The effects of age on Saccades made to Visual, Auditory and Tactile Stimuli

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Abstract:

Purpose

To investigate the effects of stimulus modality and aging on saccades in healthy human subjects.

Methods

Visual, auditory and tactile evoked saccades of young, middle aged and older healthy subjects with normal visual function, hearing and somatosensation were measured and analysed. The young group was comprised 12 subjects aged between 20 and 30 years of age, with a mean age of 23.7 (+ 2.9) years. The middle-aged group was comprised of 7 subjects ranging in age from 40 to 50 years with a mean age of 46.9 + 3.4 years. The older group was comprised of 7 subjects ranging from 60 to 70 years of age, with a mean age of 63.86 +3.0 years.

The visual stimuli were presented by light emitting diodes at 0, +5, 10, 15 and 19 degrees. The auditory stimuli were noise-emitting loudspeakers placed above the visual stimuli. The tactile stimuli were presented by bone vibrators driven at 250 Hz placed beneath the fingertips at corresponding angles.

Results

The latency of auditory saccades was significantly longer than tactile saccades, whose latencies were in turn significantly greater than visual saccades. Visual saccades were most accurate and least variable, followed by tactile saccades. Auditory saccades were found to be highly variable and grossly inaccurate. Age did not affect saccades to different sensory modalities.

Conclusions

The results suggest that non-visual stimuli undergo greater neural transformation than visual stimuli, and, specifically, auditory stimuli undergo more neural transformation than tactile stimuli for the generation of a saccade. The findings of this study provide the initial basis for eventual clinical applications of tactile stimuli in the evaluation and rehabilitation of persons with visual impairment.

Introduction

Sensory information about light and movement, sound and noise, taste, olfaction and touch (somatosensation) is constantly being transmitted to the human central nervous system (CNS). To give a better understanding to this sensory information the CNS initiates a rapid eye movement (saccade) to direct the visual axes to the point of the sensation, and then high acuity visual information about the object is obtained. This process of initiating saccades to the source of incoming sensory information gives better understanding and more meaningful interaction between humans and their surrounding environment. Based on this knowledge, studies have examined and found that saccadic eye movements can be made not only to visual stimuli but auditory and somatosensory (tactile) stimuli (1,2,3,4,5,6).

The superior colliculus (SC) of the midbrain (7) is the integral structure of the CNS involved in the generation of saccadic eye movements. Consisting of seven layers (7,8) the SC is divided into a superficial (dorsal) division (layers I to III) and a deep (ventral) division (layers IV to VII). The division is made on the basis of functional properties such as neuronal morphology, afferent-efferent projections, physiological properties and behavioural involvement (7). The superficial division of the SC serves as a sensory structure (9) receiving afferent input from the retina and visual cortex (8,9). The deep division of the SC receives afferent input from different sensory modalities and motor structures, and is involved in the transformation of sensory information into motor command (7). The cells of the SC may be specific to one sensory modality (10,11) or respond to multiple sensory modalities (7,10). Multimodal cells respond to either a combination of each sensation (ie visual and auditory or visual and tactile) or all three sensations. The sensory input into the SC enables the development of 'sensory maps' which locate the stimuli in relation to the surrounding environment. These sensory maps are retinotopic, or 'eye-centred' for visual (7) and somatosensory input (1). A craniotopic or 'head-centred' reference frame exists for auditory stimuli (12). The individual sensory maps of superior colliculus follow the same co-ordinates, but are then transformed into one sensory map. After the multimodal sensory map has been established by the superior colliculus, a small group of cells in the area of the afferent sensory input (7) code the direction, amplitude and velocity of the saccade (13) required to drive the eye to the desired position.

