Younger and older adults with low vision have similar haptic capabilities and needs in 3D virtual navigation

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H.N. Kim, T. Smith-Jackson, J.H. Bøhn. Younger and older adults with low vision have similar haptic capabilities and needs in 3D virtual navigation. Gerontechnology 2011; 10(2):72-89; doi:10.4017/gt.2011.10.2.002.00 More than 82% of the population with visual impairment consist of older adults (50 years and over), with the largest cause being age-related vision loss in individuals 65 and over. There are various assistive technologies (for instance, haptic technology) that older adults with low vision rely on to achieve greater independence in everyday life. We applied brain-plasticity theory to understand how both younger and older adults with low vision use haptic perception and its effect on their perceived needs for haptic user interfaces (HUIs) for computer navigation. Study 1 measured older and younger adults' haptic perception and Study 2 explored the HUI needs. We found no difference between the two age groups in terms of haptic perception or perceived haptic computer-interface needs.

Keywords: low vision, aging, haptic user interface, haptic perception

Approximately 314 million people worldwide are visually impaired, and this number increases by 1-2 million each year[1,2]. Every 7 minutes, an individual in the USA becomes visually impaired[3]. Low vision is more common among older adults (aged 65 and older) as a result of age-related macular degeneration (AMD), glaucoma, diabetic retinopathy, or cataracts[4,5]. More attention should be focused on older adults with low vision. Individuals over 65 years of age represent a growing proportion of the USA population[6]. People aged 65 and older numbered 35 million in 2000, which is a 12 percent increase compared to 1990[7]. The number of people in all age groups 65 years and older consistently increased during this period, except for the population aged 65 to 69 years old. The declining trend in the 65-to-69 age group reflects the relatively low number of births in late 1920s and early 1930s[7]. The population of 56 to 69 years olds will increase in 2011 as the baby boomers, born from 1946 to 1964, begin to turn age 65. Older adults will likely comprise a significantly larger proportion of the population by the year 2020[8]. Of the people who have lost their vision, two-thirds are over the age of 65[9]. Consequently, it is anticipated that the number of older adults with low vision (i.e., severe and moderate visual impairments) will increase dramatically in the future[10].

ASSISTIVE TECHNOLOGY

Assistive technology is a powerful aid for older adults to achieve greater independence in everyday life. Today, there are 23,000 assistive technology applications available; the number of which is also rapidly growing[6]. Riemer-Reiss[11] claimed that 13.1 million Americans obtain benefits from some type of assistive technology applications to accommodate for their own physical disabilities. Twenty three percent of older adults take advantage of assistive technology devices[12], from the very simple to the complex. Simple applications include eyeglasses, large print materials, and screen-magnifiers for computers. Complex devices include modified hand controls for cars and wheelchair lifts.

Currently, haptic technology is used to represent complex graphic-based information for those with visual impairment[13-17]. A haptic device interacts with virtual reality interfaces that users manipulate to receive mechanical feedback (for instance, vibrations) from two-dimensional or three-dimensional objects (for instance, images and graphs). The haptic interface is supported by a real-time display of the virtual environment, in which users can explore a virtual object by pushing, pulling, feeling, and manipulating it with a device (for instance, mouse, stylus). Users are able to experience simulations of various properties of objects, such as mass, hardness, texture, and gravitational fields. Haptic technology is relatively new, but is widely used across a variety of domains, including the automotive, mobile phone, and entertainment industries; education, training, and rehabilitation; controls and assistive technology development, and medical science; and the scientific study of touch[18,19].

Older adults are assisted in everyday life by haptic devices[6,20]. For example, accessing and seeing light switches is enhanced by touch-sensitive switches. A stove timer in the kitchen can be replaced with a timer that generates vibration. Individuals become more cautious about what they touch rather than what they see[21]. The sense of touch contributes to a variety of perceptual functions such as (i) assessments of an object's dynamic and material properties, (ii) verification of engagement and completion, (iii) continuous monitoring of ongoing activity and gradual change, (iv) building mental models for invisible parts of a system, and (v) judgments of other people[21]. Examples of haptic technology applications for older adults include an omni-directional mobile wheelchair with a haptic joystick[22], an intelligent walker with haptic handle bar[23], and vibrating insoles for balance improvement of older adults[24]. However, very few studies have considered the inclusion of older individuals with low vision in haptic technology design.

DISSATISFACTION

A national survey on technology abandonment reported that almost one-third (29.3%) of all devices previously used were completely abandoned[25]. The abandonment of assistive technology is still of great interest to today's researchers[11,26,27]. In particular, a recent study reported that the adoption rate of haptic technology is low[28]. Unfortunately, the discontinuance of the use of assistive technology devices results in a waste of time, money, freedom, and loss of function in individuals with disabilities[11,25]. Factors that cause abandonment include lack of user opinion in developing the device, poor device performance, and changes in user needs[25].

Of all the factors that lead to abandonment, the most significant is the failure to meet user needs[29] as feedback from an intended user with disabilities indicates: "Talk to the user. Be a little more considerate of the end-user. Don't assume anything. Ask the consumer. Listen to me! I know what works for me"[25,p42]. Although older adults with low vision are categorized into a group with visual disability, they are less likely to be invited to a design process. Accordingly, their needs will probably not be represented in the design.

CHANGES WITH AGE

A progressive decline in sensitivity with age results from physiological changes in the skin[30]. Pacinian corpuscles, Meissner's corpuscles, and Merkel's disks are known receptors contributing to the detection of vibrotactile stimuli at threshold[31]. Goble and colleagues[30] showed that the number of Pacinian and Meissner's corpuscles gradually decreases with age. In addition, Kenshalo[32] explored tactile absolute thresholds with age. The results showed that older participants were significantly less sensitive to mechanical stimuli (tactile and vibration) in both areas compared to their younger counterparts.

Sensory tests (for instance, threshold methods) often show differences between younger and older individuals. For instance, the vibrotactile thresholds detection test[30] was conducted in younger (aged 18-33 years, mean=22 years) and older (aged 57-78 years, mean=67 years) individuals. After participants were instructed to hold a contactor, a 10 Hz stimulus was initially presented in 5-ms bursts in durations at 2s intervals. Participants were then presented with 10 blocks of 30 trials that consisted of 10 sinusoidal frequencies (10, 25, 50, 80, 120, 160, 200, 250, 320, and 400 Hz). The results showed that the sensitivity of older participants was significantly worse than in their younger counterparts. The threshold difference between the two groups was 10 dB on average (ranged from 8 dB to 12 dB).

