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Up/down anisotropies of vertical saccades in healthy children depending on the mode and the depth of execution

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ABSTRACT

While the overall development of saccades in children has recently gained increasing interest, the precise characteristics of vertical saccades remain understudied. The few adult studies existing showed up/down anisotropies on various parameters. This study focuses on the development of vertical saccades and their interaction with vergence movements, according to the mode of initiation of the saccades (automatic and controlled). Eighty six children (9.57 ± 3.15 years) performed vertical saccades with an eccentricity of 7.5°, at 40 cm and at 150 cm viewing distance, in a gap paradigm – automatic saccades – and in an overlap paradigm – more voluntary or controlled saccades. Task and direction effects: latency was overall longer in the overlap than in the gap task, duration was longer for upward than downward saccades, conjugate vertical drift was larger after upward than downward saccades, horizontal vergence was higher during and after downward than upward saccades. Age effects: For upward saccades, amplitude, mean and peak velocity of upward saccades increased with age, while the vertical conjugate drift after downward saccades at far distance decreased with age; for downward saccades in the overlap task, the horizontal convergence increased with age concomitantly with an increase of the duration. The results are discussed in the context of hypothetical differential circuits of automatic and controlled saccades maturing progressively in children and interacting with direction (up/down). We suggest that the up/down asymmetries, more pronounced in the overlap task, are built progressively in mutual interaction with a perceptive peripheral bias, up being perceived as far and down as near.

1. Introduction

Vertical saccades eye movements are very important for exploration of the 3-D space, reading and locomotion. There are among the most complex movements, requiring a good control of the distribution of innervation to the six extraocular muscles of each eye. Few studies exist in adults with a very limited number of subjects, and even fewer in children. The adult studies showed up/down anisotropies on various parameters.

First, the majority of the studies in adult subjects showed that the latency was shorter for upward than for downward saccades (Honda and Findlay 1992; Goldring and Fischer 1997; Tzelepi et al., 2005), although some studies did not find any differences in the latency between upward and downward saccades (Miller, 1969; Yang and Kapoula, 2006). This difference was explained in terms of a better visual analysis in the lower visual field, allowing an easier identification of the target even in peripheral vision in this field. In contrast, the upper visual field allows weaker peripheral resolution, leading to lower peripheral analysis and identification of the target, thus accelerating the need to initiate a saccade for foveation (Curcio and Allen 1990; Funahashi et al., 1993). In terms of brain activation, Tzelepi et al. (2010) found later activation of the frontal lobe for downward saccades, comparing to upward saccades. These results are also in line with the ecological theory proposed by Previc (1990) that the upper visual field corresponds to the extra-personal space while the lower visual field corresponds to the *peri*-personal space. Furthermore, Collewijn et al. (1988) showed that in adults, upward saccades tend to undershoot the target while downward saccades tend to overshoot it. Yang and Kapoula (2008) confirmed these results in a large population of young adults and a group of elderly. Finally, adult studies showed a characteristic pattern of convergence during downward saccades and divergence during

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upward saccades. A controversy remains about the origin – central versus muscular – of the vergence during the vertical saccades. Indeed, Collewijn et al. (1988) proposed that this horizontal vergence is a central command of vergence to counter a hypothetical perceptual bias: targets in the lower visual field would generally be perceived as being closer to the observer than targets in the upper visual field. Enright (1989) proposed that these vergence movements are muscular artifact due to the co-contraction of the medial and lateral recti muscles, and the increase for upward movement and the decrease for downward movement of tension in the superior oblique muscles.

In children, Salman et al. (2006) examined the characteristics of vertical saccades in children and teenagers (8–19 years). They recorded subjects' eye movement during horizontal saccades to 10° and 15° target eccentricity and vertical saccades to 5° and 10° target eccentricity and examined their latency, accuracy and peak velocity. The authors found that while the latencies decrease with age, the accuracy and the mean velocity were constant over time. In particular, latency to 5° downward saccades was significantly longer than that of all other saccades and there was a negative correlation between the latency of vertical saccades and age. In a first preliminary study (Gaertner and Kapoula, 2014) limited to children of 6–10 years, we showed that children present some up/down anisotropies in terms of latency, accuracy and horizontal vergence qualitatively similar to those known in adults: shorter latency, more hypometry and less convergence during upward than during downward saccades. The control of horizontal vergence during vertical saccades changed within 6 and 10 years, tending toward a divergence, the adult pattern. We argued that the origin of such anisotropies seems to be central, i.e. an adaptation of the oculomotor properties to the perceptual needs, based on a complex interaction of the horizontal vergence and of the vertical saccades.

