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A comparative study of information input devices for aging computer users

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The fast aging of many western and eastern societies and their increasing reliance on information technology create a compelling need to reconsider older users' interactions with computers. Changes in perceptual and motor skill abilities that often accompany the aging process have important implications for the design of information input devices. This paper summarises the results of two comparative studies on information input with 90 subjects aged between 20 and 75 years. In the first study, three input devices – mouse, touch screen and eye-gaze control – were analysed concerning efficiency, effectiveness and subjective task difficulty with respect to the age group of the computer user. In the second study, an age-differentiated analysis of hybrid user interfaces for input confirmation was conducted combining eye-gaze control with additional input devices. Input confirmation was done with the space bar of a PC keyboard, speech input or a foot pedal. The results of the first study show that regardless of participants' age group, the best performance in terms of short execution time results from touch screen information input. This effect is even more pronounced for the elderly. Regarding the hybrid interfaces, the lowest mean execution time, error rate and task difficulty were found for the combination of eye-gaze control with the space bar. In conclusion, we recommend using direct input devices, particularly a touch screen, for the elderly. For user groups with severe motor impairments, we suggest eye-gaze information input.

Keywords: human–computer interaction; demographic change; aging; input devices; eye-gaze control; hybrid user interfaces

1. Introduction

Effective, efficient and satisfying human–computer interaction is strongly influenced by input information into the system. Information input occurs through the use of dedicated input devices which sense physical properties of people, places or things. There is a large variety of classical input devices, e.g. mouse, trackball, joystick, touchpad or touch screen. Moreover, one can also use advanced contact-free input systems, e.g. gesture-recognition, eye-gaze control or speech input.

The variety of devices and systems used for information input can be classified according to several input characteristics (Hinckley 2008). For example, the *property sensed* by an input device can be the absolute position of a pen on a tablet PC or the relative change in position of a mouse movement. The property sensed is essential for mapping input and output. Another input device property is the *number of dimensions* involved in information input. For example, the number of dimensions sensed is one for a knob (angular), two for a mouse (linear) and three for a gesture recognition system with data gloves (vectorial). The interaction technique can be either *direct or indirect*. A direct input device does not require a spatial or spatial-temporal transformation between the motor activity performed by the user and the calculated position of the cursor on the screen; examples include a touch screen and eye-gaze control. Indirect devices, however, require more or less complex sensumotor transformations. *Sensumotor transformation* (Heuer 1983) means the spatial transformation and the spatial-temporal transformation. The spatial transformation describes the relationship between the manual movement and the cursor movement displayed. The spatial transformation is easy when there is no spatial shift between information input and output and difficult when the plane of movement does not correspond to the plane of information output. For example, a hand movement with the mouse is transformed from a horizontal plane into a vertical plane, i.e. the cursor movement on the screen. The spatial-temporal transformation or *gain* (control to display ratio) of an input device refers to the distance moved by an input device divided by the distance (of the cursor) moved on the display.

As a result, different input device characteristics make different requirements of human abilities. Therefore, the compatibility between device characteristics and the abilities of the user determines the objective and subjective input performance to a large extent.

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Many scientific studies in the field of psychology and physiology have shown that aging can lead to significant changes in sensory, cognitive and motor abilities (Birren and Schaie 2006). Changes in motor abilities such as reduced muscle strength, reduced range of motion and greater difficulty executing fine movements are highly correlated with age (Mathiowetz *et al*. 1985, Stubbs *et al*. 1993, Walker *et al*. 1997) and of major importance for information input. Thus, elderly computer users may need other input devices or different transfer functions with less challenging motor ability requirements and less complex sensumotor transformations than younger users.

In the present paper, we will address the following research questions:

(1) Is the effectiveness and efficiency with a given input device significantly influenced by the age group of the user?
(2) Can age-related differences be compensated through the use of alternative input devices?

2. Literature review

2.1. Ergonomic evaluation of information input devices

Most ergonomic studies of information input devices distinguish efficiency (i.e. execution time) and effectiveness (i.e. task completion or errors) as the main objective usability criteria (Jordan 2002).

A widely used measure of efficiency of information input is the time needed to execute a task. In this context, Fitts' law is an important scientific foundation for predicting execution times of pointing tasks (Fitts 1954). Fitts' law predicts the movement time of goal-directed movements on the basis of two parameters: target distance and target width. The movement time (MT) is linearly dependent on the index of difficulty (ID) of a movement:

$$\mathrm{MT} = a + b \cdot \mathrm{ID} \qquad (1)$$

Fitts' coefficients a and b are determined by linear regression. The first coefficient a is a theoretical intercept for $\mathrm{ID} = 0$. It can be interpreted as reaction time. The second coefficient b is an indicator of input performance. Its reciprocal value $\left(\frac{1}{b}\right)$ describes the index of performance in bits per second (bps) (Card *et al*. 1978). The ID of a movement is defined as the logarithm of the quotient of amplitude of the movement (A) and target width (W):

$$\mathrm{ID} = \log_2\left(\frac{2A}{W}\right) \qquad (2)$$

Fitts' law can be considered as a scientific de facto standard to compare and evaluate the efficiency of information input devices (Card *et al*. 1978, Epps 1986, Ware and Mikaelian 1987, MacKenzie 1989, Brogmus 1991, Gillan *et al*. 1992, Akamatsu 1995, Guiard *et al*. 1999). It has also been successfully applied to model and assess pointing tasks for aging users. For example, Iwase and Murata (2003) used Fitts' formula to predict movement time for point-and-click tasks with a mouse. Similarly, Murata (2006) predicted movement time for mouse and eye-gaze control.

Moreover, the error rate is an important variable to measure the effectiveness of information input devices. Jordan (2002) distinguishes deviations and human errors from effectiveness on the task itself. Effectiveness on the task describes whether the task was completed at all, while deviations are divergences from the critical path. Errors, in turn, are characterised by a need for correction.

In addition to the cited objective dependent variables, subjective ratings of task difficulty, comfort or user satisfaction are important indicators for evaluating the usability of information input devices (Jordan 2002).

2.2. Input devices for aging users

Changes in motor functions and perceptual ability often occur with older age (Gogging and Stelmach 1990, Park and Schwarz 2000, Birren and Schaie 2006, Craik and Salthouse 2008) and frequently lead to ergonomic problems with information input devices.

The effect of age-induced changes on motor performance in real task settings depends on physiological constitution and lifestyle and is therefore highly individual. Consequently, some categories of computer users face age-induced changes in the human motor system which can lead to a significant decrease of motor performance in terms of speed and accuracy. Physiological changes of the human motor system pertain to a decrease in muscular strength, endurance and tone (Spirduso and MacRae 1990, Khalil *et al*. 1994, Vercruyssen 1997). With increasing age, neurophysiological changes of the central nervous system occur that involve changes in motor neuron population and motor unit properties (Darling *et al*. 1989), an atrophy of the motor cortical regions and a degeneration of the dopaminergic system (Seidler *et al*. 2010). These (neuro-)physiological changes lead to a generalised slowing of most behaviours (Welford 1984, 1981, Spirduso and MacRae 1990). An important experimental approach for the evaluation of information input devices is the analysis of rapid aimed movements. Rapid aimed movements also underlie age-induced changes. Regarding movement time, the following differences between younger and older adults were found: the elderly take more time for movement initiation (Stelmach *et al.* 1988, Amrhein *et al.* 1991, Yan *et al.* 1998), are less able to efficiently terminate movements (Pratt and Chasteen 1994, Seidler-Dobrin and Stelmach 1998, Fradet *et al.* 2008), spend more time in the error correction phase (Seidler-Dobrin and Stelmach 1998), produce higher sub-movement distances (Pratt and Chasteen 1994), rely more on visual feedback during the error correction phase of movements (Haaland *et al.* 1993, Yan *et al.* 1998) and are less able to calibrate appropriate levels of force (Walker *et al.* 1997).