Older adults are vulnerable not only to age-related visual impairments, but also to age-related touch impairments. As a result, the deficit sensory inputs from the sense of touch would influence brain plasticity in older adults with residual vision in a different way than their younger counterparts with residual vision. Ultimately, it would lead to different performances (i.e., capabilities in the haptic modality) and behaviors (i.e., interactions with HUIs, Haptic User Interfaces). A better understanding of haptic capabilities of older adults with residual vision will eventually contribute to a better design of haptic-based assistive technologies. For instance, a group of elderly users who are less sensitive to a certain tactile feedback will be recommended to be given a higher frequency or stronger magnitude of tactile feedback (for instance, Novint Falcon Device) compared to their younger counterparts.

AIM

Although both younger and older people with residual vision are placed in the same disability category, older adults additionally experience age-related sensory degeneration. In particular, changes occur in the sense of touch, which leads to limited haptic sensory inputs. According to the mechanism of brain plasticity[33], such a deficient sensory input is likely to affect one's brain plasticity, which would ultimately influence one's performance and behavior with haptic interfaces.

Thus, it is anticipated that the performance and behaviors of older people with residual vision will be different from that of their younger counterparts with residual vision.

In short, the primary aim of the present study is to characterize the haptic capability of younger and older adults with low vision, and its influence on their needs in HUIs.

METHODOLOGY

We measured haptic capability (Study 1) and perceived HUI needs (Study 2).

Participants

To distinguish between younger and older individuals by age in this research, cognitive function was considered. Salthouse has conducted the most extensive and carefully argued work with regard to the aforementioned question[34]. Salthouse's theory[35, 36] indicates that the variance in cognitive function resulting from age can be understood by the speed of information processing (for instance, encoding and retrieval). The speed of information processing and the working memory capacity decline with age, which will limit the rate at which older adults can acquire and learn new technology[37, 38]. Indeed, empirical evidence relevant to Salthouse's processing speed theory has been found in a number of previous studies, and the decline in speed tests (for instance, the speed of information processing) was observed particularly in participants aged 65 and over[39-42]. Thus, in this study, those 65 years of age and older were considered older participants. Younger participants were defined as those under the age of 30 in this research. Cognitive decline associated with information processing and working memory capacity begins at the age of 30[33,43]. Participants were compensated at a rate of US$10 per hour.

We used the classifications for visual impairment as described by WHO44. Thus, an individual with residual vision (or low vision) refers to one who is visually impaired but partially sighted, which is further divided into two categories: category 1 (moderate visual impairment) or category 2 (severe visual impairment). The vision acuity of individuals in the moderate category was worse than 20/70, but equal to or better than 20/200. The vision acuity of individuals in category 2 was worse than 20/200, but equal to or better than 20/400. An individual with intact vision was defined as belonging to category 0 (no visual impairment), where vision acuity was equal to or better than 20/70.

Table 1. Characteristics of younger and older participants; SD=standard deviation

Characteristic	Younger		Older	
	Mean	SD	Mean	SD
Age	20.7	5.2	81.9	6.9
Age of onset of visual impairments	5.3	9.0	60.3	17.4
Duration of visual impairments	15.4	8.2	21.6	16.4
Visual acuity in decimal notation	0.13	0.11	0.18	0.11

We included 10 younger individuals and 10 older individuals, all with low vision. Given $\alpha=0.05$, 10 participants per group is deemed to be sufficient to reliably detect a statistical difference between groups, with a risk for a Type I error of 0.05 and a Type II error of <0.03, with a power greater than 0.70.

The visual impairment of older participants resulted from their age-related visual sensory deficits, while their younger counterparts became visually impaired due to abnormal medical conditions related to gene, glaucoma, and cataracts (*Table 1*). Both age groups were large print readers. None were Braille readers. A Snellen chart was used to measure visual acuity of each of the participants. Participants were asked to review the informed consent form (offered in large print) and sign it before the start of the studies.

Haptic capability

In Study 1 the target users' haptic perception was measured by a magnitude estimation technique. Magnitude estimation is a psychophysical scaling technique that helps determine how much of a given objective stimulus an individual subjectively perceives[45]. Analysis of haptic perception is often conducted by a physical measurement of roughness[46], which is typically measured by using sandpaper stimuli[47-51]. Therefore, the haptic perception of participants in this study was investigated in a roughness test using sandpaper samples.

Experimental design Study 1

A 2(age)x3(stimuli) mixed factorial design was used. One goal was to examine whether age differentially influenced individuals with the same visual acuity (i.e., low vision). Independent variables included age and objective stimuli (sandpaper). The dependent variable included perceived intensity of objective stimuli. Sample size estimation was based on the International Organization for Standardization (ISO) standard ISO 11056:1999[52], which estimates a minimum of 5 participants for magnitude estimation experiences. Additional parameters used were $\alpha=0.05$, Type II error risk of <0.30 and acceptable power >0.70.

Materials and equipment Study 1

The objective stimuli were rectangular samples (9 in x 11 in) of standard commercial grades of sandpaper (for instance, 3M™ aluminum oxide sandpaper). This research referred to the ISO 6344 standard[53] that defines different grades of sandpaper: fine (120 grit), very fine (320 grit), and extra fine (400 grit). The 'grit' Is a reference to the number of abrasive particles per inch of sandpaper. Any used sandpaper was immediately discarded so that each participant was given new sandpaper samples. Alcohol was used to clean the surface of participants' fingers thoroughly before each test. Documents in the design sessions, including informed consent, were accessible to participants through various modes, for example, audio tape, designer's oral explanations, or descriptions on a computer screen.

Procedure Study 1
A representative participant with visual impairment conducted a walkthrough to make sure that the location for the experiment was safe from any potential barriers.

The magnitude estimation test was conducted[52,54]. Each participant was given the sandpaper stimuli in counterbalanced order across participants. Each participant was instructed to touch the sandpaper using the fingers of the dominant hand. Because the speed of one's finger movements is less likely to influence one's perceived roughness, at least within the range of approximately 1-25 cm/s[49], there was no requirement for participants to finish a magnitude estimation in a certain amount of time. Participants were allowed to move the fingers around and touch a sandpaper sample from all directions. The researcher helped the participant locate the sandpaper sample if needed. Participants were also permitted to touch an assigned sandpaper sample as often as he or she wanted. To avoid a decline in finger sensitivity, participants were given short breaks when he or she felt the fingers became less sensitive or if he or she felt any discomfort. We also applied the recommendation of Suzuki and colleagues[49] who set an upper limit for the number of trials: a participant should be required to take a break after every 28 judgments.

