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July 28, 2005

Blaire V. Mossman
Managing Editor
P.O. Box 13177
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Dear Dr. Mossman,

The accompanying documents are the submission of our paper to be considered for publication in the special issue of *Computers in Biology and Medicine* that will be devoted to the recent "Fourth Starkfest Conference on Vision and Movement in Men and Machines" held May 26-27, 2005 at the University of California, Berkley. The Chairs of the conference were Dr. Claudio Privetera of the University of California, Berkeley and Dr. John Semmlow of the Rutgers State University of New Jersey. Much of the material in this paper was presented at that conference, though since then we have improved our data processing and revised some of our analyses.

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Scanpaths of motion sequences: Where people look when watching movies

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***Abstract*— Magnification around the most important point of a movie scene (center of interest - COI) might be an effective aid for people with vision impairments that cause resolution loss. This requires that a COI exist for most video frames. Operationally, we defined the COI by recording the eye movements of normally-sighted subjects as they watched movies. More than half of the time most of the subjects looked within an area that was less than 12% of the movie scene. Male and older subjects were more likely to look in the same direction than female and younger subjects.**

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I. INTRODUCTION

People who suffer loss of visual resolution (low vision), often due to eye diseases, could benefit from modified information displays. The most common modification used today is magnification. Magnification inherently restricts the field of view and, thus, may impede the acquisition of information attained in normal vision by the use of scanning eye movements. This problem may be addressed by dynamic control of the displayed information. Dynamic control of large text presentation is helpful for people with low vision [1-4]. We propose a similar approach to improve access to movies and television.

Magnifying moving images using electronic zoom [5] would enable users to select and vary the desired level of magnification from time to time. However, only part of the magnified scene can be presented on the screen. Consequently, large parts of the scene become invisible. Manual zoom-and-roam devices are available in commercial television systems (e.g. DVD players). However, the rapid changing of scenes in most movies may not allow for effective manual control of the magnified section of the image. We proposed pre-selecting the point in the scene on which to center the magnified view (the center of interest - COI) and providing that position with each frame [6, 7]. This selection should maintain the most relevant details in view.

Together with DigiVision (San Diego, CA), we have developed a computer controlled zoom-and-roam device for playback of movies on a television. The computer plays a DVD and simultaneously reads the COI. These coordinates are sent to the zoom and roam device so that the magnified image is centered on the COI coordinates. We proposed using eye movement recordings from normally-sighted observers watching the movie to determine the desired COI. Although other methods of determining the COI can be envisioned, eye movement recording is automatic and objective.

Choosing the COI using eye movements is akin to finding the scanpath for a movie sequence. Much work has been done regarding the scanpath of still images [8, 9] but little is known about viewing moving images. With the exception of a few studies [10-12] most development that depends on knowing where the gaze is directed (e.g. compression schemes [13] and transmission of images for limited screen space [14]) assume that most people look at the same place all the time while watching movies. To our knowledge this assumption has not been verified experimentally. Here we quantify the proportion of the time a group of people look at the same place while watching a movie, and begin to examine the effects of age and gender on this behavior.

Film editors have used assumed knowledge of viewer's eye movements - and even blinks - to assemble movies [15]. Stelmach et al. [10] recorded 24 observers viewing 15 forty-five second clips to determine if viewing behavior can be incorporated into video coding schemes. They found that there was substantial agreement among viewers in terms of where they looked. In a follow-up experiment related to gaze-contingent processing techniques [11], recorded eye movements of subjects were used to create a "predicted gaze position". Tosi et al. [12] recorded the scanpaths of 10 subjects watching a variety of clips totaling about 1 hour and reported that, qualitatively, individual differences in scanpaths were relatively small. Theoretical saliency models [16, 17] predict where people will look and have made no assumptions regarding individual differences in predictions of regions of interest.

Here we address three specific questions relevant to our proposed low-vision aid for viewing television. (1) To what extent do people look at the same place when watching a movie? (2) Does that vary with age and gender? (3) Does the position of the COI differ from the center of the screen?

II. Methods

Six movie clips were selected to span a broad range of scene activity, from stationary newscasters to athletes in motion and to appeal to both younger and older audiences (Table 1). The movie clips from DVDs were presented in a 16×9 movie format (the "movie scene area") on a 26.5-inch diagonal NTSC (4×3) monitor as interlaced video at 30 frames per second (60 fields per second).