Clearly, the predominantly used input device is the mouse. The computer mouse has two distinct disadvantages for the elderly computer user: First, the spatial-temporal sensumotor transformation becomes particularly difficult if the control to display ratio is less than one (Laursen *et al.* 2001, Sandfeld and Jensen 2005). Second, in mouse usage the muscles in the forearm, wrist and fingers are activated in short and very frequent cycles (Goebel *et al.* 2002), which can cause repetitive strain injury syndrome (Pascarelli and Quilter 1994). In various scientific studies, problems experienced by elderly computer users while working with the mouse are reported. In a study involving one group of younger participants and one group of older ones, Walker *et al.* (1996) studied the effect of age in a point-and-click task with a mouse. The authors point out that the elderly computer users were slower and less accurate, especially when the target width was small. Age-related decrements in performance could, however, be compensated by varying the control to display ratio. Smith *et al.* (1999) draw similar conclusions regarding movement time and errors: More complex tasks such as 'clicking' and 'double-clicking' yielded significant age effects in contrast to less complex tasks such as 'pointing' and 'dragging'. A regression analysis showed that a low motor ability was the best predictor for errors. Studies by Riviere and Thakor (1996), as well as Iwase and Murata (2003), confirmed significant differences in execution time and accuracy between elderly and younger mouse users. Chaparro *et al.* (1999a, 1999b) investigated the performance and preferences of 10 younger (mean age 31.55 years) and 10 older subjects (mean age 70.15 years) making rapid aimed point-and-click and click-and-drag movements using either a computer mouse or a trackball. In addition, the muscular force of the forearm was measured by electromyography. The results show slower mean movement times for the elderly. Regarding error analysis, the elderly performed equally well or even better. The younger participants showed higher speed and accuracy when using the computer mouse. Regarding subjective perceived exertion, the elderly clearly preferred the trackball over the mouse. The mean muscular force of younger and older participants did not differ significantly, but according to Chaparro *et al.* (1999a), it is reasonable to assume that the muscular force shown by the elderly represents a greater working force relative to the maximum voluntary contraction. The authors conclude that the trackball is a better input device for the elderly than the computer mouse.

Riviere and Thakor (1996) analysed performance on two tasks, vertical and circular target tracking. In both the tasks, older users' execution times were longer and the input was less accurate. Iwase and Murata found age-related decrements in execution time but not in error rate in a simple pointing task. Rogers *et al.* (2005) found indirect input devices superior to direct input devices in terms of effectiveness in repetitive tasks such as selecting different slides and menus on a digital control panel.

An input device with fast growing popularity is the touch screen. The touch screen is a direct input device that (theoretically) requires neither spatial nor spatial-temporal transformation. As shown by Rogers *et al.* (2005), direct input devices are superior for long, ballistic movements. When using a touch screen, muscles in the shoulder, upper arm, forearm and index finger are activated. Thus, when working with a touch screen for longer periods, significant arm fatigue occurs. This is ergonomically critical especially for older users (Ahlström *et al.* 1992). There are a few comparative studies of information input with a mouse and touch screen with older computer users. In a study by Iwase and Murata (2003), the subjects had to execute a simple pointing task, in which target size, angle and distance to the target were varied. Compared to the input using the mouse, the touch screen input eliminated age effects in execution time throughout all conditions. Error rates were not significantly different between input devices and age groups. Studies concerning human performance with an email program as well as the appliance of an in-vehicle entertainment system also revealed the positive effects of touch screens compared to other input devices (Yarnold *et al.* 1996, Shneidermann 1998, Pak *et al.* 2002, Umemuro 2004, Rau and Hsu 2005).

If the computer user's eye-hand coordination is severely impeded, then eye-gaze control should be considered. The cursor position is controlled by the eye's position that can be measured either with head-mounted or contact-free systems. Compared to conventional information input by mouse, which often requires significant training, eye-gaze controlled input is based on users' 'natural behaviour' when focusing on visual objects (Jacob 1993). Moreover, eye-gaze control has the advantage of low muscular strain for eyeball movement and is therefore a promising input device for elderly users. There are many studies concerning the use of eye-gaze controlled information input. The studies of Kammerer *et al.* (2008), Wobbrock *et al.* (2008), Huckauf and Urbina (2007), Sibert and Jacob (2000), Jacob *et al.* (1994), Jacob (1993), Fray *et al.* (1990) and Hutchinson *et al.* (1989) report performance advantages over classical devices only for younger computer users. They did not consider age-specific differences. Murata (2006), in particular, focused on elderly computer users and compared eye-gaze control and mouse input. Subjects carried out a typical point-and-click task under different target sizes and distances. To confirm the selection of objects under the eye-gaze condition, dwell times of 100 ms were used. For mouse input, elderly users showed significantly longer execution times than younger users. When using eye-gaze control, no age-related differences in execution time were measured.

However, a performance and workload critical factor in eye-gaze control is the confirmation of input commands. A popular approach is to confirm the input commands through dwell times (Jacob 1993). From the literature, it is known that the optimal duration of dwell times is difficult to determine. A too short dwell time can lead to unintended input commands simply because the user was looking around ('Midas Touch Problem', Jacob 1991). Conversely, a too long dwell time does not conform to users' expectations and weakens the main advantages of vision-based control, responsiveness and speed. A more suitable alternative are so-called 'hybrid user interfaces' combining eye-gaze control with additional input devices, such as buttons, mouse or speech input (Glenn *et al.* 1986, Zhai *et al.* 1999).

The literature review shows that both direct touch and eye-gaze control are promising alternative information input techniques for aging computer users in order to enhance performance and reduce physical and mental workload.

However, a systematic comparative study especially for elderly computer users has not yet been reported in the literature. Therefore, the first laboratory study in this paper focuses on an age-differentiated analysis of touch-based input and eye-gaze control input compared to the mouse as the reference device.

For ergonomic eye-gaze input, an effective confirmation of information input is essential. In other words, it is very important to solve the 'Midas Touch Problem'. For this reason, three design variants for input confirmation were developed and their efficiency, effectiveness and satisfaction were analysed in a second laboratory study.

3. Comparative study of information input devices

In the first laboratory study, three input devices – mouse, touch screen and eye-gaze control – were analysed and compared in terms of efficiency, effectiveness and subjective task difficulty with respect to the age group of the computer user. In the second laboratory study, an age-differentiated analysis of hybrid user interfaces was conducted combining eye-gaze control with additional input devices. Input confirmation was done with the space bar of a PC keyboard, speech input or a foot pedal. Clearly, the keyboard is the most frequently used input device in computer work and was set as the reference device. The foot pedal is a rather uncommon device for input confirmation and completely different groups of muscles are used. Foot input is an interesting alternative mode for older users with limited hand and wrist mobility (Taveira and Choi 2009). Speech input precludes the need to rely on fine motor control of hands or feet and enables aging adults to use the low-strenuous method of speaking as a means of input (Czaja 1997, Jastrzembski *et al.* 2005). According to Cohen and Oviatt (1995), the most promising aspect of speech input seems to be as part of multimodal interfaces, i.e. in conjunction with vision-based and gestural input modes.

3.1. Subjects

A total of 90 subjects, 36 females and 54 males, aged between 20 and 72 years participated in the studies (average age: 47.5 years, SD = 16.77). Subjects were divided into three age groups (group I: 20–39, group II: 40–59, group III: 60–75 years) with 30 persons in each group. The age of the younger group ranged from 20 to 38 years (M = 26.7, SD = 4.04), the age of the middle group ranged from 40 to 59 years (M = 50.33, SD 6.36) and the age of the older group ranged from 60 to 72 years (M = 65.47, SD = 4.08). Most subjects from the older age group were participating in a senior study program of RWTH Aachen University. The participants received 20 Euros compensation. The participants were all in good health. When asked about computer experience, 80% indicated daily computer use. Only four participants said that they did not have a PC, and of these, two had not yet worked with a computer. E-mail programs and internet browsers were used by more than 70% of all test participants on a daily basis. None of the participants had any experience with using eye-gaze control.

