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THE PSYCHOLOGY OF EYE-HAND COORDINATION IN HUMAN COMPUTER INTERACTION

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ABSTRACT
The analysis of the eye-hand coordination is a rather recent research area which is very important for the improvement of human computer interaction and is characterized in particular by its interdisciplinary approach. At present, there is an intensive discussion concerning the specific interaction patterns between the eye and the hand (mouse-cursor). In accordance to the analysis of the specific eye-hand coordination (eye guidance, eye-hand synchronicity, and hand guidance) in the following experimental investigation, 141 participants were examined by means of eye movement analysis (eye tracking). As far as the stimulus material is concerned, three different complex labyrinth tasks were presented. With regard to the specific eye-hand coordination during the solution process of the different labyrinth tasks, the results show new evidence concerning the eye guidance, the delay time of the hand (mouse-cursor), and the specific complexity degree.

KEY WORDS
Psychological Aspects of HCI, Perceptual and Adaptive User Interfaces, Eye-Hand Coordination, Eye Movement Analysis

1. Introduction

The eye-hand coordination dominates many aspects of our daily life, e.g. raising a coffee cup, throwing a ball, or using a computer mouse when it comes to the human computer interaction. According to Crawford et al. (2003 [1]), scientists have already engaged themselves for decades with the eye-hand coordination.

As of recently, the eye-hand coordination became a distinguishable and connected research field. This is not surprising, as the complete understanding of the eye-hand coordination ought to consider information about spatial seeing, the eye movements, several aspects of cognition and neurophysiology, and the muscle control of arm and hand (Desmurget et al. 1998 [2]).

The movements from body, head, and eye to the localization of objects are one of the most complex situations for the visuo-motor system, whereas we only now start to consider the complexity of the eye-hand coordination (Whitney & Goodale, 2005 [3]). In their investigation, Henriques et al. (2003 [4]) dealt with the question whether the retinal movement during smooth pursuits contributes to visuo-motor control. The results of their investigation indicate that retinal background movements are used by the visuo-motor system and visually led actions are controlled. Hence, eye movements supply a support for the guidance of the hand. According to Crawford et al. (2004 [5]), the eye movements are nevertheless the underlying slave of the system, since only the hand movements can affect the environment directly. According to Binsted et al. (2001 [6]), the hand does not seem to be the slave of the eye, though. In their investigation, the hand remained, for instance, exactly on a goal position, while the eye rested beneath or above the goal position.

During a target-oriented hand movement, the controlling nervous system is depending on sequential information of the visual system (Horstmann & Hoffmann 2005 [7]). Therefore a coupling of these two systems is of crucial importance regarding the eye-hand coordination. At present, there is an intense debate about whether the eye is actually the slave of the hand or contrariwise the hand is indeed the slave of the eye. In accordance with Johansson et al. (2001 [8]), the view of the eye – i.e. the eye guidance – supports the planning of hand movements by the marking of key positions for the future target acquisition of the hand. Sheth and Shimojo (2002 [9]) examined the effects of a missing visuo-motor feedback related to the early stages of target-oriented movements. The loss of the visuo-motor feedback has already become apparent in early acceleration phases of the movement path. As a result of the uncontrolled absence of the visual observation, the acceleration phase of the cursor movement lasted longer, the highest motion speed was reached later, and the speed of the cursor reduced faster. The results show on the one hand that the visual feedback plays a decisive role

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in the determination of acceleration and on the other hand that it is indispensable to the late stages of the hand movement. In order to compensate the absence of seeing, the so-called non-visual modalities are too slow. The visual feedback of the human hand is used sequentially for the guidance of fast movements (Saunders & Knill, 2003 [10]).

