the vergence component started first (Fig. 2C), or the saccade component started first (Fig. 2D), or the two components started together. Figure 8 shows the percentage of each of these three types of initiation in children (A) and adults (B). In all children, the vergence started first for the majority of combined movements (group mean, 65% ± 15%). The other two patterns of initiation occurred less frequently. ANOVA with children as the random factor and the type of initiation as the fixed factor showed significant difference between the different types of initiation (F2,28 = 25.46, P < 0.01). In contrast, in the adults there was no significant difference between the three types of initiation (F2,28 = 1.15, P = 0.35). Inspection of the individual adult results in Fig. 8B shows that the vergence component precedes the saccade component, as occurred in children systematically and in only four adults. Thus, the adult results are idiosyncratic. Some subjects started their combined movements predominately by triggering the saccade first, and others by triggering the two components together. In both children and adults, the percentage of trials in which vergence started first was significantly more pronounced for convergent than divergent combined movements (F1,14 = 8.80, P < 0.01 in the children and F1,14 = 6.89, P < 0.05 in the adults).

**Developmental Aspects**

To examine developmental aspects, we regrouped the 15 children into three groups, 4.5 to 6 years of age (n = 6), 7 to 8 years of age (n = 4), and 10 to 12 years of age (n = 5). Figure 9 presents the mean latency for each age group of children for pure (A) and combined (B) eye movements. It is evident that the latency of all eye movements decreased with age. The age effect was significant in all types of eye movements (nonparametric Kruskal-Wallis test): saccades at far, H = 9.69, P < 0.01; saccades at close, H = 11.23, P < 0.01; convergence, H = 8.49, P < 0.01; and divergence, H = 8.08, P < 0.01. For the combined movements, the level of significance was saccade components of combined convergent movements: H = 8.89, saccade components of combined divergent movements: H = 8.49.
combined convergent movements

Figure 9C shows the mean percentage of different types of initiation of the combined movements, also as a function of age. There was no significant age effect on these percentages (vergence first, $F_{2,12} = 0.30$, $P = 0.75$; saccade first, $F_{2,12} = 2.12$, $P = 0.16$; simultaneous start, $F_{2,12} = 1.67$, $P = 0.23$). Planned comparison of the percentage of simultaneous starting at the age of 4.5 to 6 years versus the age of 10 to 12 years revealed a tendency, albeit weak, toward significance ($F_{1,9} = 4.39$, $P = 0.06$).

In summary, all latencies decreased with age and approached adult levels at the ages of 10 to 12 years. In contrast, the way children initiated combined movements changed little

Table 1. Comparison of Mean Latencies for Different Types of Eyemovements in Adults and in Children

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$+$, statistically longer latency; $-$, no statistical difference between the two types of eye movements; $\pm$, a difference exists in most of children; sacc., saccade; verg., vergence; conv., convergence; div., divergence; sacc comp., saccade component; conv./div. comp., convergence/divergence component.
much higher. Asynchrony was present at all ages studied, and, whereas in adults the percentage of simultaneous start was asynchrony (i.e., vergence started before the saccade), in children, most of the combined movements showed synchronization of the two components of combined movements. The main findings can be summarized follows: All latencies and their variability of eye movements in 3-D space were longer in children than in adults, and there was a progressive decrease with age. Latencies approached or reached adult lengths at approximately 10 to 12 years. There were differences between latencies in different types of eye movements, both in children and adults. Differences in latency suggest that the visuomotor spatial and attentional processes involved (e.g., for the preparation of saccade versus vergence) are not same. The presumably, synchrony of movement reached adult levels beyond the age of 12 years.

Next, we will discuss in more detail each of these findings and their physiological significance.

Saccade Versus Vergence

Latencies of pure saccades and pure vergence were longer in children than in adults. Our results for saccades are in agreement with prior studies.4–6 Note that the studies cited earlier examined saccades exclusively, whereas in our study saccades were interleaved with other types of eye movements. Thus, our study extends prior reports of long latency in children, even for saccades in more natural conditions. As mentioned, saccade latency reflects several visuomotor and attentional processes that involves activation of a large neural circuitry from the retina to visual cortex, parietal cortex, frontal lobe, and superior colliculus and then to brain stem and extraocular muscles. The longer saccade latency has been attributed frequently to underdeveloped related cortex, and some investigations also have suggested that increased latency of saccades is related to difficulty in controlling visual fixation.6 Particularly, maturation of the frontal lobe is very slow and is completed at approximately the age of 15 years in humans, as suggested by studies of cerebral blood flow (see Ogawa et al.5), EEG investigation (see Anokhin et al.23), and studies with fMRI (see Luna Sweeney26). Our observations of increased latency of saccades in children and progressive decrease with age are compatible with the idea of progressive maturation, especially of the frontal lobe.