3.2. Hypotheses

(1) Based on the literature review of age-related changes of human performance, it was

hypothesised that younger subjects perform significantly better than the elderly. In both laboratory studies, the performance indicators were execution time and task difficulty (see 3.3.4.). In the second laboratory study, human errors were also considered. Significant effects were expected between all age groups.

(2) On the basis of the findings of Murata (2006), it was hypothesised that human performance is best with eye-gaze control. Furthermore, it was expected that touch input is superior to mouse input (Iwase and Murata 2003). This hypothesis was tested in the first study on the basis of the performance indicators execution time and task difficulty.

(3) Regarding hybrid information input, it was hypothesised that human performance is superior when using eye-gaze control in combination with speech input to the combination of eye-gaze with the space bar of the keyboard and the foot pedal. The combination of eye-gaze with the space bar was assumed to be superior to the combination with the foot pedal. This hypothesis was tested in the second study on the basis of the performance indicators execution time, errors and task difficulty.

3.3. *Study 1: Age-differentiated comparison of input devices in a pointing task*

In the first study, the three input devices, (1) mouse, (2) touch screen and (3) eye-gaze control, were contrasted with one another on the basis of a classic two-dimensional pointing task in accordance with the study by Murata (2006).

3.3.1. *Apparatus*

A wireless optical Logitech mouse (model RX650) was used as the reference device for the experiment. Its cursor velocity was set at 'medium' speed and the cursor acceleration was activated. A resistive 17″ TFT LCD touch screen manufactured by Elo (model 1715; 1280 × 1024 pixels) was used as a touch input device. The touch screen had a high spatial resolution, with a root mean square error deviation of less than 0.08 inches (2.03 mm). The touch screen was embedded into a table to allow for an ergonomic sitting position (see Figure 1, right).

The eye-gaze control was based on a Tobii T/X 120 eye-tracking system that allowed for a remote, i.e. contact-free, measurement of the point of gaze. The tracking system was integrated into a 17″ TFT LCD screen. The luminescent diodes (NIR-LEDs, near infra-red light emitting diodes) attached to the bottom of the screen emit near infrared light which is reflected by the cornea. Eye movements are estimated on the basis of changes in the corneal reflex as the direction of this signal changes in relation to the position of the pupil (and thus in relation to the direction of gaze). A video camera with CCD sensors at the bottom of the screen records the reflections. The eye movements are recorded at a rate of 120 Hz and with an accuracy of 0.5% (root mean square error deviation) in the field of view. A chin rest was used in order to stabilise the head and eye positions. The analysis allows both fixations and saccades of the users to be detected.

Figure 1 (left) shows the Tobii system for eye-gaze control.

3.3.2. *Experimental task*

The three input devices were compared using a two-dimensional target pointing task. The experimental task and target object characteristics were chosen on the basis of the classic experiments by Murata (2006). The home position was displayed by a circle in the centre of the screen. The target position was represented by an initially hidden square. The first task for the participants was to move the cursor to the starting

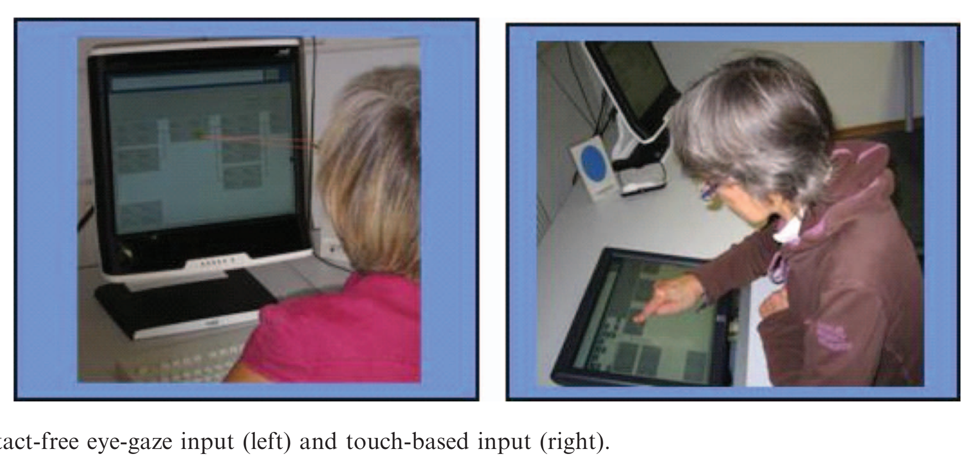

Figure 1. Contact-free eye-gaze input (left) and touch-based input (right).

position, after which the target object would appear. Then the cursor had to be moved to the target object as quickly and accurately as possible (see Figure 2). The participants had to complete this task in different ways, depending on the basic functionality of each input device.

When using the mouse, the cursor had to be positioned in the starting circle first and then moved to the target square. Arrival at the start and target positions had to be confirmed with a mouse click (start: right, target: left).

When using the touch screen, the task consisted of 'touching' the starting circle, followed by 'touching' the target square with the preferred index finger.

For the eye-gaze control, the task required the user to first visually fixate on a point within the starting circle and then to fixate the target square. According to the findings of Murata (2006), the fixation dwell time on the target object was set to 100 ms. All response trajectories and response times were recorded so that the exact execution times could be calculated.

3.3.3. *Independent variables*

The age group (I: 20–39, II: 40–59 and III: 60–75 years) and the three input devices (mouse, touch screen and eye-gaze control) were designated as independent variables. Furthermore, the width of the target object (*W*) was varied on three levels (40, 55 and 70 pixel) and the target amplitude (*A*) was also varied on three levels (130, 150 and 170 pixel). The angle between the target and the home position (β) was varied on eight levels (counterclockwise 0°, 45°, 90°, 135°, 180°, 225°, 270° and 315°).

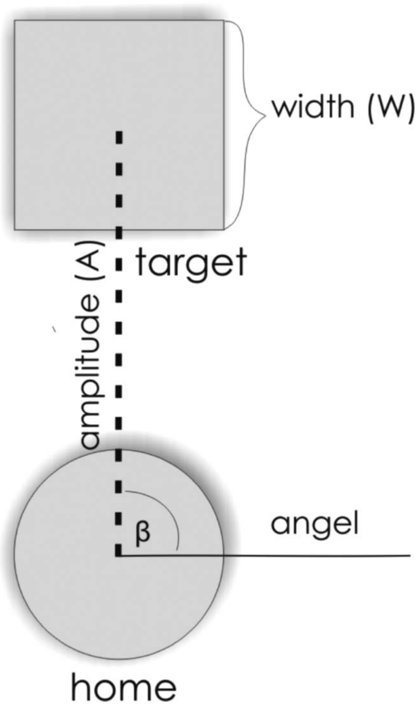

Figure 2. Illustration of the two-dimensional pointing task.

3.3.4. *Dependent variables*

The execution time required to accomplish the task was the primary dependent variable. For the mouse, the time between the appearance of the target object and the left-click onto it was measured. For the touch screen, the time between the first and second touch was measured. For the eye-gaze control, the duration between the appearance of the target object and a 100 ms fixation on the target object was calculated.