As Stevens[45] recommended, one judgment was completed per stimulus per participant. A pre-identified reference sample (or 'modulus') was used to develop a common scale among participants. The reference was a numeric value fixed by the researcher. Participants were instructed to assign numerical values to the magnitude of given stimuli (i.e., three different grits of sandpaper samples) compared to the fixed value. Participants were told that, if the roughness of a piece of sandpaper seemed twice as intense as the previous sandpaper sample (for instance, the first value=10), a number twice as large (for instance, 20) should be assigned. Participants were instructed to use round numbers such as 5, 10, and 15 in the scaling technique. Sessions lasted 30 to 45 minutes.

Data analysis Study 1
Data were log transformed[54]. Given a set of modified data, Shapiro-Wilk tests revealed that the set of modified data included non-normal data so a non-parametric data analyses such as Mann-Whitney test and Friedman's analysis of variance (ANOVA) were conducted. The aforementioned tests contributed to the investigation of the major effects of age and objective stimulus (i.e., sandpaper). To explore the interactions of AGExSANDPAPER, an Adjusted Rank Transform (ART) test was conducted[55]. Wilcoxon tests were used to further validate the results. A Bonferroni correction was also applied, so all effects are herewith reported at a 0.02 level of significance.

We sought to answer the following research question: To what extent do younger and older users with low vision share a common haptic perception of the same objective stimulus? A statistical analysis was performed on the dependent variable (i.e., perceived roughness) with ≤ 0.05 to explore age and objective stimulus effects. In addition, interaction effects were investigated. In the age-related individual-difference study, the following alternative hypotheses were considered:
[Age effect] Perceived roughness will be different for different age groups
[Objective stimulus effect] Perceived roughness will be different based on variations in objective stimuli.

Haptic user-interface needs

Study 2 aimed to explore the degree to which participants shared common user needs in HUIs.

Experimental design Study 2
We used a between-subject design. The independent variable included age (younger and older). The dependent variable was participants' agreement on the list of statements.

Materials and equipment Study 2
Prior research by the authors produced a list of 49 user needs in HUIs, especially for users with low vision (*Appendix A*)[56]. We used

these needs to examine the degree to which participants shared preferences for interface designs. A questionnaire was designed based on the list. Each statement was followed by a five-point Likert scale: 1=strongly disagree, 2=disagree, 3=neutral, 4=agree, 5=strongly agree. A participant was given a large print of the list to complete the assessment.

Procedure Study 2

Participants were given guidance to become familiar with the experimental equipment, procedures, and environments where the experiments were conducted, such as the arrangement of chairs, desks, doors, and safety-related gadgets, if available. After the orientation procedure, the researcher did not move anything in the room without informing the participant. Participants were given the set of statements (Appendix A), and instructed to rate each HUI design idea by indicating how much he or she agreed with it. All participants were able to obtain any necessary information regarding this study (for instance, experiment protocols, materials, and terms) through introduction sessions. In addition, the questionnaire method was performed in the presence of a researcher. Participants were allowed to ask questions if they had. Participants were compensated at a rate of $10 per hour. Sessions lasted approximately 60 to 90 minutes.

Data analysis Study 2

All statistical analyses were conducted with SAS software version 8.2. The Shapiro-Wilk tests were performed to check the normality of the data. Participants' responses (i.e., agreement scores) were analyzed using an independent-samples t-test (for normal data) or a Mann-Whitney test (for non-normal data). More specifically, statistical analyses were conducted using groups based on vision level as the independent variable. Study 2 sought to answer the following research questions: To what extent do younger and older users with low vision share a common preference for HUI design? The following alternative hypotheses were considered: HUI needs will differ: (i) for the two age groups, or (ii) the two vision groups.

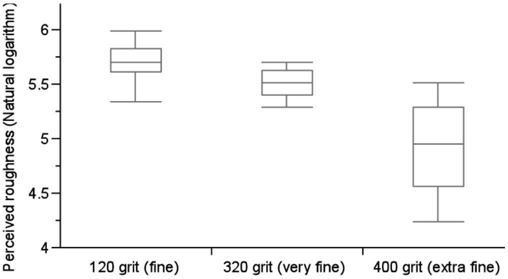

Figure 1. Range and medians of perceived roughness in the sandpaper test with grades fine, very fine and extra fine. The bottom and top of the box are the 25th and 75th percentile and the band near middle of the box is the 50th percentile. The lines refer to the minimum and maximum of all the data

RESULTS

The duration of vision loss was not different between the two age groups, t (18)=1.07, p=0.30.

Haptic capability

The AGE x SANDPAPER interaction was not significant, $F_{(2,36)}=1.06$, p=0.36. The main effect of AGE was not significant, U=414, p=0.59. However, the analysis did reveal an effect of SANDPAPER, $\chi^2_{(2)}=38.03$, p<0.001. Wilcoxon tests indicated that the perceived roughness at 120 grit, 320 grit, and 400 grit sandpaper samples differed at p<0.02 (*Figure 1*).

HUI needs

This research calculated Cronbach's alpha as the measure of internal consistency reliability. After five of the 49 HUI items were removed due to low reliability, Cronbach's alpha for the younger group was 0.81 and the older group's alpha value was 0.86.

The summated rating (or cumulative scores) represented each participant's overall agreement with the ratings that he or she assigned to the list of HUI user needs. The cumulative scores of younger participants were compared with those of older participants. The Shapiro-Wilk tests indicated that the data were normal (younger, W=0.87, p=0.10; older, W=0.91, p=0.30). Therefore, the two age groups' scores were analyzed using an independent-samples t-test. This analysis revealed no difference between the two age groups, t(18)=-0.73, p=0.48.