Concerning the research of the eye-hand coordination, the consideration of the observed saccades also has an important part. Snyder et al. (2002 [11]) demonstrated an increase of the saccade velocities in accordance to the movement coordination between arm and eye. With corresponding, simultaneous, and target-oriented eye-hand movements the response time of saccades and the number of correcting saccades is reduced (see Lünenburger et al. 2000 [12]). However, the response time increased with the opposite movement of the eye and the hand. If an error arises during the target-oriented movement, the estimation of the future hand position is computed over again. The period of the saccade inhibition following on it (which follows after the incorrect hand position) indicates the necessary time for the revaluation of the hand position. In addition to the saccades, the fixations have an important part in the analysis of the eye-hand coordination. For example, Pelz et al. (2001 [13]) showed that the hand movement is delayed until an information-attractive fixation was almost complete. Here, the hand movement was delayed until the eye attained the ability for the guidance of the movement.

In consideration of the eye-hand coordination, Henriques et al. (2002 [14]) suggest the conversion-on-demand hypothesis of the visuo-motor representation and control (see Henriques et al. 1998 [15], Crawford et al. 2003 [1]). At first, the goal representations are held in a centered context of the eye. The final retinal representation is specified with selection of an action goal. Finally, an exact three-dimensional motor signal within the motor reference framework is produced. A key feature of this model is its use of the early goal representation in a retinal framework. Therefore, the representations must be updated with each eye movement. Thereby the working memory signals of the represented field of vision are brought up-to-date (see Snyder 2000 [16]). A certain action goal is specified for following transformations in each case, as e.g. the comparison of the eye and hand orientations, the computation of the opposite, and the dynamics of the arm. In a biological perspective, this way contains a space and energy-saving characteristic.

The complex interaction of the eye and the hand represents a difficult research area, whereas the specific interaction patterns of the eye and the hand are still discussed in literature. For example, the eye-hand coordination does not proceed throughout all subjects consistently (see Smith et al. 2000 [17]). Regarding to this, three different behaviour patterns of the participants could be observed. Up to the relevant goal, the eye movement follows the cursor (1), the eye movement leads the cursor to the respective target (2), and until reaching the goal, the eye movement jumps by alternating between the target and the cursor (3). Regarding the common eye-hand coordination, the results from Sailer (2003 [18]) resp. Sailer et al. (2005 [19]) show a particularly early spatial separation between eye and hand. Thus, the eye rapidly takes up a new goal representation, while the hand still acts on the basis of earlier information on the old target. The core question of the following experimental investigation refers to the examination of the possible leadership behaviour of the eye (eye guidance) and the specific interaction patterns of the eye-hand coordination, respectively.

2. Method

2.1 Participants

In the following experimental investigation, the eye movements of 141 students of the University of Innsbruck were examined. The average age of the subjects was 24.6 years (SD = 5; 13 – 49 years). Altogether, 91 women (65%) and 50 men (35%) took part in this investigation. All subjects had normal uncorrected seeing resp. carried eyeglasses or contact lenses, which ensured a normal view in order to accomplish the examination task. The total number of participants with contact lenses or eyeglasses amounted to 41%. The subjects were paid to participate. All participants were in the dark about the purpose of the experiment.

2.2 Materials

Concerning the visual stimulus material, three different labyrinths differing in their complexity and with several entrances were presented to the subjects. The determination of the complexity degree was made by the number of entrances (1), the number of goal-prominent entrances (2), the shortest ideal way to the target (3), and the number of way deviations from the shortest ideal way (4). Thus, the labyrinths must fulfill the following conditions: They must have several entrances, lead across several ways to the center, and have dead ends. Labyrinth drafts from different artists were used in this investigation. The specified presentation sequence of the labyrinths comes with an increase in the complexity degree (see Figure 1). The first labyrinth is from Jean Francois de Neufforge: “Copper engraving with six ground plans for garden labyrinths” (Kern 1999 [20]); the second labyrinth is from Petrus Laurembergius: “Horticultura” (Bord 1976 [21]); and the third labyrinth is from Ignaz Haas: “Drafts for garden labyrinths” (Kern 1999 [20]).