The latency of visually evoked reflexive saccades has been shown to be approximately 200 milliseconds, with a standard deviation of 25 to 50 seconds (9). Santamaria (14) and Warabi et al (15) have found that target eccentricity prolongs saccadic latency, in contrast Versino et al (16) found no relationship between target position and saccadic latency. Increasing age has repeatedly been shown to prolong the latency of a saccade to a randomised target (14,16,17,18,19,20,21,22). Santamaria (149) showed that the combination of age and target eccentricity both prolong saccadic latency. Visual saccades are highly accurate, with hypometria of 10 percent considered to be within normal limits (14). Warabi et al (15), Sharpe & Zackon (20) and Santamaria (14) found that increased age results in a greater inaccuracy of saccadic eye movements; in contrast to these findings, Versino et al (16) found no relationship between increased age and saccadic accuracy.

Zahn et al (3,4) and Zambarbieri (5) have investigated auditory-evoked saccades, finding that auditory saccades have a longer latency than visual saccades. The latency of auditory saccades decreases with increased target eccentricity. Auditory saccades are less accurate than visual saccades, usually arriving within three degrees of the target position (3,5). Increased target amplitude causes decreased accuracy and a greater variability of responses for auditory saccades (5). Zahn et al (3) reported that neither the accuracy nor the latency of a saccade were affected by the frequency or intensity of narrow-band noise. Schik et al (6) examined predictable saccades to visual and auditory targets in young, middle-aged and older subjects and found increased latency and higher velocity of saccades in the older group. In contrast to the aforementioned studies by Zahn et al (3,4) and Zambarbieri (5), Schik et al (6) found shorter latencies for auditory targets. It is important to note that the study by Schik et al (6) used a very different method in his study, and these methodological differences make it difficult to compare this study to others by Zahn et al (3,4) and Zambarbieri (5).

Groh and Sparks (2) investigated the behavioural characteristics of saccades to somatosensory stimuli, using three monkeys and two human subjects. In this study subjects were requested to grasp a post which provided a pulse of vibration for 100 milliseconds, positioned 20 degrees either side of the midline. Different saccadic amplitudes were obtained by randomising the starting point for the saccade. The study found that the tactile saccades had longer latencies in comparison to visual saccades, which decreased as target eccentricity increased. It is interesting to note that when the hands were visible the monkeys often looked towards their hands and not the stimulus. Groh and Sparks (2) have demonstrated that when a large tactile stimulus is used the target can be localised by humans. It was not known whether the results could be elicited from a smaller surface area such as the fingers, and whether these responses would be more accurate. The fingers contain the largest density of tactile sensors in the human body, which would suggest that they could be localised with greater accuracy.

The present study aimed to investigate the latency, accuracy and variability of responses of saccades made to tactile stimuli presented to each of the fingers, and to compare the results with saccades made to visual and auditory targets that subtended the same angle. Subjects were divided into three different age groups to determine whether age also influences the characteristics of saccades.

Methods

Subjects

Twenty-six subjects were recruited on a voluntary basis and gave written informed consent for participation in the study. Inclusion / exclusion criteria were established to ensure volunteers could generate normal saccadic eye movements, had good general and ocular health, and had normal visual, auditory and vibrotactile sensation. These were tested using a questionnaire and various clinical tests. Potential participants with Alzheimer's disease, schizophrenia, dementia, (21,23,24,25,26,27), Parkinson's disease, progressive supranuclear palsy, Huntington's disease (27) and other psychological and neurological disorders were excluded from the study. Volunteers taking sedatives and hypnotics (including barbiturates and benzodiazepines), anti-convulsants and medications indicating the afore-mentioned disorders were excluded from the study. Volunteers were also asked to cease alcohol consumption 12 hours prior to testing.

Volunteers with nystagmus, neurogenic or mechanical extra-ocular muscle palsies, other disorders affecting eye movements, diseases affecting peripheral vision (such as glaucoma and retinitis pigmentosa) and volunteers with homonymous hemianopia (28) were excluded from the study. In addition to this, participants were required to have best corrected visual acuity of 6/12 or better in at least one eye (using Snellen's Acuity Chart), normal pupil reactions, a full visual field to confrontation testing, no strabismus and full ocular movements.