TABLE 1 GOES ABOUT HERE

26 normally-sighted subjects were seated 46 inches from the movie scene which spanned a 26.3 deg×14.8 deg visual angle. Subjects viewed movie clips while eye movements were recorded with an ISCAN model RK726PCI eye tracking system. The ISCAN had a nominal accuracy of 0.3 deg over a ±20 deg range and a

sampling rate of 60Hz. Thus we could acquire two eye samples per video frame. The ISCAN compensated for modest head movements, permitting gaze monitoring without head restraint, thus allowing a comfortable viewing situation. The ISCAN was calibrated using its 5-point calibration scheme. To optimize eye tracking [18, 19], we performed a 5-point, pre-clip calibration (external to the ISCAN) before each movie clip was viewed. If we could not obtain satisfactory data yield for the pre-clip calibration we repeated the ISCAN calibration until satisfactory pre-clip calibration was achieved. A post-clip calibration was also recorded and the analysis program averaged the pre- and post-clip results for the calibration parameters.

During the recording phase, immediate feedback was available regarding the amount of valid data (eye samples) available. If less than 80% was valid for any clip, the subject's data were not considered for inclusion, and recording stopped. We did not repeat movie clips, as we wanted to record the subject's eye movements during their first viewing of the clip. People may view a movie clip differently on subsequent occasions, as occurs when instructions are altered for viewing static images [8]. Inadequate eye sample yield happened only with one subject. Of the remaining 25 subjects, the 5 subjects with the highest eye sample yields in each of 4 groups were selected. The 20 subjects were grouped by age and gender: Younger Female 18-29y, Male 16-36y; and Older Female 51-62y, Male 42-66y. Eye sample data yields from these groups are shown in Table 2.

TABLE 2 GOES ABOUT HERE

III. ANALYSIS

A. Preprocessing of individual records

The individual subjects' eye movement recordings were processed to apply the calibration to the eye sample data and remove recording artifacts caused by blinks and other failures. Recording could fail if the head moved too quickly or when specular reflections, such as tear film menisci, were erroneously detected by the ISCAN as the corneal reflection. Blinks and loss of tracking were filtered from the file by removal of records containing zero value data or frames where the pupil diameter was out of a set range.

Video presentation and data collection were controlled with a Visual Basic program that used the DirectX 8.1 (Microsoft, Redmond, WA) DVD interface. This interface only interrupts the processor every 0.4 to 1.0 second with timing (frame number) information request. Frame numbers between such interrupts were calculated from the elapsed time, assuming a 30 frame per second rate. This procedure resulted, on occasion, in non-monotonic or duplicate frame numbers. Non-monotonic frames were discarded. Because the video and ISCAN data were recorded asynchronously, each assigned frame could be associated with one, two or three eye samples. We designated these multiple eye samples per frame as “subframes” (note – these subframes are not video fields). When there were more than two subframes, we re-assigned eye samples to nearby frames that had less than two subframes. Subframes that could not be re-assigned were discarded (there were very few such subframes). In total, we collected and analyzed 2.4×10^6 eye samples within 1.3×10^5 subframes.

B. Merging of eye recordings of multiple subjects' records to find extent of overlap

The 120 subject data files (20 subjects × 6 clips) were processed to count how many of those subjects had valid eye sample data for each subframe (Fig. 1).

FIGURE 1 GOES ABOUT HERE

For each subframe, the calibrated (x, y) coordinates of subjects’ eye samples, the gaze points, were distributed across the screen. Various methods have been applied to compute the coincidence between the gaze points of multiple subjects [10, 20-24]. We chose to calculate the area of the best-fit bivariate contour ellipse (BVCEA) to quantify the spatial coincidence of the gaze points of all the subjects with valid eye samples. This measure has been used in the past to quantify fixation eye movement stability [2, 25]. The k parameter of the BVCEA determines the enclosure of the ellipse. We set k=1, for which 63% of the points would have been enclosed by the ellipse. Note that the calculation of the BCVEA does not require that an ellipse be fitted to the data (gaze points).

Before calculation of the BCVEA, gaze-point outliers were removed from each subframe’s data. To determine if a particular gaze point was an outlier, the x and y distributions of the gaze points in a subframe were considered separately. If a gaze point had either a x or a y value that fell outside the 99.5% probability range (t distribution), the point was considered an outlier. As an example of outlier removal, Figure 2 shows a single subframe of data before and after removal of an outlier. Outliers were removed from 22.5% of subframes, and for those subframes the BCVEA was reduced by a median 48% (inter-quartile range 40 to 60%) and the location of the COI (the mean x and y coordinates of the gaze points of the group) changed by a median of 2.4 deg. (inter-quartile range 1.2 to 4.1 deg.). The number of outliers removed, 1.3 %, was higher than predicted based on the two confidence limits (i.e. 1%; $z = 40$, $p < 0.0001$), suggesting that many of the eye samples that were removed were true outliers, like that shown in Fig. 2.

