COMPUTER TECHNOLOGY

An artificial eye for evaluating videobased eye recording systems

DANIEL CAVEGN, JOHAN VAN RENSBERGEN, and GÉRY D'YDEWALLE
University of Leuven, Leuven, Belgium

Videobased corneal-reflection-to-pupil-center systems are widely used in eye movement research. In this paper, an artificial eye drawn on a computer screen is presented. The artificial eye provides a way to simulate measurements of eye position in human subjects. The method allows testing videobased systems on the level of the signal and on the level of the calibration algorithm used to map the eye position parameters to stimulus space. In addition, the artificial eye can be used to evaluate specific hypotheses concerning the functioning or malfunctioning of the eye recorder and as a help in developing data analysis programs.

Videobased corneal-reflection-to-pupil-center systems for recording the point of regard are the method of choice in much research (see Young & Sheena, 1975). No attachments to the subject are necessary, head movements are permitted to some degree, and the current point of regard can be superimposed on-line on an image of the scene, which facilitates both the monitoring and the analysis of the experiments. On the other hand, such systems have considerable limitations. Temporal resolution is limited to the fixed video frequency (50 or 60 Hz), spatial resolution is limited to the video raster, and the analysis of the video image may focus on irrelevant features (such as reflections caused by tears). The methodological discussion has thus far focused on the problem of data reduction (Karsh & Breitenbach, 1983; Kliegl, 1981, 1984; Kliegl & Olson, 1981; Mandel, 1979; Mason, 1976; McConkie, Scouten, Bryant, & Wilson, 1988; Widdel, 1984; but see also Bronson, 1983; Hainline, 1981; Harris, Abramov, & Hainline, 1984; and Loftus, 1979). In this paper, a method is presented that allows one to test videobased machines on more basic levels—that of the signal and that of the calibration algorithm used to map the eye position parameters to stimulus space.

Videobased Eye Recording Systems

Videobased systems are used to find the point of regard—to determine the fixation point of the subject in

the visual world. Two parameters of the eye are combined in order to compute the point of regard: the center of the pupil and the center of the corneal reflection. The eye is illuminated by near-infrared light that the subject normally does not notice. The infrared light is reflected by the cornea and by the retina. Because the observing optics are coaxial with the illumination optics, the pupil appears bright and in clear contrast to the iris. In the analysis of the video image, the center of the pupil and the center of the corneal reflection have to be determined. The vector between these two points is unaffected by lateral head movements and has a specific value for each eye position. During calibration, the pupil–corneal vector is determined for a number of points whose position in stimulus space is known. Through use of a mathematical procedure (e.g., linear interpolation) on the calibration vectors, the pupil–corneal vector obtained during the experiment can be interpreted as indicating a fixation position in stimulus space. A more detailed technical description of the method can be found in the classic paper by Young and Sheena (1975).

For a good experiment, it is essential that the calibration be as accurate as possible, and that the recording conditions during measurement not change in comparison with the conditions during calibration. It is not always possible, however, to fully assess the quality of the calibration, or to ensure exact correspondence between the conditions during calibration and the conditions during measurement. For instance, the size of the pupil may vary, owing to the intensity of the stimuli during the experiment; head movements along all three axes may occur; or some calibration points may simply have been measured incorrectly. Further complications arise if one wants to ensure that the calibration algorithm does not distort the mapping of the raw data to fixation positions in stimulus space (this can happen if the algorithm assumes

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linearity and if nonlinearities in the signal arise because of corneal aspherism).

Because it is not always feasible to control for all of the preceding contingencies, we found it desirable to run a number of methodological studies to directly investigate their impact. Because we observed that the amount of noise varies between subjects and conditions, and because we are often faced with the problem of data loss, we also hoped to gain insight into the factors causing noise and data loss. One way would be to engage in methodological studies with human subjects. However, this approach allows very little control on the input side. The output of the eye recorder depends on many factors that can interfere with the extraction of the pupil–corneal vector (e.g., relative luminance of corneal reflection and backlit pupil for different eye positions, dropping eyelids, other reflections due to tears). Other factors change the pupil–corneal vector directly (e.g., head movements toward or away from the eye camera). When human eyes are measured, these factors can hardly be controlled and varied independently. An artificial eye, on the other hand, ensures exact knowledge of what is presented to the machine and allows one to study the impact of a single factor separately.