Figure 1: The set presentation sequence of the labyrinth tasks, showing an increase in the degree of complexity in the labyrinth tasks from the left (labyrinth 1) to the middle (labyrinth 2) to the right (labyrinth 3).

2.3 Apparatus

In the following experimental investigation a so-called table-mounted remote eye-tracking system was applied. The recording of the eye movements occurred with a gazepoint sampling rate of 120 Hz (binocular cameras), while the Eyegaze Analysis System from LC Technologies, Inc. was used. Viewing was binocular and both eyes were monitored. The labyrinths were presented in full-screen mode on a View Sonic VG700b 17-inch monitor with an image repetition frequency of 75 cycles per second at a viewing distance of 60 cm (about 23.6 inches). With the help of two control monitors during testing, the right and the left eye may be deemed to be in real time and the position of the subjects can be corrected if necessary. The eye-tracking analysis software NYAN version 1.2 was used for the recording of the eye movements. The monitor and the eye-tracker were interfaced with a Pentium IV PC.

2.4 Procedure

At the beginning of the experimental investigation, the participants received a detailed written instruction concerning how to carry out the tasks and accomplish the specific solution of the three labyrinth tasks. The subject was instructed to begin the eye movements with an entrance of his or her choice. Simultaneously with the eye movement, the subject should try to hold the mouse-cursor in the particular place of view. If the subject comes to a dead end, he or she would have to move him- or herself backwards along this way by means of eye and cursor movement in order to turn into on another way. If all ways of one entrance were unsuccessfully gone through, the participant had to begin again with another entrance of his or her choice. After the subject reached the center of the labyrinth, the goal of the labyrinth task was fulfilled and the specific task was completed. The participant could change to the next labyrinth task via mouse-click. The time frame for the solution of the labyrinth tasks was open. In general, the subjects were instructed to move their head and body only slightly during the eye-tracking experiment. The initial calibration of the eye tracker took on the average three minutes and the complete experiment took about 20 minutes.

3. Results

In relation to the analysis of the eye-hand coordination in each labyrinth task the individual solution time of a subject was divided by seven. As uncoordinated eye-hand interactions frequently take place at the beginning and at the end of the solution process, five specific points for each labyrinth task were used for the final data analysis. Beside the analysis of possible difference times at the five coincidentally marked points, the frequency examination of the following criteria was recorded: the eye is before the hand (mouse-cursor) (1), the eye and the hand (mouse-cursor) are at the same point (2), and the hand (mouse-cursor) is before the eye (3).

Throughout the three labyrinth tasks, altogether 1.905 specific points were registered according to the eye-hand coordination (labyrinth 1: 640; labyrinth 2: 645; labyrinth 3: 620). All analyses were done with an alpha level of .05 (two-tailed), whereas Cohen's f indicates effect size for the ANOVA.

The results show a clear delay time of the hand (mouse-cursor) throughout all three labyrinth tasks. Related to the specific eye fixation, the smallest delay time (in ms) of the mouse-cursor shows up with the third and most complex labyrinth (M = 511, SD = 290). The simplest labyrinth task (labyrinth 1) exhibits also a cursor delay time of over half a second (M = 536, SD = 475), while the longest delay can be registered with the second labyrinth (M = 660, SD = 443). An analysis of variance (ANOVA) revealed a significant main effect of the labyrinth condition on the delay time (in ms) of the mouse-cursor, $F(2, 378) = 4.78$, $f = .15$, $p = .09$ (see Figure 2).