The item rating (or individual score) represented each participant's agreement with the rating that he or she assigned to each item of user needs. The set of scores of the younger participants were compared with that of the older participants across all items. This analysis revealed statistically significant differences between the two age groups in terms of the following user needs:

(i) After hitting a virtual button, a user should receive verbal feedback about the button's function, such as Undo, Help, and Find; younger (Median=5.0), older (Median=4.0), U=22, p<0.05.
(ii) A user should be allowed to assign a certain point as a reference point based on the user's preference; younger (Median=4.5), older (Median=4.0), U=18, p<0.05.
(iii) The color of user interfaces should allow a user to change colors, for example, black and white, yellow on black, and inverted brightness; younger (Median=4.5), older (Median=3.5), U=23, p<0.05.

With regard to the three user needs above, younger participants showed higher agreement scores compared to their older counterparts; however, both age groups' agreement scores were still above 3.5, between Neutral and Agree, indicating that both age groups were in favor of the three user needs.

Screening out of HUI user needs with lower agreement scores such as 'Disagree' (score=2) or 'Strongly disagree' (score=1) can deliver a refined set of HUI user needs. Both younger and older participants (strongly) disagreed with the statement 'A virtual spherical widget should not be used' (mean agreements scores 2.4 and 2.9, respectively). Younger but not older participants (strongly) disagreed with the statement 'Virtual widgets should not all be arranged on the same sagittal plane (parallel to the midline of body' (mean agreement scores 2.8 and 3.7, respectively).

DISCUSSION

We had anticipated that the perceived intensity of older participants would be different from their younger counterparts when the same objective intensity according to the brain-plasticity theory as mentioned in the abstract. By considering international standard protocols[52, 54], the same value of the magnitude estimation for the two groups refers to the same haptic perception in relation to a relative estimation to a standard stimulus although authors acknowledge that the overall (absolute) response strength could possibly differ between the groups. Contrary to our expectation, we found that the perception of the same objective stimulus was not significantly different between younger and older participants.

When a sensory modality is damaged, brain plastic changes occur and continue with age[57]. However, since the duration of vision loss did not differ between the younger and the old, the time intervals for brain plastic changes to occur were equivalent. Thus both groups possibly shared the same degree of brain plastic changes and enhancement of haptic perception.

Explaining similarity

However, Mora et al.'s study[57] revealed that the degree to which the brain reorganizes its structure indeed varies at different ages; that is, greater changes were observed in younger individuals than in their older counterparts. Given those researchers' result, despite the same duration of vision loss, greater brain plastic change would be typically expected in the younger group than the older group.

Based on the logic above, younger participants with low vision in Study 1 were still anticipated to show a significantly different haptic perception compared to their older counterparts in the magnitude estimation test. We found, however, additional factors that could possibly explain why younger participants with low vision did not show a significantly different haptic perception compared to their older counterparts: (i) the onset of vision loss and (ii) the level of expertise in a haptic-related task.

The onset of vision loss

First, the two age groups had slightly different vision conditions in terms of the onset of visual impairment, which might affect brain plastic changes and mental models mitigating differences. On average, younger participants in the present study had experienced vision impairment at the age of 5.3 years while older participants experienced their vision loss at age 60.3. More specifically, eight (80%) of the younger participants experienced their vision loss at or before the age of 7, which is a critical period in which one's visual imagery and mental model construction are significantly influenced[58]. Furthermore, 60% of all younger participants with low vision were visually impaired from birth.

While younger participants in the present study were considered a congenital or early-onset visual impairment group, older participants were considered a late-onset visual impairment group. Indeed, many prior researchers[59, 60] have pointed out that the onset of vision loss affects the degree of brain plasticity and capability in the remaining modalities of people with visual impairment. For instance, Marmor and Zaback[61] empirically witnessed that individuals with early-onset visual impairment took longer and made more errors than those with late-onset visual impairment when performing a mental rotation test with 3D objects. The same mental rotation test was also conducted by including individuals with congenital visual impairment and late-onset visual impairment[62]. Those who were visually impaired from birth took longer compared to participants with late-onset visual impairment.

Although the age factor might help younger participants have haptic perceptions, their early-onset vision loss possibly interfered with the younger group's performance. Based on all discussions above, it is possible to expect that haptic performance of younger individuals with low vision (early-onset) would not be different from their older counterparts (late-onset) despite age differences.

Level of expertise

Second, in addition to the onset of vision loss, level of expertise in a certain task associated with a sense of touch might also influence younger participants' brain plastic changes and performance. Dulin[63] explored the relationship of participants' performance with various levels of expertise in raised line materials. 'Expert' participants who were visually impaired from birth outperformed 'non-experts' with early- and late-onset visual impairment. Additionally, 'expert' participants with early-onset visual impairment outperformed 'non-expert' participants with late-onset visual impairment.

Consequently, it is possible that a high level of expertise in a certain task is one of the critical attributes driving brain plasticity with positive outcomes. None of the participants was a Braille reader. There was no particular event that significantly enhanced a participant's haptic capability through brain plasticity before the experiment.

It is possible that the degree to which the structure of the brain changed was not enough to invoke a significant enhancement of younger participants' haptic perception. In addition, older participants with low vision in the present research were a group who actively engaged in cognitively and physically stimulating activities, such as computer classes, local community meetings, and regular exercises. Such an enriched environment typically helps older adults defend against negative physical, sensory, and cognitive aspects of aging[33 64], which might also contribute to the similarity of the two age groups.

Sharing preferences

No differences were found in the overall preferences on the HUI designs. Differences were found for only three HUI design ideas, but none of those three was strongly disliked.

However, it turned out that younger and older groups generally viewed the restric-

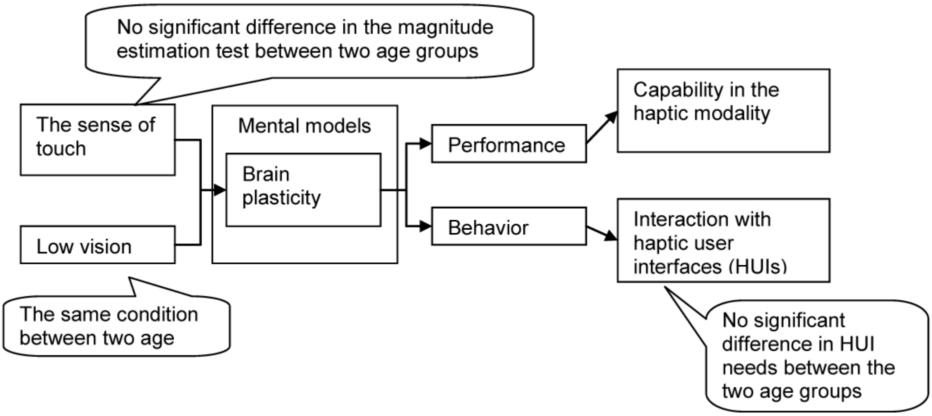

Figure 2. Explaining the observed similarity in haptic capability of the younger and the older group with lower vision, based on the brain-plasticity theory33; HUI=Haptic User Interface

tion of using a particular shape of haptic widgets unnecessary. It can be interpreted that, instead of merely avoiding complex images or shapes, it is recommended to provide appropriate assistive functions or tools for users to better locate and understand such complex figures as haptic widgets.