FIGURE 2 GOES ABOUT HERE

The cumulative distributions of the BCVEA found for each movie clip (Fig. 3 and 4) were fit with a logistic function,

$$y = c + (1-c)/\left(1+\exp\left(-(x-a)/b\right)\right) \qquad (1)$$

where a is the mid-point of the function, b is related to the rate of rise, and c is the lower asymptote. Similarly, to quantify effects of age and gender, the BCVEA was calculated for every subframe for which there were gaze points for at least 4 subjects from each group of 5 subjects. In subsequent data analyses we used these fit values of a and b. Data were evaluated using analysis of variance, with movie clip treated as a within-subject factor.

FIGURE 3 GOES ABOUT HERE

IV. RESULTS

People do tend to look in the same place (here represented by a small BCVEA). As shown in Fig. 3, for all six movie clips, more than half of the time most of the subjects (15 to 20) looked within an area that was less than 12% of the movie scene. This represents an area equivalent to a circle with a diameter of about 8 deg.

To examine the effects of age and gender on whether people look in the same place we performed analyses of variance on *a* and *b* of the fits to the BCVEA data shown in Fig. 4. As shown in Fig. 5, male and older subjects were more likely to look in the same direction (smaller *a*) than female ($F_{1,20}$=6.1, p=0.02) and younger ($F_{1,20}$=21, p<0.001) subjects, respectively. Older subjects were slightly more variable (slower rise – larger *b*) than younger subjects ($F_{1,20}$=3.9, p=0.06). Between the movie clips, there were significant differences in *b* ($F_{5,18}$=5.4, p=0.003) but not of *a*, indicating that the area within which most people looked was more variable for some movies. Subjects were more variable when watching *Network* than *Planet* (p=0.01), *Big* (p=0.016) and *Sunday* (p=0.002). It appears that, as might be expected, movies with high level of motion more tightly control the observer gaze locations than movies with relatively static scenes.

FIGURE 4 GOES ABOUT HERE

FIGURE 5 GOES ABOUT HERE

For those subframes for which there was gaze-point data for 15 or more of the 20 subjects, the position of the COI was calculated. The distributions of those COIs (32×24 bins for the movie scene area) are shown in Fig. 6 for each of the six movie clips. In general, the peaks of the COI distributions were approximately in the center of the movie scene, though they varied by as much as 1/4 of the width or height from center.

The COI distributions were tested on a pair-wise basis using the one-factor independence test for similarities of distributions [26]. The distributions shown in figure 6 (clip by clip comparisons), as well as distributions from the different gender-age groups were tested. All distributions were statistically different from each other ($\chi^2 \geq$ 1,271, p < 0.0001). The practical significance of these statistically significant differences is not clear, as our sample sizes were very large.

FIGURE 6 GOES ABOUT HERE

V. DISCUSSION

Measuring and providing the coordinates of the COI along with each frame may allow magnification to be used to its full potential as a low vision aid for watching movies (and other television programs). The eye movement method presented here is a natural and efficient way of determining these COIs. We envision that, just as programs are now being provided in "closed captioned" and described video formats, movies can be provided with these COIs encoded.

We have demonstrated that it is possible to determine the COI in a movie scene by recording the eye movements of normally-sighted observers while they watch a movie. Over half of the time, the gaze of more than 15 subjects was contained within an area that was less than about 12% of the movie scene (Fig. 3) or about 5% of the screen for 4 or 5 subjects (Fig. 4). This is crucial for our application. We rarely expect to need to magnify the image by greater than a factor of 4 (showing 1/16th (6%) of the frame). Higher magnification might cause too much loss of context. The distribution of COIs (Fig. 6) illustrates that magnification centered on the COI would provide more information than magnification simply centered on the center of the movie scene. If magnification is applied around the center of the movie scene we would not want the COIs to be close to the edge of the screen, as that would potentially obscure important details. Thus if we consider a factor of 4 magnification we should determine the fraction of the frames for which the COI would be outside of the central 4% (associated with a factor of 5 magnification). We found that 73% of COIs lay outside the central 4% of the movie scene area, which would be unsatisfactory. Also, we found that there are some significant differences in the observation behaviors between gender and age groups. The current analysis only found that the older and male observers' COIs were more tightly grouped than the younger and female observers (Fig. 4 and 5). We still need to determine if the COI locations varied with gender and age. Also, conditions or scenes that resulted in a large BCVEA (spread of gaze points) might be just as interesting as the condition of a small BCVEA.

In addition to our interest in the application of this technique to our movie (or television) magnification device, we see this work as a beginning of an interesting examination of the nature and characteristics of the motion scanpath of dynamic environments — the movie environment being one that is simpler to study —

perhaps followed by the dynamic real world of a mobile observer.

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SUMMARY

Magnification around the most important point of the scene on a display (center of interest - COI) might be an effective aid for people with vision impairments that cause resolution loss (low vision). This requires that a COI exist for most video frames. Operationally, we defined the COI by recording the eye movements of normally-sighted subjects as they watched movies. We address three specific questions relevant to our proposed low-vision aid for viewing television. (1) To what extent do people look at the same place when watching a movie? (2) Does that vary with age and gender? (3) Does the position of the COI differ from the center of the screen?