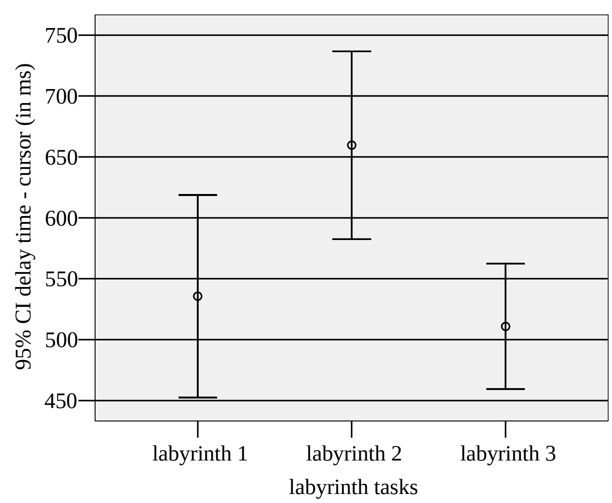

Figure 2: Mean delay times (in ms) of the hand (mouse-cursor) in relation to the respective eye position throughout the three different complex labyrinth tasks. Error bars display within-subjects 95% confidence intervals.

The analysis of the mean differences occurred by means of the Games-Howell post hoc test. Hereby, a significant difference between labyrinth task 2 and 3 can be observed (p = .005), whereas there were no significant differences found between labyrinth 1 and labyrinth 2 (p = .079) as well as labyrinth 1 and labyrinth 3 (p = .871).

In the following analyses, we entered into the question whether there are differences concerning the frequency of the mouse-cursor delay time regarding the three different complex labyrinth tasks. By means of the Kruskal-Wallis H-test, the mean ranks of the frequency of the mouse-cursor delay time (labyrinth 1: 205; labyrinth 2: 214; labyrinth 3: 155) refer to a significant main effect (H = 22.09, p = .000). The single comparisons between the labyrinths take place with the U-test. There was no significant difference observed between labyrinth 1 and labyrinth 2 (U = 7975, p = .478). However, between labyrinth 1 and labyrinth 3 (U = 5997.50, p = .000) as well as labyrinth 2 and labyrinth 3 (U = 5523.50, p = .000) significant differences were found.

Other than the observation of the mouse-cursor delay time, certain frequencies of eye-hand synchronicity could be observed in this investigation. This means that the eye and the hand were at a coincidentally selected time accurately at the same point. The examinations of the three labyrinth tasks supply the following mean ranks: labyrinth 1: 91, labyrinth 2: 80, and labyrinth 3: 93. The analysis by means of the H-test does not show a significant main effect (H = 3.81, p = .149). In addition, the single comparisons by means of the U-test do not show significant differences concerning the mean ranks of the frequency of the eye-hand synchronicity: labyrinth 1 and labyrinth 2 (U = 1536.50, p = .093), labyrinth 1 and labyrinth 3 (U = 1939.50, p = .800), and labyrinth 2 and labyrinth 3 (U = 1141, p = .062).

The mean ranks of the specific frequency of the mouse-cursor delay time and the eye-hand synchronicity show the following values for each labyrinth: labyrinth 1: mouse-cursor delay time: 136, eye-hand synchronicity: 41; labyrinth 2: mouse-cursor delay time: 113, eye-hand synchronicity: 27; labyrinth 3: mouse-cursor delay time: 114, eye-hand synchronicity: 36. In this connection significant differences between the mouse-cursor delay time and the eye-hand synchronicity yield over all single comparisons by means of the U-test: labyrinth 1: U = 334.50, p = .000; labyrinth 2: U = 112, p = .000; labyrinth 3: U = 454, p = .000. Therefore the frequency of the mouse-cursor delay time in each case differs significantly from the frequency of the eye-hand synchronicity.

4. Conclusion

The results of the experimental investigation concerning the specific eye-hand coordination show a clear evidence in favor of the eye guidance. Based on the large sample (N = 141) of this investigation, an average delay time of the hand (mouse-cursor) could be registered by over half a second (570 ms). Regarding the complexity degree, a significant difference can be observed throughout the three labyrinth tasks concerning the delay time of the hand (mouse-cursor). The labyrinth with medium complexity (labyrinth 2) shows the longest mouse-cursor delay time with 660 ms; the simplest labyrinth task follows with 536 ms and the most complex labyrinth 3 with 511 ms. These results are extremely important since the participants were instructed to hold their eyes and the mouse-cursor in each case at the same place during the solution process of the labyrinth task. Besides the registered samples of the eye guidance and the eye-hand synchronicity, the hand guidance could not be observed in this study, though. Therefore, this dimension was excluded from the frequency analyses. Concerning the complexity degree of the three labyrinth tasks, a significant main effect shows up, whereby the specific post hoc analysis shows a significant difference between the middle and the most complex labyrinth task. The general influence of the complexity of the stimulus material on the delay time of the hand (mouse-cursor) must be examined in further studies.