Because of the different characteristics of the input devices, the classical methodology for evaluating both execution times and error rates was not chosen. When using the mouse or the touch screen, a click/touch far away from the target could be considered as an error. However, when using the eye-gaze input, it is hard to say if such an eye movement is not subconsciously controlled. It could just as well be caused by a shift of attention, which causes rapid movements of the eye, but not in the hand or arm. For this reason, it is very difficult to define an objective error measurement for eye-gaze input. In accordance with Sibert *et al.* (2001), indirect movements towards the target or off-target clicks/touches were not considered as errors but as deviances (Jordan 2002) that lead to longer execution times.

In addition to the execution time, task difficulty was measured with the help of the ZEIS scale (Pitrella and Käppler 1988). The ZEIS scale provides a subjective measure of task difficulty – which is known as an essential dimension of mental workload – on a two-level intensity scale (Pitrella and Käppler 1988). In the computer-based test, a coarse-grained estimate of task difficulty occurs first according to categories labelled 'difficult', 'medium' or 'easy'. Then, a fine-grained assessment is made using an 11-level rating scale.

3.3.5. *Procedure*

The Tobii system, which is used to record the participants' eye movements, was calibrated before the start of the trials. The calibration was carried out by having the participant visually follow a moving dot across the screen for a few seconds.

First, the participants were given three minutes to practice the task with each input device. In the subsequent investigation, the participants had to process three blocks of 72 tasks (corresponding to the maximum number of combinations, target width × amplitude × angle) with each of the three input devices. The participants were instructed to complete the task as fast and as accurately as possible.

The sequence of 72 tasks within a block was selected at random. There was a brief pause (15 s) between each block. After every three blocks, the participants had a longer break (5 min), in which they rated the most recently used input device with the help of the ZEIS scale. The order of presentation (mouse, touch screen and eye-gaze control) was counter-balanced across participants in each age group.

3.4. *Study 2: Age-differentiated comparison of hybrid user interfaces in a drag-and-drop task*

In the second study, eye-gaze controlled information input was analysed. Three devices for input confirmation, (1) space bar, (2) speech input and (3) foot pedal, were compared on the basis of a drag-and-drop task.

3.4.1. *Apparatus*

The Tobii T/X 120 eye-tracking system was the basic measurement system in the investigation of hybrid user interfaces. The eye-gaze control was combined with the space bar of a keyboard manufactured by Cherry (model G80-3000), the VoCon 2.1 voice control software by Philips and a self-designed foot pedal. The design of the foot pedal was optimised in previous experimental studies with handicapped and able-bodied subjects (Springer and Siebes 1996). It is based on a computer mouse and consists of a rectangular plastic board with a pressure sensitive bar at the upper edge. In order to use the pedal, one has to touch the bar with the preferred foot. This activates a mouse click (see Figure 3).

Figure 3. The self-designed foot pedal.

3.4.2. *Experimental task*

Participants were instructed to move rectangles of different sizes into specified target positions by means of the aforementioned hybrid user input devices, graphically represented in Figure 4. This drag-and-drop task can be divided into four sub-tasks: (1) select the object, (2) confirm the selection, (3) move the object to the target position and (4) drop the object in the target position. These four subtasks were assigned in such a way that the eye-gaze input was used to visually select the object and move it to its target position. The object selection and the dropping of the object were indicated through one of the additional input devices (Ware and Mikaelian 1987). With the space bar, the object was selected and dropped by simply pressing the bar; pressing the foot pedal with the preferred foot had the same effect. For the combination with speech input, the words 'Okay' or 'Ja' (German 'yes') were used. During the experimental task, the participants' head position was stabilised by a chin rest.

3.4.3. *Independent variables*

The age groups (I: 20–39, II: 40–59 and III: 60–75 years) and the three hybrid input methods (the combination of eye-gaze control with (1) the space bar, (2) speech input and (3) foot pedal) determined the factor levels of the independent variables.

Furthermore, three experimental factors (the width of the objects (W), their position on the screen (P) and the amplitude to the target position (A)) were considered. The width was analysed in four levels (58 × 38 pixel^2, 164 × 82 pixel^2, 224 × 102 pixel^2 and 280 × 126 pixel^2), the amplitude in two levels (320 and 640 pixel) and the position in four levels (top, bottom, left and right) (see Figure 5).

3.4.4. *Dependent variables*

The execution time, error rate and subjective assessment of task difficulty (using the ZEIS scale) were dependent variables. Tasks that participants could not solve within 15 s were aborted and counted as errors. This stopping criterion was used due to the particularly small objects that were difficult to identify for some participants. The stopping criterion was determined in a pre-test. The pre-test showed that the majority of participants were able to solve the tasks in less than 10 s.

3.4.5. *Procedure*

The procedure consisted of three parts – system calibration, user training and data acquisition. In the

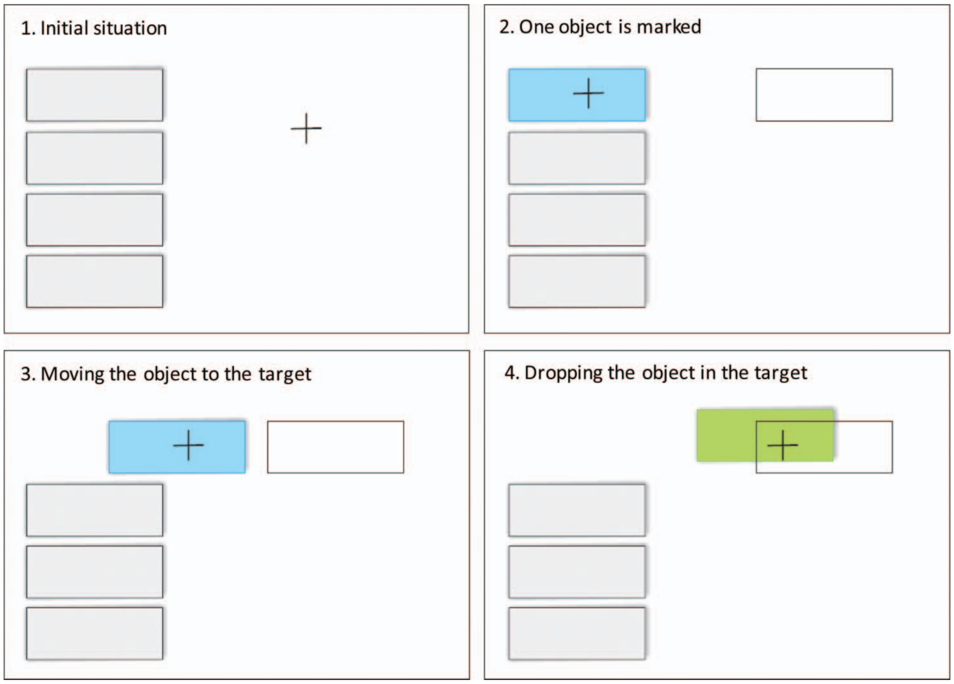

Figure 4. Illustration of the drag-and-drop task for left aligned objects.

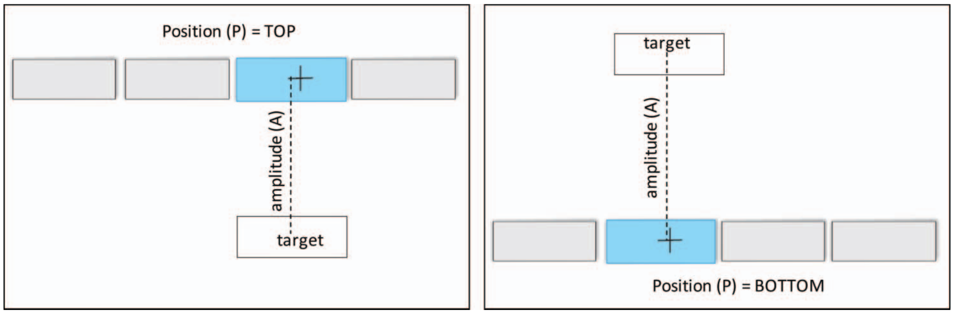

Figure 5. Example tasks for the two positions top (left) and bottom (right).

data acquisition phase, the participants had to process three blocks consisting of 32 tasks each (width × amplitude × position). The participants had a 15-s break between the blocks and a longer break of 5 min between the different hybrid input methods. During the 5-min break, the participants rated the task difficulty with the ZEIS scale.