We recorded eye movements (at 60Hz) of 20 normally sighted subjects watching 37½ minutes of 6 movie clips of various types (sports, comedy, documentary, news, game show and drama). The subjects were divided into four age-gender groups (younger and older; males and females). The 120 subject data files were preprocessed to apply calibrations and to remove recording artifacts. The eye recordings of multiple subjects were merged to examine the distribution of gaze points. The coincidence between the gaze points of multiple subjects was determined by calculating the area of the best-fit bivariate contour ellipse expressed as fraction of the movie screen area. The position of the COI was determined as the mean *x* and *y* coordinates of each group.

The subjects did tend to look in the same direction. Over half of the time, the gaze of 15 or more subjects was contained within an area that was less than about 12% of the movie scene or about 5% of the screen for groups of 4 or 5 subjects. This is crucial for our application since we rarely expect to need to magnify the image by greater than a factor of 4 (showing 1/16th - 6% of the frame). Male and older subjects were more likely to look in the same direction than female and younger subjects, respectively. This inter-subject variability in gaze points also varied between the movie clips. The peaks of the COI spatial distributions were approximately in the center of the movie scene, though they varied by as much as ¼ the width or height from the center, and the distributions varied between movie clips.

Measuring and providing the coordinates of the COI along with each frame may allow magnification to be used more successfully as a low vision aid for watching movies (and other television programs). The eye

movement method presented here is a natural and efficient way of determining these COIs. We envision that, just as programs are now being provided in “closed captioned” and described video formats, movies can be provided with these COIs encoded.

TABLE AND FIGURE LEGENDS

Table 1. Category, titles of the movies from which taken, and length of the six movie clips.

Table 2. Yield of acceptable eye sample data from each movie clip did not vary significantly between clips. Yield was greater for male subjects ($F_{1,16}$=7.8, p=0.01) and slightly greater for older subjects ($F_{1,16}$=3.2, p=0.09).

Fig. 1. The percentage of the total number of subframes for which the number of subjects had valid eye samples. The percent of subframes where 15 or more subjects contributed data (right of vertical line) was 94%.

Fig. 2. The gaze points of the 18 subjects with valid eye samples (of the 20 subjects) for subframe 230 of the movie-clip "Quiz Show" are shown on the left. On the right are the 17 remaining gaze points following removal of the outlier. Removal of that outlier reduced the BCVEA (measure of the spread of the gaze points) from 34 sqDeg. (square degrees) to 20 sqDeg. (41%). The arbitrary units shown were used in data processing of the 26.3 deg.×14.8 deg. movie scene (inner rectangle). The crosses mark the COIs (mean of the gaze points), which moved by only 0.8 deg. on removal of the outlier. Note that this COI would be outside the screen for most magnification levels if magnification was to be centered at the center of the movie scene.

Fig. 3. For each movie-clip subframe, after removing outliers (see Fig. 2), the spread of the gaze points was estimated using the BVCEA, reported here as a fraction of the movie scene area. Only those subframes where 15 or more subjects had valid eye samples were used (see Fig. 1). The cumulative curves (heavy lines) show the proportion of the total subframes for which the BVCEA was less than a given fraction of movie screen area. Logarithmic transforms of the distributions were fitted to a logistic function (with c=0) (shown as the thin lines) that were then used to calculate the screen fraction for which 1/2 of the samples had a

smaller BVCEA (a: vertical line and the value indicated by the inset). The residuals of the fits are shown (right y-axis for units).

Fig. 4. As for Fig.3, the cumulative distributions of the BCVEA and positions of a from the fit (not shown) of each movie clip for each age-gender group (where at least 4 out 5 subjects had useable data). Older and male groups had smaller spreads of their gaze points (smaller BCVEA) than younger and female groups, respectively.

Fig. 5. There were statistically significant effects of gender and age on the likelihood that the subjects in a group looked in the same direction (a); and there was a small, non-significant age effect on the variability of direction of gaze (b). Note that the scale labels for (a) are non-linear, since the fit was done in the logarithmic transform of the area. Error bars indicate SEM.

Fig. 6. COI distributions for all movie clips for all subjects (for subframes with eye samples for at least 15 subjects). The border represents the movie scene area. Data were normalized so that the maximum is 1.0 and levels are drawn at 0.1 intervals. Although generally, the distributions peak near the center of the screen, the spread indicates that a large proportion of the time, people did not look at the center of the movie scene.