A new model

Based on findings and inferences, our brain-plasticity framework was accordingly modified by adding new attributes: duration, onset, level of expertise in a haptic task, and enriched environment. Given the similarity in haptic capability between the two age groups with low vision, HUI designers can develop a haptic system with a certain range of force feedback magnitude (for instance, frequency of vibration) that is applicable to both age groups with low vision.

Future research could include individuals with total blindness in order to compare their haptic modality to those with low vision. HUI designers can, thus, take into account the totally blind group's haptic capability in facilitating inclusive design of haptic technology.

In addition, future research could include middle-aged adults with low vision who are between the ages of 30 and 65. For the middle-age user groups, the model should be modified to include new factors, such as brain weight and neuronal degeneration. In addition, the stimuli (for instance, 120, 320, and 400 grits of sandpaper samples) might be too noticeable for both groups of participants leading to similarity, which is referred to as a ceiling effect. In that regard, a future study could be conducted including a greater variety of sandpaper samples (for instance, 800 and 1000 grits).

The magnitude estimation test in Study 1 indicated that younger and older groups with low vision had no significantly different haptic capabilities. By applying these results a new model arises (*Figure 2*). It is evident that the two age groups result in being placed under the same condition associated with vision loss and touch sensitivity. Consequently, both groups might have developed similar mental models as a result of brain plastic change, which may also have accounted for the similarities in performance and behavior related to haptic technology.

Study limitations

The list of HUI user needs was limited to four design situations: navigation, finding objects, getting an overview, understanding an object, and discriminating between objects. Although the four situations can be regarded as fundamental HUI design components for any type of device that embeds haptic technology, there is also a possibility that more various UI design components could exist. In addition, older and younger participants might have different prior experiences in using a computer in terms of frequency, purpose, software, and operating system, which possibly influenced the results of this research (for instance, user interface preference scores). This research, however, attempted to minimize the gap of computer literacy between the two age groups. Overall, most participants who were invited to the present study possessed the knowledge and ability to use computers and/or other technology (for instance, cell phone, ZoomText and JAWS, a screen reader). Additionally, there is the likelihood that participants' preference could change if a working prototype were given to those participants. Although the tangible prototype widgets were given to participants to help them understand future system interfaces and reduce their cognitive workload, they probably relied on their imagination somewhat. Each individual's projected image might be varying, which is also likely to influence the results of the present study.

CONCLUSION

The two age groups were similar in haptic capability and HUI user needs. Some differences in preference did exist, however, and designers should take these into account.

References

1. National Institutes of Health. Vision problems in the U.S.: Prevalence of adult vision impairment and age-related eye disease in America. National Eye Institute; 2002; http://www.preventblindness.net/site/DocServer/VPUS_2008_update.pdf?docID=1561; retrieved May 15, 2010
2. World Health Organization. Visual impairment and blindness. 2011; www.who.int/mediacentre/factsheets/fs282/en/; retrieved May 15, 2011
3. Mroczka MA. Effects of study modality and study order on learning braille and other haptic alphabets used by blind persons. Dissertation, North Carolina State University; 2005
4. Center for Persons with Disabilities. Visual disabilities: Low vision: Center for Persons with Disabilities. 2008; www.webaim.org/articles/visual/lowvision.php; retrieved May 15, 2010
5. Horowitz A, Brennan M, Reinhardt JP, MacMillan T. The Impact of Assistive Device Use on Disability and Depression Among Older Adults With Age-Related Vision Impairments. Journals of Gerontology Series B: Psychological Sciences and Social Sciences 2006;61(5):S274-S280
6. Virginia Assistive Technology System. Assistive technology and aging: A handbook for Virginians who are aging and their caregivers. 2004 ; www.vda.virginia.gov; retrieved May 15, 2010
7. U.S. Census. The 65 years and over population: 2000. 2001; www.census.gov/prod/2001pubs/c2kbr01-10.pdf; retrieved May 15, 2010
8. Dewsbury I, Sommerville P, Bagnall M, Rouncefield M, Onditi V. Software co-design with older people. In: Clarkson J, Langdon P, Robinson P, editors. Designing Accessible Technology. London: Springer; 2006
9. Ross DA. Cyber crumbs for successful aging with vision loss. Pervasive computing 2004;3(2):30-35; doi:10.1109/MPRV.2004.1316815
10. Burggraaff MC, Nispen RMA, de Boer MR, van Rens GHMB. Optometric and Multidisciplinary Approaches in Prescribing Low Vision Aids-Revised. Visual Impairment Research 2006;8(1):17-24; doi:10.1080/13882350600812502
11. Riemer-Reiss M. Assistive technology discontinuance. CSUN 2000 Conference Proceedings; 2000
12. Hartke R, Prohaska T, Furner S. Older adults and assistive devices. Journal of Aging and Health 1998;10(1):99-116; doi:10.1177/089826439801000106
13. Kim HN. Haptic user interface design for students with visual impairments. ASSETS 2009, 11th International ACM SIGACCESS Conference on Computers and Accessibility-Student Research Competition, Pittsburgh, PA, October 26-28; 2009; pp 267-268
14. Kim HN, Nam CS, Smith-Jackson T. User Interface Design Guidelines of Haptic-Thermal System for Visually Impaired Students in Obtaining Scientific Information. 4th International Conference on Social and Organizational Informatics and Cybernetics (SOIC), Orlando, Florida, June 29-July 2, 2008
15. Oh K, Anand S, Kim HN, Mi N, Kleiner H, Yamaguchi T, Smith-Jackson T. Usability evaluation of haptic science learning system using critical incident technique. International Applied Human Factors and Ergonomics Conference, Miami, Florida, July 17-20, 2010
16. Yamaguchi T, Johnson S, Kim HN, Li Y, Nam CS, Smith-Jackson T. Haptic Science Learning System for Students with Visual Impairments: A Preliminary Study. Lecture Notes in Computer Science Series (LNCS)2009;5616:157-166; doi:10.1007/978-3-642-02713-0_17