4. Statistical analysis

Execution time, error rate (study 2) and task difficulty were analysed by a mixed design ANOVA with age group as a between-group factor and input device, width, amplitude and position as within-subjects factors. The ANOVA were calculated with the help of the statistical software package SPSS version 14.0.

The main assumption in an ANOVA with repeated measures is sphericity (see Doncaster and Davey 2007). If this assumption was violated, the degrees of freedom were adjusted with Huynh-Feldt or Greenhouse-Geisser corrections.

The level of significance for each analysis was set to $\alpha = 0.05$. The Bonferroni post hoc test was used for multi-level comparisons of the means. Furthermore, the effect size ω^2 was calculated for significant results (see Field 2005, p. 452). Outliers were eliminated according to the theorem by Tschebyscheff (Sachs 1999).

5. Results

In the first study, the data of seven subjects were classified as outliers and therefore excluded from the sample. The performance and task difficulty data of the remaining 83 subjects were further analysed. In the second study, the data of eight subjects were classified as outliers and thus excluded. The data of the remaining 82 subjects were further analysed. The subjects excluded in both studies were not identical.

5.1. *Study 1: Age-differentiated comparison of input devices in a pointing task*

5.1.1. *Execution time*

The analysis of the execution times across all input devices shows a significant main effect in relation to age groups ($F(2,80) = 37.236$; $p = 0.000$), with an effect size of $\omega^2 = 0.55$. Following the post hoc paired comparisons of means, significant differences between the 20- to 39-year olds and the 40- to 59-year olds ($p = 0.000$) as well as between the 20- to 39-year olds and the 60- to 75-year olds ($p = 0.000$) were identified. However, it was unexpected that the 40- to 59-year olds did not perform significantly faster than the 60- to 75-year olds (see Figure 6). Contrary to the formulated hypothesis, we could not find significant differences between all three age groups.

The input device also has a significant effect on execution time ($F(2,160) = 95.369$; $p = 0.000$) with an effect size of $\omega^2 = 0.51$. The touch screen leads to significantly better performance than the eye-gaze control ($p = 0.004$) and mouse input ($p = 0.000$). A comparison of mouse to eye-gaze control shows that the participants required significantly less time for eye-gaze control ($p = 0.000$) (see Figure 7). However, it was unexpected that the eye-gaze input did not lead to the shortest execution time.

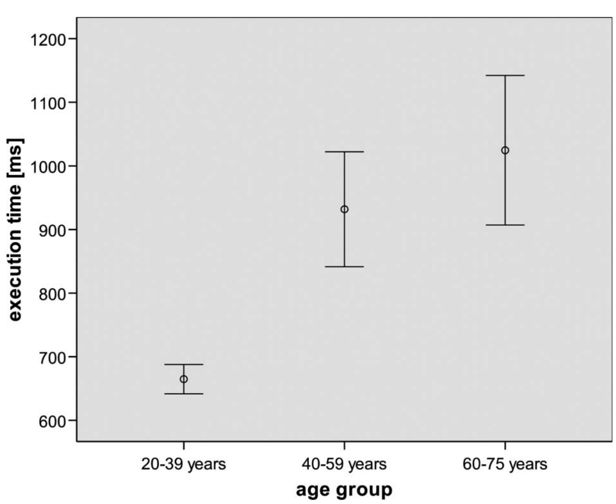

Figure 6. Mean execution time and 95% confidence intervals concerning the different age groups.

Furthermore, a significant interaction between age group and input device occurs ($F(4,160) = 7.190$; $p = 0.000$). The data show that the average execution times between the 40- to 59-year olds and the 60- to 75-year olds differ significantly only for mouse input, while the execution time for the other two input devices are not significantly different between the two age groups (see Figure 7).

Another factor influencing execution time is the target width ($W_1 = 40$ pixel, $W_2 = 55$ pixel and $W_3 = 70$ pixel). A significant effect ($F(2,160) = 190.100$; $p = 0.000$) with an effect size of $\omega^2 = 0.44$ can be identified for all three widths. As Fitts' law predicts, the execution time significantly decreases with increasing target width.

The influence of the target width differs between the age groups ($F(4,160) = 2.754$; $p = 0.031$) as well as between the input devices ($F(4,320) = 31.579$; $p = 0.000$). The differences in execution times are less for the 20- to 39-year-old age group than for the 40- to 59-year olds and the 60- to 75-year olds. Furthermore, the target width has a greater effect for eye-gaze control than for mouse or touch screen input.

The different amplitudes to the target position ($A_1 = 130$, $A_2 = 150$ and $A_3 = 170$ pixel) also have a significant effect ($F(2,160) = 34.977$; $p = 0.000$) on the execution time. In accordance with Fitts' law, the execution time increases with increased amplitude.

Another significant effect ($F(7,560) = 5.292$; $p = 0.000$) can be found for the investigated eight positions of the target objects ($P_1 = 0°$, $P_2 = 45°$, $P_3 = 90°$, $P_4 = 135°$, $P_5 = 180°$, $P_6 = 225°$, $P_7 = 270°$ and $P_8 = 315°$, see Table 1).

5.1.2. *Analysis of the data on the basis of Fitts' law*

Due to the fact that in the original experiments by Fitts (Fitts 1954) only horizontal movements were analysed, as well as the fact that the design of the point-and-click task did not allow the recommended ID-range of 2–8 bits (Soukoreff and MacKenzie 2004) to be covered, we expected that the predictions by Fitts' law would not be precise for the acquired data.

In the original study by Fitts, only horizontal movements with angles of 0° and 180° were investigated. MacKenzie and Buxton (1992), Gillan *et al.* (1990), MacKenzie (1989) and Murata (1996, 1999) analysed additional movement directions and found that opposed positions have the same effect on execution time and can therefore be described by the same ID. These findings cannot be confirmed by our experimental data (Table 1). As mentioned above, the eight positions of the target objects have a significant effect on execution time but no geometrically consistent influence could be identified. According to

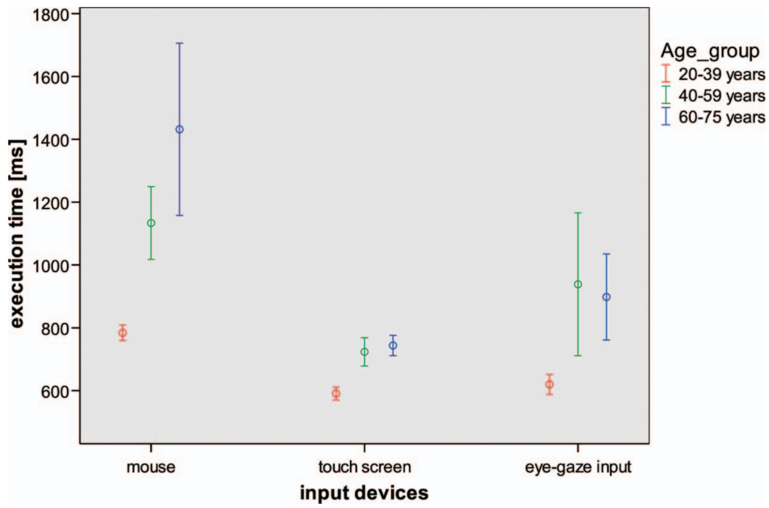

Figure 7. Mean execution times and 95% confidence intervals concerning the three input devices as well as the age groups.

Table 1. Significant effects concerning the eight investigated angles between the target objects.