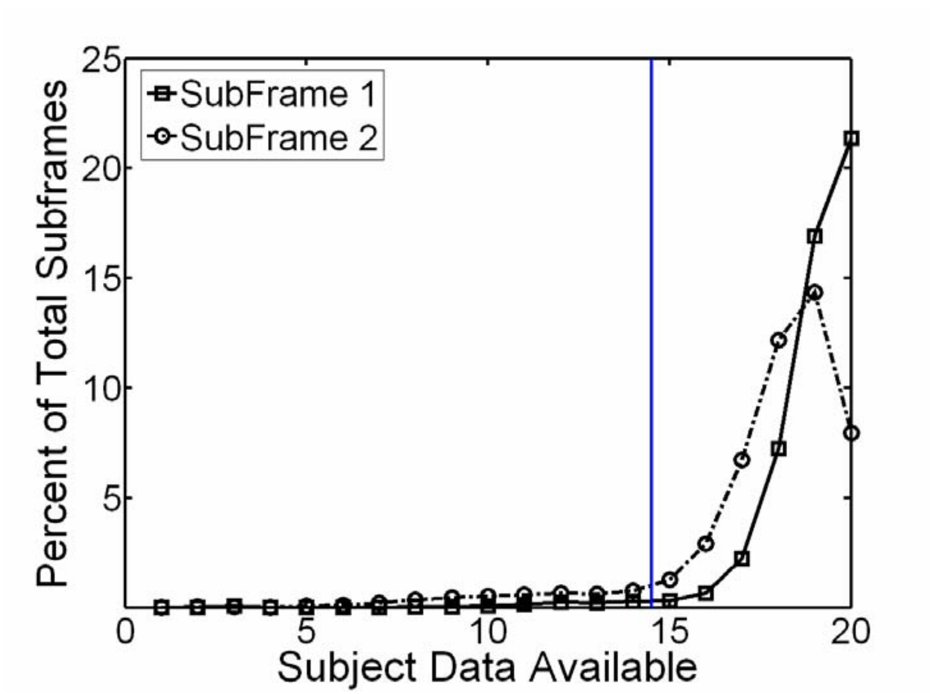
FIGURES AND TABLES

Table 1. Category, titles of the movies from which taken, and length of the six movie clips.

Category	Title	Time (min)
Sports	Any Given Sunday (1999)	4:12
Comedy	Big (1988)	6:29
Documentary	Blue Planet (2001)	8:14
News	Network (1976)	4:02
Game Show	Quiz Show (1994)	6:40
Drama	Shakespeare in Love (1998)	7:06
	Total per subject	**37:29:00**

Table 2. Yield of acceptable eye sample data from each movie clip did not vary significantly between clips. Yield was greater for male subjects ($F_{1,16}$=7.8, p=0.01) and slightly greater for older subjects ($F_{1,16}$=3.2, p=0.09).

	OM	YM	OF	YF
Sunday	97%	95%	93%	93%
Big	97%	95%	95%	93%
Blue	98%	94%	95%	93%
Network	96%	96%	93%	93%
Quiz	96%	94%	94%	91%
Shakes	96%	95%	94%	92%



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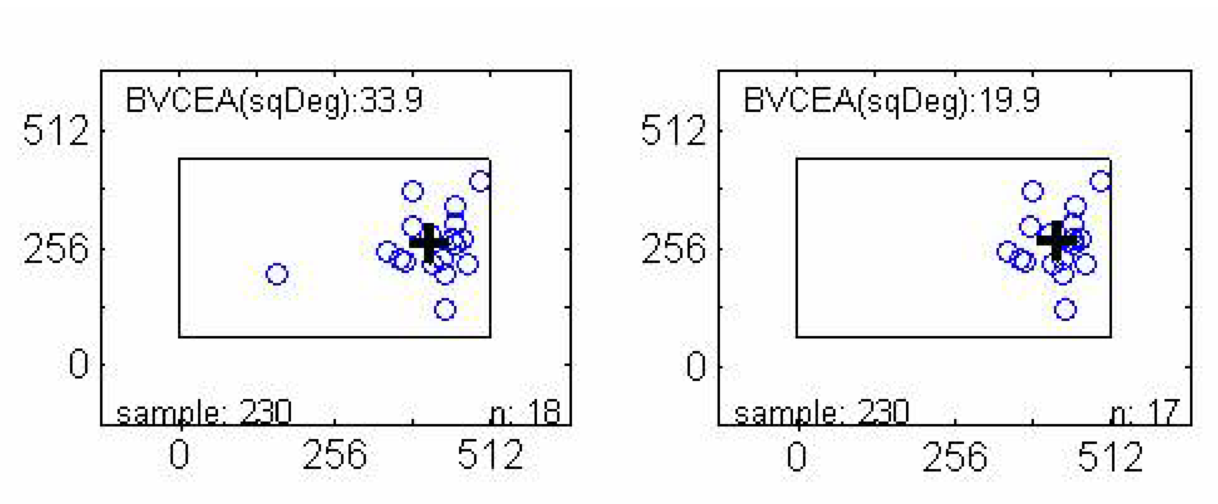