17. Johnson S, Yamaguchi T, Li Y, Kim HN, Nam CS. Analyzing the behavior of users with visual impairments in a haptic learning application. International Applied Human Factors and Ergonomics Conference, Miami, Florida, July 17-20; 2010
18. Kortum P. HCI beyond the GUI: Design for haptic, speech, olfactory, and other nontraditional interfaces. Burlington: Morgan Kaufmann; 2008
19. Hayward V, Astley O, Cruz-Hernandez M, Grant D, Robles-De-La-Torre G. Haptic interfaces and devices. Sensor Review 2004;24(1):16-29; doi:10.1108/02602280410515770
20. Baccini M, Rinaldi LA, Federighi G, Vannucchi L, Paci M, Masotti G. Effectiveness of fingertip light contact in reducing postural sway in older people. Age and Ageing 2006; 36(1):30-35; doi:10.1093/ageing/afl072
21. MacLean K. Designing with haptic feedback. Proceedings of IEEE Robotics and Automation(ICRA 2000); 2000; www.cs.ubc.ca/~maclean/publics/icra00-DesignWithHaptic-reprint.PDF; retrieved May 21, 2011
22. Urbano J, Terashim K, Miyosh T, Kitagawa H. Collision avoidance in an omni-directional wheelchair by using haptic feedback. Proceedings of the 4th WSEAS International Conference on Signal Processing, Robotics and Automation 2005; p 18
23. Shim HM, Lee EH, Shim JH, Lee SM, Hong SH. Implementation of an intelligent walking assistant robot for the elderly in outdoor environment. Proceedings of the 2005 IEEE 9th International Conference on Rehabilitation Robotics June 28 - July 1, 2005; Chicago; 2005; pp 452-455
24. Priplata AA, Niemi JB, Harry JD, Lipsitz LA, Collins JJ. Vibrating insoles and balance control in elderly people. The Lancet 2009;362(9390):362; doi:10.1016/S0140-6736(03)14470-4
25. Phillips B, Zhao H. Predictors of assistive technology abandonment. Assistive Technology 1993;5(1):36-45; doi:10.1080/10400435.1993.10132205
26. Hoppestad BS. Inadequacies in computer access using assistive technology devices in profoundly disabled individuals: An overview of the current literature. Disability and Rehabilitation 2007;2(4):189-199; doi:10.1080/17483100701249540
27. Riemer-Reiss ML, Wacker RR. Factors Associated with Assistive Technology Discontinuance Among Individuals with Disabilities. The Journal of Rehabilitation 2000;66(3):44
28. Bjelland HV, Tangeland K. User-centered design proposals for prototyping haptic user interfaces. Haptic and audio interaction design 2007;4813:110-120; doi:10.1007/978-3-540-76702-2_12
29. Riemer-Reiss M. Assistive technology use and abandonment among college students with disabilities. International Electronic Journal for Leadership in Learning 1999;3(23):1-14; http://www.ucalgary.ca/iejll/riemer-reiss_wacker; retrieved May 15, 2010
30. Goble AK, Collins AA, Cholewiak RW. Vibrotactile threshold in young and old observers: The effects of spatial summation and the presence of a rigid surround. Journal of the Acoustical Society of America 1996;99(4):2256-2269; doi:10.1121/1.415413
31. Bolanowski SJ, Gescheider GA, Verrillo RT, Checkosky CM. Four channels mediate the mechanical aspects of touch. Journal of the Acoustical Society of America 1998;84(5):1680-1694; doi:10.1121/1.397184
32. Kenshalo DR. Somesthetic sensitivity in young and elderly humans. Journal of Gerontology 1986;41(6):732-742; doi:10.1093/geron/41.6.732
33. Mahncke H, Bronstone A, Merzenich MM. Brain plasticity and functional losses in the aged: scientific bases for a novel intervention. Progress in Brain Research 2006;157:81-109; doi:10.1016/S0079-6123(06)57006-2
34. Baddeley A. Working memory, thought, and action. New York: Oxford University Press; 2007
35. Salthouse TA. Mechanisms of age-cognition relations in adulthood. Hillsdale: Erlbaum; 1992
36. Salthouse TA. The processing-speed theory of adult age differences in cognition. Psychological Review 1996;103(3):403-428; doi:10.1037//0033-295X.103.3.403
37. Schieber F. Human factors and aging: Identifying and compensating for age-related deficits in sensory and cognitive function. In: Charness N, Schaie KW, editors. Impact of technology on successful aging. New York: Springer; 2003; pp 42-84
38. Liu L, Park D. Technology and the promise of independent living for adults: A cognitive perspective. In: Charness N, Schaie KW, editors. Impact of technology on successful aging. New York: Springer; 2003; pp 262-289
39. Cooper BP, Lee MD, Goska RE, Anderson MM, Gay PE, Fickes LA, Fisk AD. Age-related effects in consistent memory search: performance is the same but what about learning? In: Rogers WA, editor. Designing for an aging population: ten years of human factors/ergonomics research. Santa Monica, CA: Human Factors and Ergonomics Society; 1997; pp 124-128
40. Perlmutter M. Cognitive skills within the

context of adult development and old age. In: Fisher C, Learner R, editors. Applied developmental psychology. New York: McGraw-Hill; 1994; pp 101-135