Angle (average time)	Angle (average time)	p
45° (807.78 ms)	90° (845.16 ms)	0.035
45° (807.78 ms)	225° (917.39 ms)	0.014
45° (807.78 ms)	315° (866.43 ms)	0.045
180° (806.55 ms)	225° (917.39 ms)	0.007

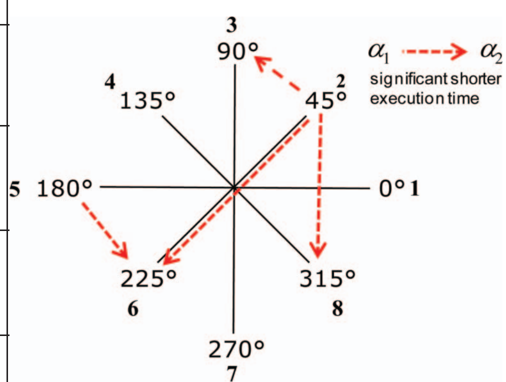

Table 2. Regression equations for the three input devices ($\beta = 0°$ and $\beta = 180°$).

	Regression equation	R^2	p
Mouse	$t = 153.219 \cdot \text{ID} + 607.461$ [ms]	0.019	0.000
Touch screen	$t = 78.005 \cdot \text{ID} + 481.429$ [ms]	0.022	0.000
Eye-gaze input	$t = 328.736 \cdot \text{ID} - 97.222$ [ms]	0.04	0.000

Soukoreff and MacKenzie (2004), the application of Fitts' law requires a large range (2–8 bits) of ID values. Our task setting covers only an ID range between 1.51 and 2.39 bits.

In Table 2, the calculated regression equations for the three input devices according to Fitts' law are shown. In line with Fitts, the equations were only calculated for the horizontal positions of the target, i.e. $\beta = 0°$ and $\beta = 180°$. Significant effects were found for all three input devices. But as one must expect, the coefficient of determination R^2 of the regression equation is rather low for all input devices.

5.1.3. *Subjective task difficulty*

The subjective evaluation of task difficulty with the help of the ZEIS scale did not show significant effects for the age group. Unexpectedly, the elderly and younger participants are similar in their evaluation of task difficulty when using the different input devices.

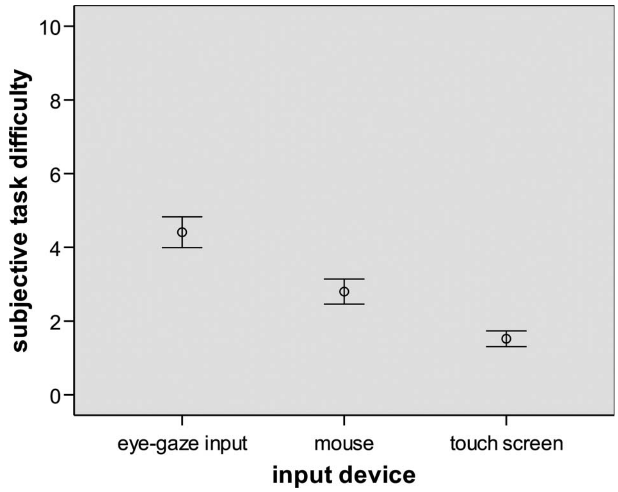

Figure 8. Average subjective task difficulty and 95% confidence intervals.

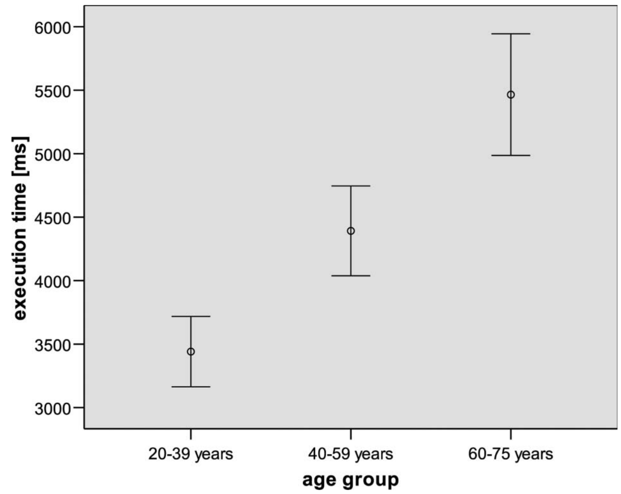

Figure 9. Mean execution time and 95% confidence intervals for the three age groups.

However, the results of the ZEIS scale show a significant effect regarding the different input devices ($F(2,162) = 103.938$; $p = 0.000$), with an effect size of $\omega^2 = 0.36$. Information input with the touch screen is thereby assessed as 'easiest' and the interaction with eye-gaze control as 'most difficult' (see Figure 8). The subjective evaluation by the participants therefore does not confirm the objective performance data. However, it must generally be noted that all three input devices are evaluated as rather easy on the total scale from 0 to 10 (0 = very easy, 10 = very difficult).

5.2. *Study 2: Age-differentiated comparison of hybrid user interfaces in a drag-and-drop task*

5.2.1. *Execution time*

A significant age effect ($F(2,77) = 17.794$; $p = 0.000$) with an effect size of $\omega^2 = 0.36$ was also found for the execution time in the second study. The 20- to 39-year olds work significantly faster with hybrid input methods than the 40- to 59-year olds ($p = 0.008$) and the 60- to 75-year olds (p = 0.000). There is also a significant age effect ($p = 0.019$) between the participants of the second and the third age group (see Figure 9). As hypothesised, the younger subjects perform significantly better.

A significant effect ($F(2,154) = 120.242$; $p = 0.000$) of the three hybrid input methods (eye-gaze control combined with the space bar, speech input and a foot pedal) was also found. As expected, the execution time is strongly influenced by the input method ($\omega^2 = 0.50$).

The combination of eye-gaze control with the space bar leads to a significantly shorter execution time than the combination with speech input ($p = 0.000$) or with a foot pedal ($p = 0.000$). When the combination with a foot pedal is compared to speech control, the former is significantly faster ($p = 0.000$). Contrary to our hypothesis, the combination of eye-gaze with speech controls leads to the longest execution time.

Figure 10 shows the execution times for the three hybrid input methods in relation to the three age groups. No significant interaction was found for the input combinations and the age groups, i.e. the age-induced performance differences in regard to execution time are equally pronounced for each of the three hybrid input devices.

The width of the object ($W_1 = 58 \times 38$ pixel^2, $W_2 = 164 \times 82$ pixel^2, $W_3 = 224 \times 102$ pixel^2 and W_4 280×126 pixel^2) also has a significant effect ($F(3,231) = 245.491$; $p = 0.000$) with an effect size of $\omega^2 = 0.71$. As expected, the paired comparisons of means again show a significant increase in execution time for a decrease in object width.

Moreover, a significant interaction effect ($F(6,462) = 6.853$; $p = 0.000$) was found for width and input combination. The influence of the object width on the execution time is different for each of the three input combinations. Concerning the combination of the eye-gaze control and foot pedal, significant effects were only found between $W_2 = 164 \times 82$ pixel^2 and $W_4 = 280 \times 126$ pixel^2.

The analysis of the two amplitudes ($A_1 = 320$ pixel and $A_2 = 640$ pixel) from the target position also shows a significant effect ($F(1,77) = 22.431$; $p = 0.000$). Thus, in accordance with Fitts' law (1954), execution time increases with increasing amplitude.

The influence of position on execution time ($F(3,231) = 7.197$; $p = 0.000$) with $\omega^2 = 0.04$ is still relatively small. Significant differences between the positions of 'top' and 'left' ($p = 0.002$) as well as 'bottom' and 'right' ($p = 0.001$) were found.