Fig. 2. The gaze points of the 18 subjects with valid eye samples (of the 20 subjects) for subframe 230 of the movie-clip "Quiz Show" are shown on the left. On the right are the 17 remaining gaze points following removal of the outlier. Removal of that outlier reduced the BCVEA (measure of the spread of the gaze points) from 34 sqDeg. (square degrees) to 20 sqDeg. (41%). The arbitrary units shown were used in data processing of the 26.3 deg.×14.8 deg. movie scene (inner rectangle). The crosses mark the COIs (mean of the gaze points), which moved by only 0.8 deg. on removal of the outlier. Note that this COI would be outside the screen for most magnification levels if magnification was to be centered at the center of the movie scene.

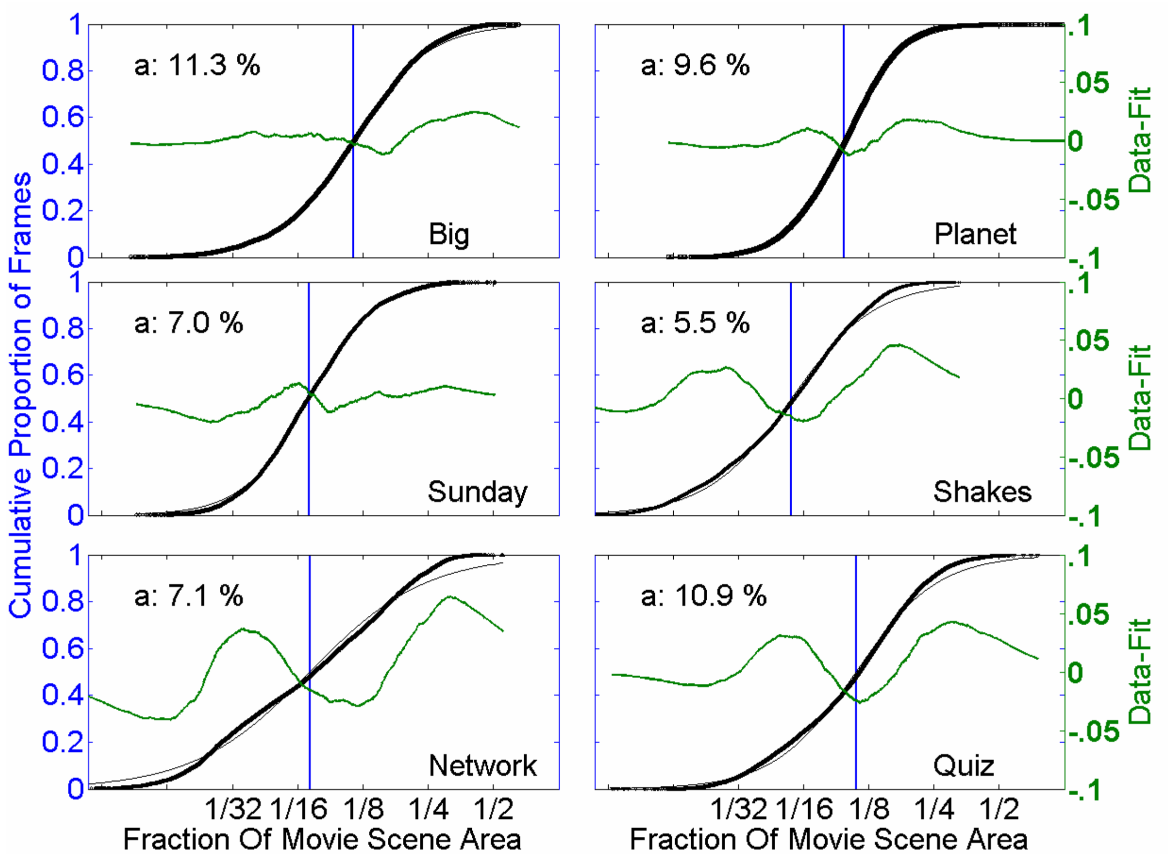

Fig. 3. For each movie-clip subframe, after removing outliers (see Fig. 2), the spread of the gaze points was estimated using the BVCEA, reported here as a fraction of the movie scene area. Only those subframes where 15 or more subjects had valid eye samples were used (see Fig. 1). The cumulative curves (heavy lines) show the proportion of the total subframes for which the BVCEA was less than a given fraction of movie screen area. Logarithmic transforms of the distributions were fitted to a logistic function (with *c*=0) (shown as the thin lines) that were then used to calculate the screen fraction for which 1/2 of the samples had a smaller BVCEA (*a:* vertical line and the value indicated by the inset). The residuals of the fits are shown (right y-axis for units).