Studies of latency in vergence in children are, to our knowledge, nonexistent. Latencies in vergence in the children in our study were also longer than in adults, and they decreased with age. The explanation for the length of latency in vergence could be similar to that for latency in saccades. Indeed, it is likely that the triggering of saccade and vergence activates similar cortical circuitry and visuospatial and attentional processes. Note that the cortical circuitry controlling vergence is not well known in humans. There is, however, some evidence from animal studies for the involvement of the posterior parietal cortex (PPC; see Mays and Gamlin25) and frontal lobe (see Gamlin and Yoon26). Moreover, Hasebe et al.27 provided evidence in a positron emission tomography (PET) study of humans for activation of left parietal lobule in relation to vergence eye movements and Kapoula et al.28 showed that transcranial magnetic stimulation (TMS) of the right PPC increases the latency of both saccades and vergence.

In the children’s group, vergence had a slightly shorter latency than did saccades. The mean difference was approximately 15 ms and was statistically significant. This mild difference in children’s saccade and vergence latencies also suggests that the two triggering mechanisms are not absolutely identical, even though similar cortical circuitry is involved in triggering both types of movements. In adults, we observed shorter latency of vergence than saccades in a few subjects only. This result indicated that the difference in latency between saccade and vergence becomes subject dependent at the adult stage.

Saccades at Close Versus Saccades at Far

For both children and adults, latency in saccades at close viewing distance was shorter by approximately 20 ms than that at far viewing distance. This observation is, to our knowledge, new. The origin of this difference could be sensory, oculomotor, attentional or any combination of these factors. The sensory factor could be related to the increased angular size of the LEDs at close distance and/or to a more pronounced change of luminance produced by the extinction of the central LED viewed at close distance. This is compatible with electroen-
cephalogram studies that also show dependence of latency in visual evoked potentials (VEP) on spatial frequency (see Mihaylova et al.\textsuperscript{29}) and luminance (see Osaka and Yamamoto\textsuperscript{30}) even though VEP studies use gratings rather than single LEDs. It is also compatible with the study by Raymond,\textsuperscript{31} showing that the reaction time to detect the change of a small letter of constant size was shortest at an individually determined close optical distance and that the time lengthened with the increase in viewing distance. Oculomotor reasons could include facilitation of disengagement of oculomotor fixation when the eyes are at high degree of convergence, such as is needed to fixate the close LED located at a 20-cm viewing distance. Finally, attentional reasons could include facilitation of disengagement of visual attention when the eyes converge at close.

**FIGURE 9.** (A) Latency of pure movements (saccade and vergence) as a function of age in children. (B) Latency of components of combined eye movements in children as a function of age. (C) Percentage of different types of initiation of combined movements in children as a function of their age. In all graphs, adult data are shown on the right.
Convergence Versus Divergence

In the adult group, the results showed significantly longer latency for convergence than divergence (the mean difference was approximately 20 ms). This is consistent with the results of Krishnan et al.\textsuperscript{9} and with the results in two of the three subjects studied by Tagaki et al.\textsuperscript{17} but contradicts the results of Semmlow and Wetzel,\textsuperscript{10} and Hung et al.\textsuperscript{11} Tagaki et al.\textsuperscript{17} found that the latencies for convergence were greater than for divergence in the two subjects with exophoria and the opposite in the third subject with esophoria (latent inward deviation of the eyes, observed with the cover–uncover test). They suggested that the inherent phoria itself influences the initiation of vergence responses. In our study, phoria was grossly evaluated in all adults (by covering one eye and observing the movement made by the covered eye on removal of the cover). Adult subjects S2 and S8 with visible esophoria showed longer latency for convergence than for divergence, as was the case in several other subjects with exophoria (S1, S3, S4, S5, S6, S7, S11, S12, S13, and S15). We could not confirm the observation of Tagaki et al.\textsuperscript{17} In our experiment, latency for divergence was longer than that of convergence in only 2 of the 15 subjects. The adult group mean latency was significantly longer for convergence than divergence. Thus, measurement in a large sample of subjects confirms a consistent difference in latency between convergence and divergence. Our observation of shorter latency for divergence is compatible overall with the idea of differences in the visuomotor and attentional processes involved in the preparation of these two types of eye movements.