Volunteers with a known history of hearing loss and diabetes mellitus were excluded from the study. All potential participants were required to demonstrate the ability to hear a 30 decibel sound presented at three pitches (500Hz, 1000Hz and 2000Hz) in each ear, using a Beltone audiometer calibrated to 4000Hz, which is within the normal range of hearing for all age groups (29). Participants were required to demonstrate the ability to perceive the commencement and cessation of vibration on each fingertip, tested using a standard E tuning fork.

All 26 volunteers were eligible for participation with normal visual, auditory and somatosensation. A young group (aged between 20 and 30 years), a middle-aged group (aged between 40 and 50 years) and an older group (aged between 60 and 70 years) were formed. The young group consisted of 12 subjects (8 female, 4 male) with a mean age of 23.7 (sd +2.9). The middle-aged group contained 7 subjects (4 female, 3 male) with a mean age of 46.9 (sd +3.4). The older group had a mean age of 63.9 (sd +3.0) and was comprised of 7 subjects (5 female and 2 male).

Procedure

The visual, auditory and tactile stimuli were purpose built for this study. The visual stimuli were light emitting diodes (LEDs). The visual stimuli were mounted onto an arc which was positioned 1.6 metres from the patient, and could be adjusted to eye level. At this distance, the visual stimuli were located at 5, 10, 15 and 19 degrees to left and right. An LED served as the zero point for visual stimuli, and was aligned with the visual axis.

The auditory stimuli were speakers that emitted narrow-band noise of 250Hz at 85 decibels. The speakers were positioned directly above the LEDs, therefore subtending the same angles as the visual stimuli. An audiometer was used to control the speakers.

The tactile stimuli consisted of Radioear B-7 bone transducers mounted into foam as a means of limiting the vibrations from spreading to the other fingers. The input was a 250 Hz sine wave. The transducers were placed such that one thumb served as the zero point when aligned with the visual axis of one eye. The other four fingers of each hand subtending angles of 5, 10, 15 and 20 degrees to the left and right when placed 34 cm from the eyes. The foam was then placed into a metal box for support and mounted to raise the structure to eye level. When testing was conducted, one thumb was aligned with the right visual axis to avoid the effects of convergence.

For all stimuli, positions to the left were deemed to be negative whilst positions to the right were categorised as positive.

Subjects were fitted with the Microguide eye tracker, which was adjusted for comfort and aligned with the visual axis of both eyes. Subjects were then positioned into a headrest mounted on the desk, and the head was stabilised using an adjustable chin height and forehead strap. The eyes aligned with the tactile stimuli and then the visual and auditory stimuli at the respective distances required, and the room darkened. Subjects were instructed to keep their head still whilst testing, and to look as quickly as possible at the stimuli, holding that position until the next stimulus appeared. An oscilloscope was used to view the eye movements from each eye, approximately calibrating the eye tracker by adjusting it for symmetrical output at +19 degrees. A calibration program presented visual stimuli at all nine target positions, the data from which was used to linearise the testing data via a cubic polynomial curve fit.

For each type of stimulus, programs written in the Viewdac programming environment were used to randomly present the stimuli in each of the eight target positions. A standardised method was used to present the stimuli for each stimulus type. Testing commenced with the presentation of the target at zero, followed by a stimulus at one of the eight target positions, and then again at zero and so forth. Each target position was tested eight times in a randomised order, with the interval stimuli randomised between 1.5 and 3 seconds. The order that the three stimulus types were presented was randomised between subjects. Eye movements recorded by the eye tracker travelled to an oscilloscope and digitised at 12-bit resolution at 400 Hz for subsequent analysis.

The data files were re-named by an independent source for blind analysis. Analysis was performed using a Matlab 5.2 program developed by one of the authors (LA), which was based on the Zoomtool interactive graphics package as modified by Jonathan Jacobs, Case Western Reserve University. For each subject the calibration data was matched to each of the nine target positions, so eye movements were accurately scaled. A cubic polynomial was fitted to these points and used to scale other recordings. Saccades that overshot the 20-degree point were saturated and hence excluded from analysis. Saccades that commenced prior to or at the same time as the presentation the stimulus were regarded as anticipatory saccades and were excluded from analysis. The data were then transformed into Microsoft Excel files. The codes were then broken and the data analysed using the program SPSS version 8.0.