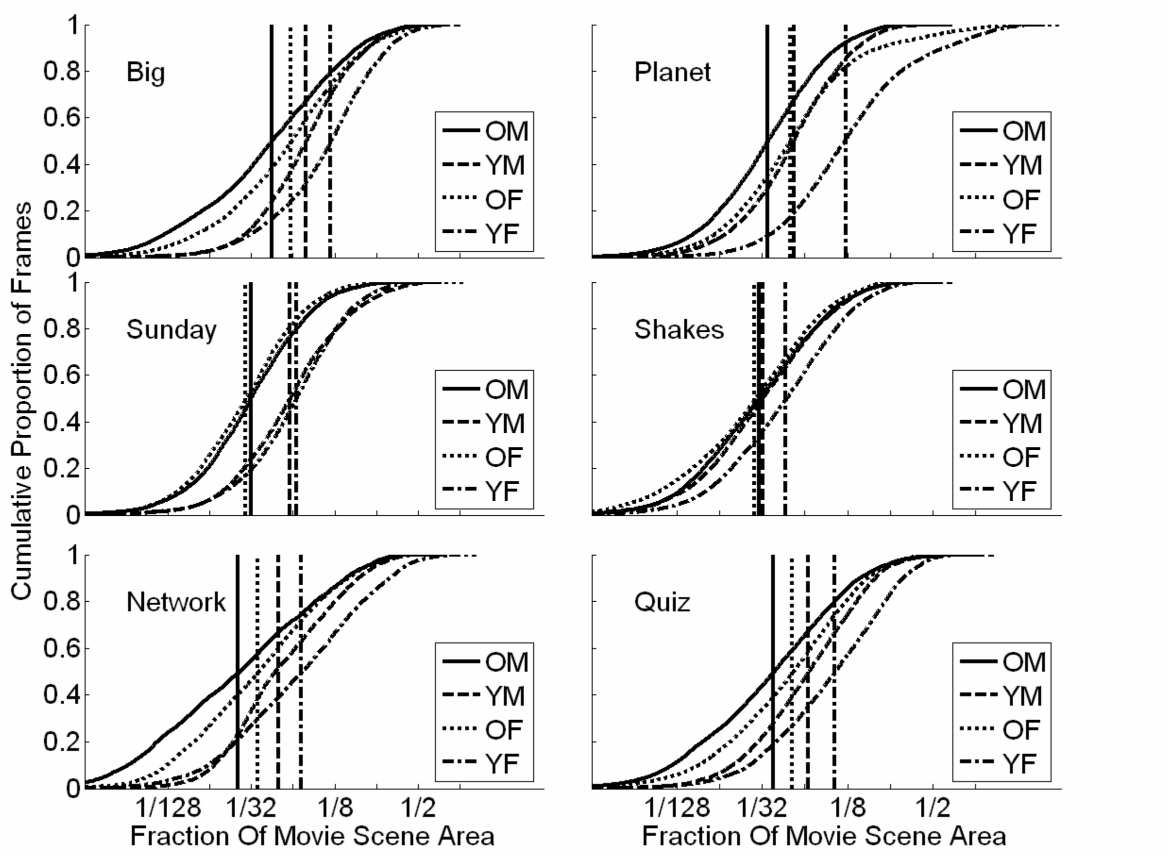

Fig. 4. As for Fig.3, the cumulative distributions of the BCVEA and positions of *a* from the fit (not shown) of each movie clip for each age-gender group (where at least 4 out 5 subjects had useable data). Older and male groups had smaller spreads of their gaze points (smaller BCVEA) than younger and female groups, respectively.

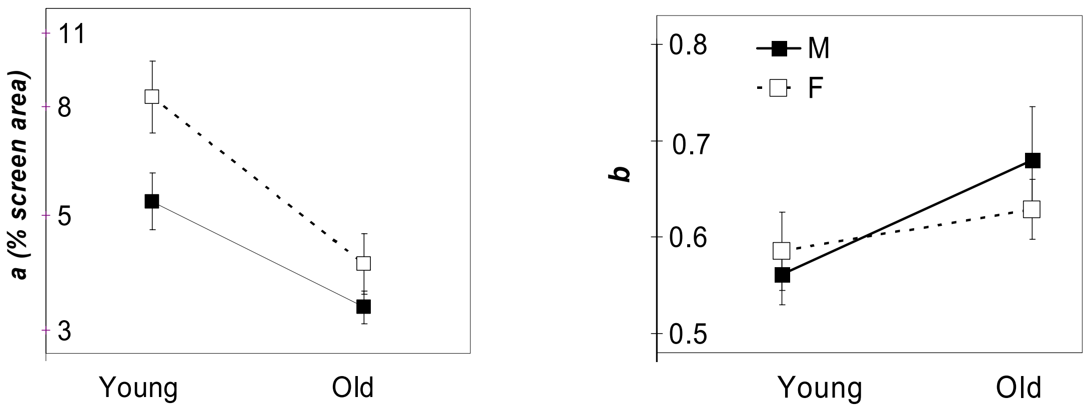

Fig. 5. There were statistically significant effects of gender and age on the likelihood that the subjects in a group looked in the same direction (*a*); and there was a small, non-significant age effect on the variability of direction of gaze (*b*). Note that the scale labels for (*a)* are non-linear, since the fit was done in the logarithmic transform of the area. Error bars indicate SEM.