In the children, although no significant difference in latency was found between convergence and divergence, at the individual level, in most of the children, divergence showed shorter latency than convergence. Thus, the difference in latency, although subject dependent, was evident from childhood. The neurophysiological mechanisms involved in the initiation of vergence are not identical for convergence and divergence. For instance, Mays\textsuperscript{32} identified at the brain stem level fewer neurons used in divergence than in convergence. It is not known whether at the cortical level, convergence and divergence activate different subcircuits, as is known to be the case in reflexive versus volitional saccades (see Pierrot-Deseiligny et al.\textsuperscript{38}).

Combined Movements

Initiation. Yarbus\textsuperscript{34} suggested that vergence starts first, followed by the saccade and then by the residual vergence. He also suggested that during the saccade the vergence simply adds to the saccade. Subsequent studies,\textsuperscript{12,13,15,19,55} dealing with saccade–vergence interactions have questioned the second observation of Yarbus. Vergence has been reported to be accelerated by the saccade and, reciprocally, saccade was decelerated by the vergence.\textsuperscript{2,15} Nevertheless, this is an unresolved controversy, and it is not known whether such a vergence component is central “facilitation” (see Zee et al.\textsuperscript{19}) or peripheral “enhancement” (see Hung\textsuperscript{50}). Collewijn et al.\textsuperscript{14} observed that frequently vergence starts first, perhaps more frequently for convergence components than for divergence components. Combined divergent movements, nevertheless, when studied with high resolution also showed presaccade divergence. The average percentage of trials for which vergence starts first was 40% in our adult population, which is less than that reported by Collewijn et al.\textsuperscript{14} It may be related to the different spatiotemporal arrangement of the target presentation used in the two studies. The most novel result of our study is the difference between children and adults in this aspect of behavior. Children clearly show frequent asynchronous behavior, namely the preceding of the vergence component, ANOVA, with adults versus children as the fixed factor applied on the percentage of simultaneously starting combined eye movements, shows a significant difference between adults and children ($F_{1,28} = 5.25, P < 0.05$). Moreover, our data show that the ability for synchronization develops very slowly with age and continues beyond the age of 10 to 12 years (see Fig. 9C).

Thus, the study of combined eye movements provides a useful tool for examining this delicate aspect of visuomotor control in children, which is presumably related to cognitive development and ability to handle multiple motor commands together.

Lengthening of Latency of Combined Movements. For adults, latencies of both components of combined movements were found to be longer by 20 to 40 ms than those of corresponding pure movements. This is in agreement with the study of three subjects by Takagi et al.\textsuperscript{17} They proposed the following conceptual model for the control of combined movements. Once a decision to generate eye movement toward the visual target is made, activity is initiated in two independent trigger circuits: one for the saccade system and the other for the vergence system. The investigators also proposed an eventual difference in the thresholds or in the delays for triggering these two brain stem circuits. This model is thus still related to the brain stem, although it also deals with cortical aspects, such as fixation requirements. Increased latency of combined eye movements is an observation also compatible with the more general framework in the psychology–physiology literature showing that reaction time, for example, for simultaneous bimanual responses, is longer than that of unimanual ones. Note that the difference is also small—on the order of 10 to 20 ms (see Steenbergen et al.\textsuperscript{57} and Taniguchi et al.\textsuperscript{38}). Thus, consistent with other modalities, combination of two oculomotor commands takes approximately 20 ms more. Our study shows that a similar phenomenon exists in children. At least one of the components of combined movements was significantly longer than that of the corresponding movement programmed alone.

Variability of Latency

Variability in the length of latency was significantly larger in children for all types of eye movements. Our observations are in agreement with the study by Munoz et al.\textsuperscript{5} who found that young children (5–14 years) had wider distribution of latency length in saccade than did adults (15–39 years). This was attributed to poor control over visual fixation. Frick et al.\textsuperscript{59} found that in early infancy (3–4 months), the latency of shifts of fixation from a central to a peripheral target also showed great variability. They suggested that developmental and individual differences in latencies are linked to the development of the neural attentional systems that control the ability to disengage or to inhibit the visual fixation. More recently, Mostofsky et al.\textsuperscript{40} reported that unmedicated children with attention deficit hyperactivity disorder (ADHD) showed significantly greater variability in latency of prosaccades than did control subjects. According to these investigators, latency variability could reflect the prefrontal dysfunction underlying the behavioral abnormalities observed in ADHD. Thus, there is an overall agreement in various fields of research in young subjects or in pathology that increased variability of latency reflects immaturity on the control of the visual fixation system, perhaps linked to prefrontal development. Our observations in the variability of latency in the present study are compatible with this line of thinking.

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References