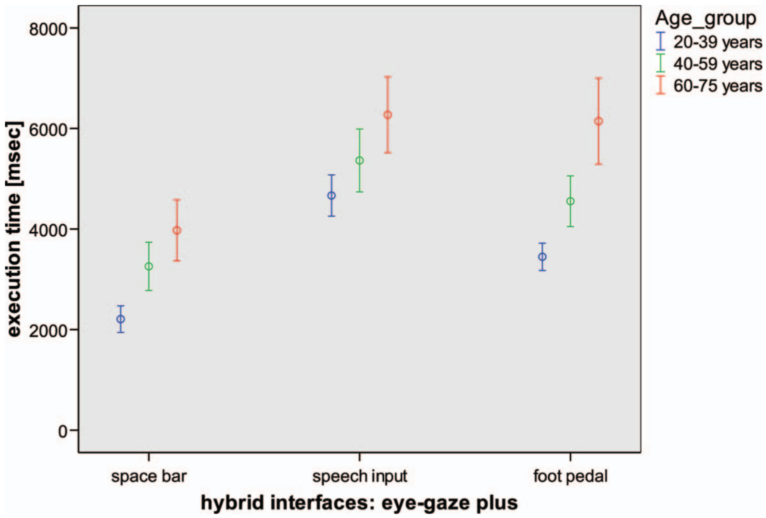

Figure 10. Mean execution time and 95% confidence intervals concerning the different hybrid user interfaces as well as the three age groups.

Furthermore, a significant interaction ($F(6,231) = 3.375$; $p = 0.003$) occurs between the position and the age group. The average execution time for the participants in the first and second age group is shorter for the horizontal movement direction than for the vertical. However, this effect does not occur in the third age group; here, the left and downward movements result in the shortest execution time.

5.2.2. *Number of errors*

If the data were analysed concerning human errors, i.e. the number of unsolved tasks, a significant age effect can be found ($F(2,77) = 12.840$; $p = 0.000$). The 20- to 39-year olds make less errors than the 40- to 59-year olds ($p = 0.033$) and the 60- to 75-year olds ($p = 0.000$). Unexpectedly, there is no significant difference regarding the number of errors between the 40- to 59-year olds and the 60- to 75-year olds (see Figure 11).

The three hybrid input modes had a significant effect on errors ($F(2,154) = 32.891$; $p = 0.000$). The results are similar to the results of the execution times. The eye-gaze control in combination with a space bar yields the least amount of errors when compared to the speech control ($p = 0.000$) or foot pedal ($p = 0.000$) combinations. The error rate is significantly lower when using the foot pedal than with speech control ($p = 0.000$). Like the analysis of execution time, the formulated hypothesis could not be confirmed by our data. The combination with speech input leads to the highest number of errors.

Furthermore, there is a significant interaction ($F(4,154) = 2.785$; $p = 0.030$) between the age group and the hybrid input modes being used. In the case of combined eye-gaze and speech control input, there is a large age-induced performance difference with regard to the number of unsolved tasks between the young and middle age group. Conversely, the differences in the middle age group and the old age group are most pronounced for the combination with the foot pedal (see Figure 12).

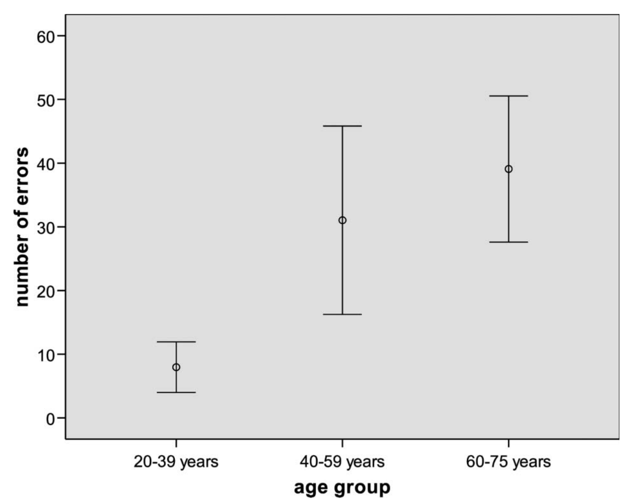

Figure 11. Mean number of errors and 95% confidence intervals for the three age groups.

5.2.3. *Subjective task difficulty assessment*

A significant effect ($F(2,75) = 6.712$; $p = 0.002$) of the age group on the subjective evaluation of task difficulty was found. There are unexpected differences between the assessments of hybrid input methods by subjects of different ages. The evaluations made by the 20- to 39-year olds and those made by the 60- to 75-year olds differ significantly ($p = 0.001$). Elderly subjects generally rate the tasks as 'more difficult' than younger subjects. When examining the different hybrid input methods, the subjective evaluation of the participants reflect the objective performance data (execution time and error rate) quite well. The evaluations of the three methods are significantly different ($F(2,150) = 41.939$; $p = 0.000$) (see Figure 13).

6. Discussion

6.1. Study 1: Age-differentiated comparison of input devices in a pointing task

In the first study, execution times differed significantly between all three age groups. The average execution times of younger participants were shorter than those of the middle and older age group. This is in line with several studies on the effect of age in a wide range of tasks (Hawthorn 2000, Czaja and Lee 2008). However, the ratings of subjective task difficulty did not reflect the performance data, as no differences were uncovered between age groups.

6.1.1. Mouse

Our results show that mouse input leads to the poorest average performance (in terms of long execution times) among all age groups. Therefore, our results confirm previous findings (Walker *et al.* 1996, Iwase and Murata 2003) but with a more pronounced effect for

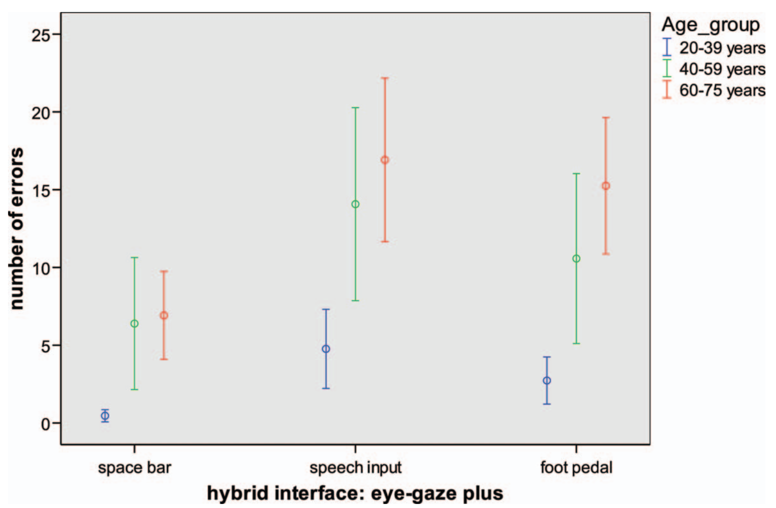

Figure 12. Mean number of errors and 95% confidence intervals concerning the three hybrid user interfaces as well as the age groups.

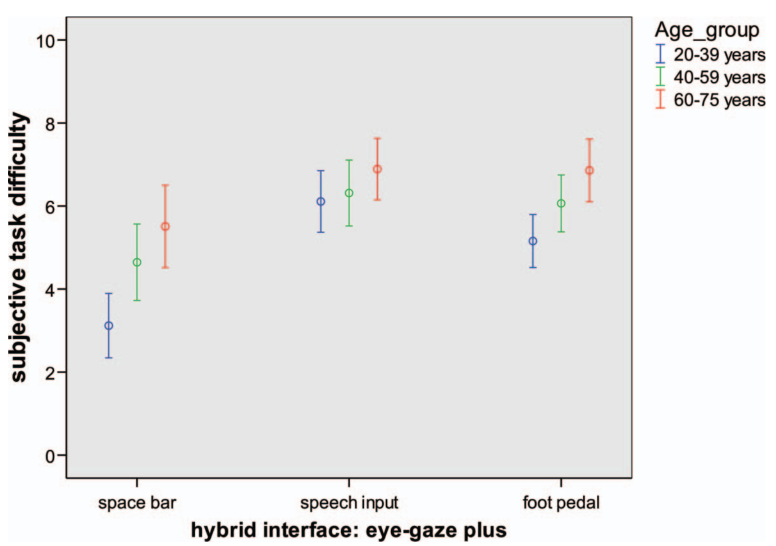

Figure 13. Mean subjective evaluation of task difficulty and 95% confidence intervals concerning the three hybrid user interfaces as well as the age groups.

older users. Ratings of subjective task difficulty support this effect; ratings were higher for the mouse compared to the touch screen.