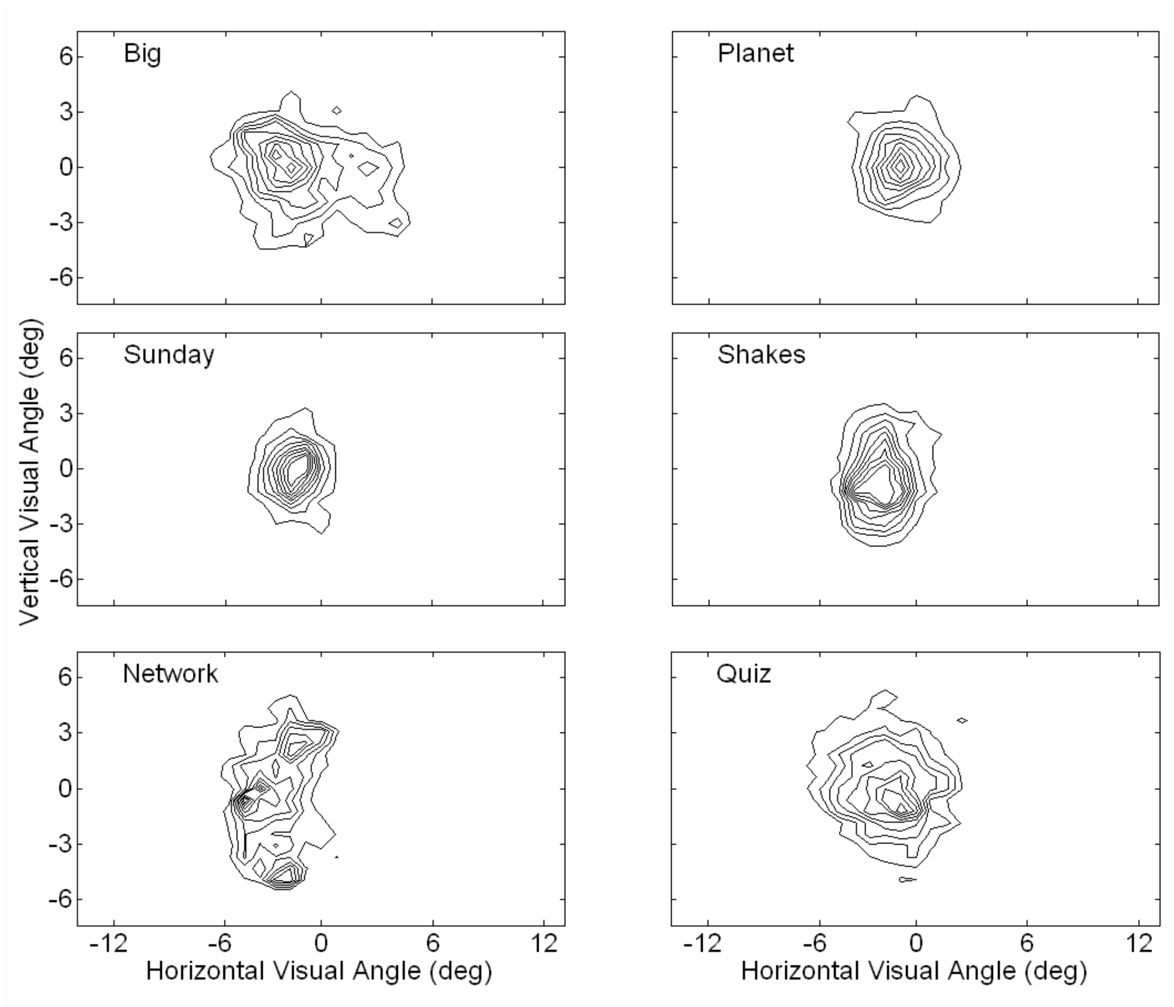

Fig. 6. COI distributions for all movie clips for all subjects (for subframes with eye samples for at least 15 subjects). The border represents the movie scene area. Data were normalized so that the maximum is 1.0 and levels are drawn at 0.1 intervals. Although generally, the distributions peak near the center of the screen, the spread indicates that a large proportion of the time, people did not look at the center of the movie scene.