An Artificial Eye on a Computer Screen

Simple artificial eyes for videobased machines are easy to build, in comparison with those for other eye movement equipment. The eye position is determined by computing the center of the pupil and the center of the corneal reflection from a video image of the eye. The artificial eye need not physically resemble a real eye, but it has to allow the extraction of the same information from its video image as the human eye does. In principle, two round disks of paper with a different luminance (a large one for the pupil and a small, brighter one for the corneal reflection) on an appropriate background may already be sufficient. More flexibility is achieved by replacing the “paper” eye with an image on a computer screen. This allows precise temporal and spatial control of the input. The eye that we programmed and tested with our videobased machine consisted of nothing more than two different circular disks on a CRT screen. On a black background, a large, light gray disk (the artificial pupil) was presented that contained a much smaller white disk (the artificial corneal reflection). Changes of fixation position were simulated by movements of the corneal reflection (this is equivalent to movements of the pupil around a stable corneal reflection).

At least two technical difficulties have to be solved before one can measure the artificial eye. First, the recording camera has to be modified so that it can pick up the image of the computer eye. This can be achieved either by removing the infrared filter from the recording camera or by replacing the regular camera with a normal video camera with equivalent output. The second difficulty is related to the refresh rate of the computer screen. Because the information on a CRT display is refreshed at a certain rate (e.g., 50 or 60 Hz), and because the recording

device also works on a cyclic basis, problems of asynchronization may arise. If these problems cannot be solved otherwise, external synchronization of the screen and the recording camera should be considered. For our recording system, there was no problem as long as the refresh rate of the artificial eye was the same as the sampling frequency of the recording system, and as long as the artificial corneal reflection was not too small on the CRT screen (note that a big artificial eye on the CRT screen is not a problem, because it can be zoomed in to a standard size with the lens of the recording camera; if the light spot functioning as corneal reflection is built by many CRT lines on the screen, problems of asynchronization do not occur as frequently as when the corneal reflection is built with just two or three lines). We strongly advise testing the input to the eye recorder with the use of an oscilloscope. In this way, each video line can be visualized and the physical appearance of the artificial eye can be compared with a human eye.

Simulation of the Measurements of a Human Eye

The first study that we ran ensured that the artificial eye did indeed provide the same data as a normal human eye does. First, we calibrated and measured a human eye. Next, we calibrated and measured the artificial eye. The parameters of the artificial eye (size and luminance of pupil and corneal reflection, all pupil–corneal vectors in calibration and measurement) were adjusted so that they corresponded to those of the human eye.

The artificial eye was drawn with an ATVista (TrueVision Inc., Indianapolis, IN) graphics card (set in PAL, 50 Hz, interlaced mode, with a display resolution of 740×578 pixels) on a Barco CD233 CRT display. The pupil was a light gray disk with a radius of 6.5 cm; the corneal reflection was white and had a radius of about 0.5 cm; the background was black. In the video image, the pupil extended vertically over about 78 of the 312 lines of a half image; the corneal reflection, over about 6 video lines. The eye recording device was a Debic 90 system (Demel GmbH, Haan, Germany). Debic 90 functions at 50 Hz and has, according to the manufacturer, a spatial accuracy of 0.5° (for more information on the system, see Cavegn, Van Rensbergen, De Graef, & d'Ydewalle, 1992). To measure the artificial eye, we replaced the regular eye camera (a Sony video camera with an infrared filter) with the video camera normally used to record the scene (the same Sony video camera without the infrared filter). The output of the camera was sent to the video boards of the recording system, where the incoming images are analyzed.

In a first phase, we calibrated and measured a human subject. Calibration involved the presentation of a random sequence of 20 predefined LED lights, which were ordered in four rows of 5 lights (at a distance of 137 cm, the LED lights subtended a visual angle of 25°×20°). During the measurement, the subject had to look in a fixed sequence (left to right, top to bottom) at points in the middle of the 12 quadrants defined by the 20 LED lights of the calibration matrix (these points subtended a visual an-

Figure 1. Output of the Debic eye recording system for a human eye and for the artificial eye intended to mimic the human eye. The top row of each panel denotes the x-values—changes of fixation position in the horizontal dimension. The bottom row shows the y-values—changes of fixation position in the vertical dimension. The figure represents 14 sec of measurement, during which three rows of four locations were fixated.

gle of $18.7^\circ \times 13.3^\circ$). The subject looked at every point for about 1,000 msec.

The parameters of the artificial eye were fitted to those of the human eye. The eye of the subject had been videotaped; this videotape was used to assess the mean vector between the center of the pupil and the center of the corneal reflection for all fixation positions in calibration and measurement. The coordinates of the artificial corneal reflection were changed so that the artificial eye executed the same changes of fixation position as did the human eye. For the present purpose, the amplitudes of these changes were rectified and all other parameters were held constant within a fixation (i.e., we did not take into account the small variations in the records of the human subject; also the specific elliptic form of the pupil in the different eye positions was not simulated). Figure 1A gives the measurement values of the human subject; Figure 1B shows the result of the simulation with the artificial eye.