The dependent variables in this study are latency, accuracy and variability of subject accuracy. The accuracy of a saccade was defined as the magnitude of error (measured in degrees) and the variability of accuracy was defined by the variability of the magnitude of error. The two independent variables of this study were age and stimulus modality. Post-hoc analysis was conducted using pair-wise comparisons. As the samples originate from three different families no Bonferoni adjustment was used. Statistical significance was set at 0.05.

Results

The study found that the latency of a saccade is affected by the stimulus used to initiate the saccade ($F(1.659)=73.845$, $p<0.001$). Visual saccades have the shortest mean latency of 0.193 + 0.047 seconds, followed by tactile saccades with a mean latency of 0.352 + 0.169 seconds. Auditory saccades have the longest mean latency of 0.528 + 0.267 seconds (see Figure 1). Post-hoc analysis showed that a statistically significant difference exists between all three types of stimuli ($p<0.001$). One-way analysis of variance (ANOVA) showed no difference no significant effects for age ($F(2)=0.645$, $p=0.534$). Two-way ANOVA revealed that there was no interaction effect between age and stimulus type for the latency of saccades ($F(3.319)=0.283$, $p=0.8550$). These results are demonstrated in figure

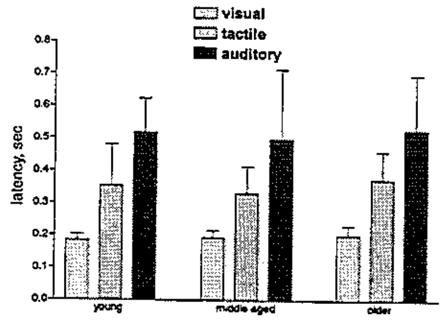

Figure 1: The effects of age and stimulus type on the latency of saccades.

The accuracy of a saccade was found to be influenced by the type of stimuli used to elicit the saccade (F (1.23)=269.248, p<0.001), with statistically significant differences existing between all three types of stimuli (p<0.001). The study did not find a significant effect for age (F (2)=0.626, p=0.543), or an interaction effect between the two variables of age and stimulus type (F (2.46)=0.235, p=0.835). See Figure 2.

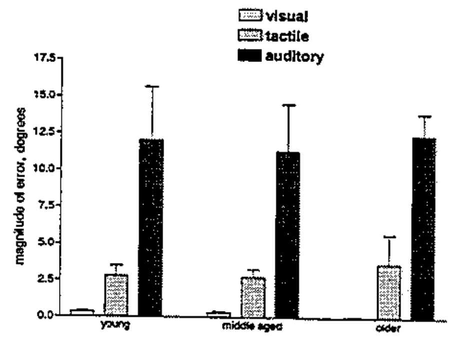

Figure 2. The effects of age and stimulus type on the accuracy of saccades.

The variability of subject accuracy was determined by the standard deviation of each subject's response to each stimulus type. One way ANOVA showed the type of stimulus used to elicit a saccade significantly influences the variability of the subject's accuracy (F (1.459)=370.321, p<0.001). Pair-wise comparisons confirmed that the differences between each of these stimulus types were statistically significant (p<0.001). Age was found to have no statistically significant influence on the variability of a subject's response (F (2)=0.770, p=0.475). No interaction effect was found to exist between the two independent variables (F (2.917)=0.197, p=0.893). See Figure 3.

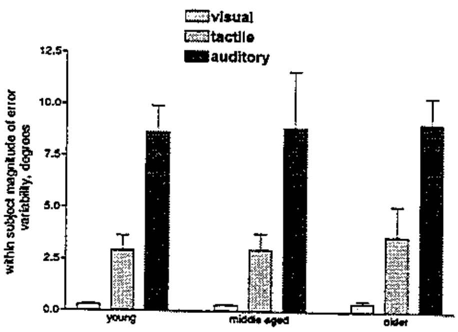

Figure 3. The effects of age and stimulus type on the variability of saccadic accuracy.