41. Ranney TA, Simmons LA. The effects of age and target location uncertainty on decision making in a simulated driving task. Designing for an aging population: ten years of human factors/ergonomics research: Santa Monica, CA: Human Factors and Ergonomics Society, 1997: pp 319-323
42. Llaneras RE, Swezey RW, Brock JF. Older commercial vehicle drivers: abilities, age, and driving performance. Designing for an aging population: ten years of human factors/ergonomics research. Santa Monica, CA: Human Factors and Ergonomics Society, 1997; pp 933-937
43. Salthouse TA. Adult cognition: An experimental psychology of human aging. New York: Springer; 1982
44. World Health Organization. Magnitude and causes of visual impairment. 2008; www.who.int/mediacentre/factsheets/fs282/en/; retrieved May 15, 2010
45. Stevens SS. Issues in psychophysical measurement. Psychological Review 1971;78(5):426-450; doi:10.1037/h0031324
46. Bergmann TWM, Kappers AML. Analysis of haptic perception of materials by multidimensional scaling and physical measurements of roughness and compressibility. Acta Psychologica 2006;121(1):1-20; doi:10.1016/j.actpsy.2005.04.005
47. Bergmann TWM, Kappers AML. Haptic and visual perception of roughness. Acta Psychologica 2007;124(2):177-189; doi:10.1016/j.actpsy.2006.03.002
48. Lederman SJ, Abbott SG. Texture perception: Studies of intersensory organization using a discrepancy paradigm, and visual versus tactual pschophysics. Journal of Experimental Psychology: Human Perception and Performance 1981;7(4):902-915; doi:10.1037//0096-1523.7.4.902
49. Suzuki Y, Gyoba J, Sakamoto S. Selective effects of auditory stimuli on tactile roughness perception. Brain Research 2008;1242:87-94; doi: 10.1016/j.brainres.2008.06.104
50. Diamond J, Lawless HT. Context effects and reference standards with magnitude estimation and the labeled magnitude scale. Journal of Sensory Studies 2001;16(1):1-10; doi:10.1111/j.1745-459X.2001.tb00286.x
51. Verrillo RT, Bolanowski SJ, McGlone FP. Subjective magnitude of tactile roughness. Somatosensory & Motor Research 1999;16(4):352-360; doi:10.1080/08990229970401
52. International Organization for Standardization. ISO 11056: 1999: Sensory analysis - methodology - magnitude estimation method
53. International Organization for Standardization. ISO 6344: 1998: Coated abrasives-Grain size analysis
54. Chambers IE, Wolf BM. Sensory testing methods. Philadelphia: American Society for Testing and Materials, ASTM; 1996
55. Sawilowsky SS. Nonparametric tests of interaction in experimental design. Review of Educational Research 1990;60(1):91-126;doi:10.2307/1170226
56. Kim HN. Usable Accessibility and Haptic User Interface Design Approach. 2010; Doctoral Dissertation, Virginia Tech, Blacksburg, VA.
57. Mora F, Segovia G, del Arco A. Aging, plasticity and environmental enrichment: Structural changes and neurotransmitter dynamics in several areas of the brain. Brain Research Reviews 2007;55(1):78-88; doi:10.1016/ j.1745-459X.2001.tb00286.xj.brainresrev.2007.03.011
58. Jastrow J. The dreams of the blind. The New Princeton Review 1888;5(1):18-34; doi:10.2307/1411326
59. Hannan CK. Review of Research: Neuroscience and the Impact of Brain Plasticity on Braille Reading. Journal of Visual Impairment & Blindness 2006;100(7):397-413; http://www.afb.org/jvib/jvib000704.asp; retrieved May 15, 2010
60. Hatwell Y, Streri A, Gentaz E. Touching for knowing: cognitive psychology of haptic manual perception. Philadelphia: John Benjamins Publishing, 2003
61. Marmor GS, Zaback LA. Mental rotation by the blind: Does mental rotation depend on visual imagery? Journal of Experimental Psychology: Human Perception and Performance 1976;2(4):515-521; doi:10.1037//0096-1523.2.4.515
62. Kerr NH. The role of vision in 'visual imagery' experiments: Evidence from the congenitally blind. Journal of Experimental Psychology: General 1983;112(2):265-277; doi:10.10370096-3445.112.2.265
63. Dulin D. Effects of the use of raised line drawings on blind people's cognition. European Journal of Special Needs Education 2007;22(3):341-353; doi:10.1080/08856250701430935
64. Wilson RS, Bennett DA, Bienias JL, Mendes de Leon CF, Morris MC, Evans DA. Cognitive activity and cognitive decline in a biracial community population. Neurology 2003;61(6):812-816; doi:10.1212/01.WNL.0000083989.44027.05

*Appendix A. Mean and standard deviation agreement scores for 10 younger and 10 older adults with low vision as related to statements concerning computer navigation; *=values differ between the young and the old group at a confidence level of 0.05*

Condition	Formulated need	Explanation	Degree of agreement	
			Younger	Older
1. Audition - Speech				
Besides a main menu bar and menu, a virtual button can be embedded in the 3D virtual space; A user wonders whether s/he clicked the right one	After hitting a virtual button, a user should receive verbal feedback about the button's function: such as 'Undo', 'Help', 'Find', and so on	The system keeps a user informed of the current situation through appropriate feedback within a reasonable time	4.7±0.5*	3.9±0.9*
A user would like to be briefly introduced with regard to the whole structure before performing any activity	A system should verbally describe the structure of the interfaces (for instance, location of buttons or objects) via a natural human voice instead of a synthesized voice	Building a mental image of interfaces in the 3D virtual space will contribute to a user's space perception	4.1±0.7	3.7±0.8
A user is seeking a certain widget such as a reference point; S/he would like to rely on a sense of hearing instead of other senses, such as a sense of touch or vision	If a user prefers to depend on auditory feedback, speech sounds should describe a route from a reference point to a certain point (for instance, 3D virtual space boundary, reference point)	A user's space perception is efficiently enhanced by accommodating the user's personal preference	4.3±1.0	3.8±0.6
A user spends a lot of time adapting to different tones of a system's speech sounds	Speech sounds should be tonally consistent	Users should not have to wonder whether different words, situations, or actions mean the same thing	4.3±0.5	4.5±0.5
A user would like to receive responses after completing an action	A user's performance should always be confirmed through a speech sound: for example, 'It is successfully completed' in a dialog box	The confirmation message contributes to a user's error prevention	4.1±1.0	4.2±0.4
2. Audition - Non-speech				
A user lost contact while following the contour of a virtual widget (for instance, a button)	A system should generate a non-speech sound (for instance, beeping) once a user loses contact while following the contour of an object	Non-speech sounds immediately inform a user of the lost contact	4.0±0.5	4.3±0.5
3. Touch - Accuracy				
A user often makes mistakes in computing; for example, s/he ends up clicking 'OK' on the dialog 'Are you sure you would like to quit the program without saving?'; S/he does not pay attention to the dialog because s/he clicks 'OK' too often	A reset or undo button should be available; A user should be able to escape from an unwanted status by using a reset or undo button; The reset or undo button lets a user start from the beginning	By hitting a reset or redo button, a user can work his / her way back to the point before the mistake was made; As a result, a user's feeling of being in control will also increase	4.5±0.9	4.0±1.4
A user touches an unwanted button in the virtual space that is located next to a wanted button	A virtual button should be sturdy	Sturdy buttons prevent a user from accidently pushing an unwanted button that is placed close to a wanted button	4.2±0.9	4.4±0.5