The analysis of the frequency of the hand (mouse-cursor) delay time shows a specific pattern regarding the complexity degree throughout the three labyrinth tasks. The highest frequency of the mouse-cursor delay time can be observed with the first and simplest labyrinth, followed by labyrinth 2 and the most complex labyrinth 3, whereas this main effect is significant. In this connection, the single comparisons show significant differences between the simplest and the most complex and between the middle and the most complex labyrinth task, respectively. In addition to the occurrence of the mouse-cursor delay time, also cases of the eye-hand synchronicity were observed throughout the three labyrinth tasks. That means the respective eye fixations and the cursor positions were precisely at the same place. Regarding the first and simplest labyrinth, the most frequent cases of eye-hand synchronicity could be registered, followed by the most complex labyrinth and by the second labyrinth task, whereas no statistic difference results throughout the three labyrinth tasks. In addition, the single comparisons between the labyrinths do not supply significant differences regarding the eye-hand synchronicity.

In the last analysis step the frequencies of the mouse-cursor delay times were compared with the respective cases of the eye-hand synchronicity. Concerning this matter, the difference examinations show a clear result. In the case of all three labyrinth tasks, a significant more frequent delay time of the mouse results. In comparison to the results from Smith et al. (2000 [17]), the findings of this investigation show a distinct eye guidance. Against the opinion of Crawford et al. (2004 [5]) or Binsted et al. (2001 [6]), the eye does not show under any circumstances the role of a potential slave of the hand. The results concerning the eye guidance support the observations of Sailer (2003 [18]) or Sailer et al. (2005 [19]), regarding a rather early spatial separation from the eye and the hand with reference to a rapid visual orientation and anticipation from new information of the visual world. The findings concerning the complexity degree of a stimulus supply a starting point for following investigations, whereas an effect can be expected concerning the complexity of a task and the delay time of the hand (mouse-cursor).

At this point, a comparison of the available results with findings from the neurophysiology concerning the eye-hand coordination is interesting. Miall and Reckess (2002 [22]) accomplished an extensive review over the different methods and realizations for the study of the eye-hand coordination, whereby in particular the cerebellum plays an important part according to the time course of the eye-hand coordination (see e.g. Miall et al. 2000 [23], Miall et al. 2001 [24], Iacoboni 2001 [25]). The forward model of the cerebellum generates time-specific signals, which predicts the movement of any motor effectors, whereby this process is substantial for the predictive control of eye and hand movements. With pursuit of the same spatial path, the process achievement of the common eye-hand coordination is better than during an individual performance (e.g. only with the eye or the hand). However, the accomplishment is still better if the eye leads the hand with a time interval of approximately 75 – 100 ms. Thus, the eye control system supplies the manual system with important information about the further process. Apart from the cerebellum, the parietal lobe plays an important part regarding the eye-hand coordination. Lesions in the parietal cortex lead to impairments of visually guided movements (cf. Mascaro et al. 2003 [26], Jackson et al. 2005 [27]). In particular, the posterior parietal lobe (PPL) could be a possible communication center for the eye-hand coordination (Cohen & Anderson 2002 [28]). All told, the observed eye guidance of the available experimental investigation will be supported by findings from neurophysiology. The results concerning the eye guidance and the specific delay time of the hand (mouse-cursor) of approximately half a second provide, for example, application areas in the range of the improvement of human computer interaction, the organization and development of user interfaces, or may also be used for the development and the research in robotics.

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