Saccades can be elicited under automatic versus controlled mode of initiation with the use of gap and overlap paradigm respectively (e.g. Kapoula et al., 2011). The parietal-frontal oculomotor circuits involved in saccade preparation may be different for the two types of eye movements; namely, for the automatic initiation might be done by the posterior parietal cortex while controlled initiation the posterior parietal cortex would relay information to the frontal eye fields which would be in charge of the initiation of the saccades. Such conceptual framework has been presented by Kapoula et al. (2011); these authors provided some evidence for such model using double-pulse TMS on the posterior parietal cortex in the gap versus overlap saccades in healthy adults and showing differential effects in variability in the two tasks. To our knowledge, developmental studies of vertical saccades depending on the mode of initiation are inexistent. Yet, the maturation of parietal and frontal areas do not follow the same time course, the latter being slower to mature (see Sweeney et al., 1996). The objectives of the preset study are:

1. Examine the development of vertical saccades in children as a function of the mode of initiation, automatic versus controlled;
2. Examine the development in a wide age range of 6–17 years;
3. Focus on up/down asymmetries and investigating possible interaction between mode of initiation, age and depth (close versus far).

2. Material and methods

2.1. Subjects

Eighty six subjects participated in this study; their age ranging from 6 to 17 years. All subjects were healthy, did not present neurologic, vestibular or ophthalmologic symptoms that could affect their performance, and had normal or corrected to normal vision: the range of visual acuities was 8/10 to 12/10 and range of stereoacuities of 30–60 arcsec. The dominant eye was measured with the unilateral cover-test: the subject fixated a target at 5 m and the orthoptist covered alternately each eye observing the viewing eye. If the viewing eye did not move, then it was considered as the dominant eye. This test is one of most commonly used techniques in clinical evaluation. The stereoacuity was measured with the TNO test. This study was conducted during a Hospital Project of Clinical Research (PHRC Verve) between the Robert Debré paediatric Hospital and the French National Center of Scientific Research (CNRS). The investigation adhered to the principles of the Declaration of Helsinki and was approved by our institutional human experimentation committee, the "Comité de protection des personnes (CPP), Ile-de-France V, Hôpital Saint-Antoine in Paris, France. Informed parental consent was obtained for each subject after the nature of the experimentation had been explained.

2.2. Visual display

The visual display consisted of LEDs mounted on a vertical table, adjusted to be at eye level of all subjects and at a distance of 40 cm or 150 cm from the subjects. The subjects were seated in a chair with a chin rest. Five LEDs were used: one at the center, at the subject's eye level serving for the initial fixation, one up and one down at 7.5° of eccentricity from the central point for the vertical saccades tests. The test was done at 2 different distances (40 cm and 150 cm), the LED subtending always 7.5° were different for near and far. Furthermore, for the calibration task that involved both horizontal and vertical saccades, 2 more LEDs were added at 10° left and right. (See Fig. 1A)

2.3. Oculomotor task and procedure for calibration

A calibration test was run first, consisting of a LED target stepping by 10° as follows: from center to left, center, right, center, up, center, down, center; this sequence was repeated twice. All the LEDs (center and eccentric) stayed illuminated for 1000 ms. The subjects were asked to make a vertical saccade to the target LED as rapidly and accurately as possible. Two calibration blocks were done, one at 40 cm of distance from the subject and one at 150 cm. In each block, vertical saccades were randomly interleaved between the up and down direction.

2.4. Oculomotor task and procedure for vertical saccades

Two paradigms were used in this study. The gap paradigm, leading to automatic saccades, wherein the target LED lights 200 ms after the disappearance of the central LED of fixation. And overlap paradigm, inducing voluntary saccades, the central and peripheral target are lit simultaneously for 200 ms. Details of spatiotemporal parameters for each task are given in the legend of Fig. 1B. Briefly, the fixation LED was on for 2000 ms, then it was switched off and 200 ms later the saccades target LED was switched on for 1000 ms (gap task); a blank period of 500 ms was inserted before next trials. Trials with upward versus downward location of 7.5° were interleaved pseudo randomly, 20 saccades were performed by the subjects at each distance (10 saccades up, 10 saccades down). This block was repeated at far and at near distance (40 and 150 cm).

In the overlap paradigm, the sequence of events in every trial was similar, except that the initial fixation target stayed light on for an additional 200 ms after the target LED was switched on. The sequence of gap-overlap task was counter balanced between subjects.