The x-values refer to changes of fixation position in the horizontal dimension; the y-values, to changes of fixation in the vertical dimension. About 14 sec of measurement are depicted. Figure 1B shows that the artificial eye can be used to simulate measurements of a human eye. With exception of the small instabilities in the y-dimension, Debic 90 did perfectly follow the changes of fixation position of the artificial eye.

Changes of Pupil Size and Pupil Luminance

One of the real merits of the artificial eye is that it enables isolating factors that affect the quality of eye recording. For instance, we were confronted with the following problem: In the intertrial interval, the room was dark; the subsequent presentation of a bright stimulus resulted in a strong contraction of the pupil, which caused increased noise and often the complete loss of the eye recording signal. We will now describe a small study in

Figure 2. Output of the Debic eye recording system for the artificial eye. In the upper panel, the pupil-corneal vector remained constant after a first change, but pupil size was varied for 2 sec from 100% to 87.5%, 75%, 62.5%, and 50%, and then back to 100%. Pupil luminance remained constant. No problems were observed. In the second panel, the same changes of pupil size were executed, but they were accompanied by darkening and brightening of the pupil. Problems of noise and instability were observed with the smallest and darkest pupil.

which we used the artificial eye to determine the reason for this problem.

First, we tested the influence of decreasing or increasing the pupil size independently of pupil luminance. The artificial eye was the same as in the previous simulation. The luminance of the artificial pupil was kept constant; it corresponded to the luminance of the pupil of a human subject (as determined by an oscilloscope). The beginning of the test phase was marked by a change to a new eye position. Starting from this moment, pupil size was changed every 2 sec. The pupil sizes used were 100%, 87.5%, 75%, 62.5%, 50%, and again 100% (the normal pupil size of 100% corresponded to 78 video lines; 50%, to about 39 video lines). As can be seen in Figure 2A, there were practically no measurement problems related

to the quite drastic changes of pupil size in the artificial eye.

In a second study, we changed both pupil luminance and pupil size. To obtain an indication of how big the changes of pupil luminance should be to be comparable with those of human subjects, we measured a human subject once with the room lights turned off and once with the lights turned on. The luminance of the smallest artificial eye was adjusted to the value obtained with the small pupil of the human subject and then increased in equal steps to the normal luminance used previously (again, the adjustments were made with the help of the oscilloscope; the changes of voltage corresponding to iris, pupil, and corneal reflection were read out for the video line in the middle of the artificial corneal reflection).

Pupil size was changed in the same way as in the preceding study. Figure 2B shows that more problems occurred in this case, especially with the smallest and darkest pupil.

In a further test, we did not change pupil size but only pupil luminance. It turned out that indeed the latter was responsible for the problems of noise and instability of the signal. Further tests showed that a bad "level adjust" is the reason for the problem related to the dark pupils. Level adjust in the case of the Debic systems refers to the procedure in which the user adjusts two thresholds, one to detect the pupil in the dark background, and one to detect the corneal reflection (there is also an option for automatic level adjust). In all the studies, we set the first threshold at the mean position between the luminance levels of background and pupil, and the second threshold at the mean position between the luminance levels of pupil and corneal reflection. With dark pupils, the first threshold can be set too high so that the pupil is not detected clearly any longer (see Young & Sheena, 1975). Wrong level adjusts can result in substantial amounts of noise and in data loss for several seconds.

The previous studies demonstrate how the artificial eye can be applied to isolate causes of measurement problems. In our lab, we used the artificial eye to evaluate the built-in and undocumented calibration procedure of Debic 80 and Debic 90 (Cavegn et al., 1992). For instance, we introduced explicit (nonlinear) distortions of the calibration values and varied the size of the whole artificial eye (in order to mimic movements of the subject toward or away from the camera). The artificial eye can also serve to test the reliability of the equipment over time, as a training device for people who start eye movement research, and as help in developing data analysis programs (with an artificial eye, the physical changes of fixation position are known).

Conclusion

In this article, an artificial eye has been presented as a way to test the functioning of videobased eye recording systems. The artificial eye allows precise temporal and spatial control of the input to the eye recorder. It can be used to test the quality of measurements and the adequacy of calibration, and to evaluate specific hypotheses concerning the functioning or malfunctioning of the system. All these applications can help users understand their eye recording equipment better. The artificial eye approach

may also be a way of achieving the standards in reporting data quality in eye movement research that were proposed by McConkie (1981).

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