6.1.2. Touch screen

Participants' performance was best when using a touch screen. This is in line with the findings of Rogers *et al.* (2005), who reported the advantages of touch input for long ballistic movements. It is important to note that the different age groups did not show a significant difference in execution time when using a touch screen: the elderly participants perform at a level very similar to the younger participants (see Figure 7). These results are consistent with the findings by Iwase and Murata (2003), who also report almost equal performance between age groups when using a touch screen. This could be due to the characteristics of the touch screen as a direct input device, as no spatial transformation between hand-arm movements and cursor movements on the screen is necessary. In contrast, when using the mouse, participants of the oldest age group need on average twice as long as the youngest age group. Average ratings of subjective task difficulty were lowest for touch screen input, which confirms the findings on the basis of the objective data.

6.1.3. Eye-gaze

As a third direct input device, eye-gaze control leads to shorter execution times compared to input by mouse and longer execution times compared to input by the touch screen. This is somewhat surprising. We hypothesised that the lower muscular strain of eye-gaze control would lead to a better performance compared to input by the touch screen. One explanation may be that while the motor demands are rather low, the mental demands are higher for this perception-based information input. This explanation is supported by the high ratings of subjective task difficulty. However, similar to the touch screen, eye-gaze control eliminated age-related effects on performance. This confirms the results of Murata's study (2006), who also did not find significant differences in execution times between younger and older participants when using eye-gaze control.

6.2. Study 2: Age-differentiated comparison of hybrid user interfaces in a drag-and-drop task

In the second study, we analysed eye-gaze control in combination with three different devices used for input confirmation. The results show that execution times differ significantly between all three age groups. Average execution times of younger participants are shorter than those of the middle and older age group. This is in line with results of other studies (Hawthorn 2000, Czaja and Lee 2008). Human errors and ratings of task difficulty show a similar pattern, although the middle and older age group do not differ significantly.

6.2.1. Space bar

The combination of eye-gaze control and input confirmation via the space bar of a keyboard, regardless of age, leads to the best average performance (execution time as well as number of errors). The space bar yielding the best performance can be explained by the fact that arms and fingers are better suited to fast motor movements than the foot. This confirms the findings of prior studies on younger computer users (e.g. Ware and Mikaelian 1987).

6.2.2. Speech input

The combination with speech input shows the poorest performance. This unexpected finding can be explained, however, by the slight speech-induced delay during input confirmation when the participant was no longer fixating the object. The oral input confirmation, particularly for smaller visual objects, occurs at a point in time when the participant is no longer fixating the object.

6.2.3. Foot pedal

When using the foot pedal for input confirmation, execution time was faster compared to speech input but slower compared to the space bar. The same holds for the number of errors. An explanation for the high error rate while using the foot pedal can be explained by the relatively uncommon use of this device.

Task difficulty ratings were lowest for the space bar, higher for the foot pedal and highest for the speech input, which confirms the results of the objective data. To the best of our knowledge, no prior study has investigated age-differentiated effects of hybrid user interfaces, and hence, we cannot discuss our findings in the light of other studies.

6.3. Discussion of the research questions

- Is the effectiveness and efficiency with a given input device significantly influenced by the age group of the user?

  The results of both experiments show significant age effects. Especially, between the subjects of the first age group (20–39 years) and the other two age groups (40–59 years and 60–75 years), strong effects could be measured. The elderly users need more time to perform the pointing as well as the drag-and-drop task and make more errors than the younger users. Regarding the information input, the effectiveness as well as the efficiency is significantly influenced by the age group of the users.

- Can age-related differences be compensated through the use of alternative input devices?

  The performance of the users can be significantly improved by the use of a direct input device (touch screen and eye-gaze input) that does not require a spatial or spatial-temporal transformation between the motor activity performed by the user and the calculated position of the cursor on the screen. The execution time was significantly shorter for the touch screen and the eye-gaze input than for input by mouse. This effect is independent of the age group of the user although especially the elderly benefit from these input devices. The 'performance gap' between elderly and younger users can be reduced by the application of an eye-gaze input and particularly by using a touch screen. Here, the performance differences between the age groups could be nearly eliminated. Regarding age-induced perceptual-motor changes, eye-hand coordination when using a touch screen is easier for two reasons: First, when controlling the cursor movement of a computer mouse, spatial information of the cursor position has to be fused with kinesthetic feedback of the hand position provided by the nerves of the joints and muscles. With indirect input devices, the feedback information of the position of the hand relative to the target provided by visual and kinesthetic feedback is more difficult to process. It is hypothesised that the ability to coordinate and integrate different spatial information sources is especially subject to age-induced changes (Agnew *et al.* 1988). Second, the ability to calibrate appropriate levels of hand and arm forces is particularly important when using a computer mouse as movements overshooting the target are more likely to occur (Smith *et al.* 1999) and more difficult to control. This holds particularly true if the acceleration function of the cursor is activated.

7. Limitations of the study

It has to be considered that the users of the third age group who participated in both laboratory studies were senior students who were highly motivated and accustomed to innovative information technology. Thus, they represent a small proportion of healthy elderly computer users but definitely not the whole spectrum of older people in society.

Another limitation is the comparability of the analysed input devices in terms of transfer functions. A confounding factor that might have exacerbated the age differences when using the computer mouse is the use of the acceleration function. In this paper, however, we focus on applied ergonomic research in order to give design recommendations for aging users. We therefore compared the input devices respective to their typical context of use at work and not on the basis of control-theoretic models. In fact, the generalisability of the results is limited as they depend to a certain extent on the spatio-temporal device characteristics. Due to the narrow range of motion and corresponding IDs, age-related changes in range of motion and motor control were probably underestimated. For example, when using a large-scale touch screen of a table-top display, one can hypothesise that the computer mouse is ergonomically superior to the touch screen particularly for distant targets.

Age-related changes that impede the use of information input devices include reduced muscle strength, reduced range of motion and greater difficulty in executing fine movements (Mathiowetz *et al.* 1985, Stubbs *et al.* 1993, Walker *et al.* 1997). Future studies should analyse the motor skills of the subjects by a pre-examination of, for example, control precision, psychomotor speed, rate of arm movement and wrist-finger speed. Thus, correlations between reduced motor skills, age and performance while using the different input devices could be determined. Furthermore, muscular load measured by EMG measurements should be analysed as another dependent variable.

8. Conclusion

In our study, the predominantly used input device, the computer mouse, leads to the poorest average performance in terms of long execution times among all age groups. Furthermore, our findings suggest that elderly computer users clearly benefit from using the touch screen or eye-gaze input. Likewise, the ratings of subjective task difficulty clearly argue for the touch screen as the input device of choice. The rather high subjective rating of task difficulty for the eye gaze input can be explained by the unfamiliarity and lack of experience with this interaction technique. Which of the two direct input devices to choose clearly depends on the task characteristics, the individual level of motor performance and not least on individual preferences. In conclusion, we recommend using direct input devices, particularly a touch screen, for the elderly. For user groups with severe motor impairments, we suggest eye-gaze information input.

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