Discussion

Most previous studies have shown that auditory (3,5) and tactile (2) saccades have longer latencies than visual saccades. This study supports these findings, but furthermore establishes the relationship that exists between the latencies of all three types of saccades. This study's finding of shorter saccadic latency in visual saccades would suggest that visual information undergoes less transformation and/or processing than saccades to other auditory and tactile stimuli. Whilst Zahn et al (3), Zambarbieri (5) and Groh and Sparks (2) hypothesised that increased saccadic latency is the result of extra sensory processing of auditory and somatosensory stimuli. The results of the present study not only support this theory but suggests that the shorter latency of tactile saccades (0.355 + 0.169 seconds) compared to auditory saccades (0.528 + 0.267 seconds) suggests that tactile information undergoes less transformation and/or processing than auditory information for the generation of a saccade.

As was expected, the present study found that visual stimuli produce the most accurate saccades. Although not as accurate as visual saccades, the present study did establish that the eyes could localise some tactile stimuli presented to the fingers with relative accuracy. In this study the bone transducers used were broad and flat and provided vibratory stimulation to the entire fingertip, which subtended up to 3 degrees of visual angle. Therefore using these calculations, the endpoint of the saccade was on average only 1 degree either side of the finger. The study did not, however, examine if accuracy was dependent on the subjects' handedness, and it may be possible that saccades to the fingers of the 'dominant' hand yield a greater accuracy.

It was anticipated that tactile saccades would be much more accurate, and, upon debriefing subjects it was found that the foam did not always adequately dampen the vibrations from spreading from one finger to another. In future studies a better defined and isolated vibratory stimulus may improve accuracy. It is possible that after prolonged vibratory stimulation of the fingers, it became increasingly difficult to localise the location of the target.

In the present study the auditory saccades were highly inaccurate, with a mean error of approximately 12 degrees. Furthermore the variability of the accuracy of the auditory saccades was significantly higher than the other two types of saccades. During the analysis of these saccades it was noted that many of the subjects made saccades in the opposite direction to the target. This result is in contrast to the findings of Zahn et al (3), who found that an auditory saccade was relatively accurate, arriving within 3 degrees of the target. The result in this experiment may be explained by the close proximity and the small angular displacement of targets, meaning the auditory signals from each ear would arrive to the primary auditory cortices from each ear at very similar times, hence making localisation of the stimuli exceptionally hard.

The low numbers of subjects in each age group and large standard deviation of responses under each test condition may have led to the absence of a significant age effect. It is important to note that even when the middle-aged group was removed from the analysis, still no age effect was present. The analysis by Whitaker and his co-authors (13) showed that there is a decrease in saccadic latency during the eighth decade of life (71 to 80 years of age). The absence of a group of participants in the eighth decade of life may be a contributing factor in the absence of an age effect.

Using a normal population the present study found that saccades to a tactile stimulus displayed relatively high accuracy. Future studies could examine the accuracy of eye movements in patients with central vision loss from causes such as age-related macular degeneration, or childhood pathologies such as Stargardt's disease.

The high degree of saccadic accuracy creates many possible clinical applications for tactile stimuli. Visual field testing relies strongly on the patient's visual feedback to keep steady fixation, to allow accurate analysis of the visual field. In patients with central vision loss tactile stimulation could be used to promote steady central fixation as there is no visual feedback to promote central fixation. This vibrotactile stimulus system could also be used in clinical practice to maintain central fixation during A-scan biometry, keratometry, fundus photography and retinal laser treatment. The same technique may also be appropriately used to calibrate the recordings of the eye movements of patients with central vision loss to provide increased accuracy of test results. Central vision loss is commonly associated with visual disorders of aging such as macular degeneration, and the absence of an age effect indicates that vibrotactile sensation may lend itself to clinical applications easily.

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