Appendix A, continued

Condition	Formulated need	Explanation	Degree of agreement	
			Younger	Older
A user gets lost while navigating or finding certain widgets; S/he does not know where a reference point is located from the user's current position; S/he decides to ask the system for help in order to return to a reference point	A user's 3D virtual pointer is automatically guided by a system toward a previous position or a reference point upon the user's request	Automatic movement will ease a user's cognitive workload	4.0±0.8	3.7±0.8
A user gets lost while navigating or finding certain objects; S/he does not know where a reference point is located from the user's current position; S/he decides to ask the system for help in order to return to a reference point	When a user's virtual pointer is guided by a system, different routes should be available for a user to choose, based on duration and distance; for instance, a user can either directly jump to the reference point or follow his / her track	The choice of following in his / her track back contributes to a user's space perception. The choice of directly jumping helps to save users' time.	4.2±1.2	3.9±0.9
A user is likely to lose contact with a virtual widget while following its contour	When a user loses contact with a virtual widget (for instance, contour following), a context menu should be available to ask the user whether s/he would like to rely on automatic guidance to go back to the previous position of the object	Such an auto movement will help a user concentrate on his or her primary work	4.1±0.9	4.2±0.4
A user gets lost while navigating or finding certain objects	A reference point should be available in the 3D virtual space	A reference point serves as a 'lighthouse' for a user in the 3D virtual space	4.2±0.9	3.9±0.7
A user gets lost while navigating or finding certain objects	A user should be allowed to assign a certain position as a reference point based on the user's preference	A reference point serves as a 'lighthouse' for a user in the 3D virtual space.	4.5±0.7*	3.5±0.9*
A reference point is located differently over subpages (or virtual subspaces)	A reference point should be located at the same place through all subpages; A system should provide consistency in user interfaces throughout the whole system	A reference point serves as a 'lighthouse' for a user in the 3D virtual space.	4.2±0.8	4.4±0.9
A user chooses to rely on a programmed movement of the virtual pointer that guides him / her toward a certain virtual widget; When s/he touches a virtual pointer to the widget, s/he realizes that the widget is not what the user wanted	A user should be given a confirmation message that asks whether the user wants to stay or leave (for instance, going back to the reference point or previous point); No activity should be allowed until the confirmation message is cleared	The dialog box enables a user to control how to carry out an action. It contributes to a user's error prevention.	4.0±1.2	3.8±0.6
4. TOUCH - FORCE BANDWITH				
A user's virtual pointer moves around to get an overview of the virtual environment	A user should experience haptic feedback when his / her virtual pointer is hovering over widgets in the virtual space; Feedback is given upon a user's request	A novice user is not good at operating the system and exploring the virtual space; Additional feedback will enhance the user's operation	4.3±0.7	4.1±0.3

Appendix A, continued

Condition	**Formulated need**	**Explanation**	**Degree of agreement**	
			Younger	**Older**
		5. TOUCH - SENSING ACUTENESS		
Besides a main console (for instance, a menu bar and toolbar), a 3D virtual button is often embedded in a 3D virtual space; Such a user interface element provides a user a simple way to trigger an event; A user switches a button from 'on' to 'off' or vice versa	When a push button is switched from 'on' to 'off' or vise versa, different textures should be assigned to the button	In graphical user interfaces, activating a button makes its associated content visible and the button itself usually becomes highlighted with different colors to distinguish it from other, inactive ones; In haptic user interfaces, different textures should be used instead of different colors	3.1±1.2	3.9±0.7
How should it be designed to effectively deal with disabled buttons/menus/taps that are not supposed to allow double clicks?	After a push button is pushed down, the push button should return to the original height	Disabled buttons can still be used as reference points for users with visual impairments; It is a critical design issue	3.9±0.7	3.3±1.2
All virtual buttons are identical in terms of size, regardless of function; A user gets confused and should carefully pay attention to distinguish them; Even a returning user must put considerable effort into recall	Virtual buttons in the 3D virtual space (besides a main menu bar) should be grouped and separately placed according to their size; Different aspects (for instance, functions) of virtual buttons should be indicated by different size and/or shape	Using different size and/or shape for different functions of buttons can contribute to a user's ease of understanding	3.9±1.2	3.8±0.8
A user touches virtual buttons in the 3D virtual space	A convex (bulging outward) button should be used rather than a concave (inward-curving) button	A convex type widget in the virtual space increases the possibility of being detected by a user's touch	3.7±1.4	3.8±0.9
A user spends a lot of time touching and understanding virtual key pads that are placed in the 3D virtual space	When virtual button numbers are in ascending order (such as 1, 2, and 3), increasing toughness of textures should be assigned to the buttons, respectively	A user should not need to put a lot of efforts into remembering information and/or content presented by a system; Tactile clues will ease the user's memory load	3.6±1.2	3.9±1.1
A user gets lost while navigating or finding certain objects	To build multiple reference points, each reference point should be unique in terms of texture, shape, sound, size	A reference point serves as a 'lighthouse' for a user in the 3D virtual space	4.4±0.7	4.0±0.5
A user's virtual pointer explores the space by touching different widgets; However, s/he is likely to miss 2D virtual widgets	Virtual objects should be represented in 3D instead of 2D	3D figures are more distinctive and easier to detect than 2D	3.8±1.2	3.3±1.1
If virtual widgets are widespread, a user is likely to miss some of them	Virtual objects should be arranged close to the midline of a user's body	In general, users with visual impairments tend to focus in front of the body because they have a vision field that is limited to the center	3.6±1.0	3.7±0.7
When a user interacts with a set of virtual objects, s/he typically tends to scan a working area by moving from left to right and vice versa instead of up and down.	3D virtual objects should be arranged on a horizontal line instead of a curvy line	Systemically displaying widgets, such as having all on a horizontal line, is likely to help a user successfully locate all objects by moving horizontally	3.9±1.2	4.3±0.5

Appendix A, continued

Condition	Formulated need	Explanation	Degree of agreement	
			Younger	Older
A user with Carpal Tunnel Syndrome may have abnormal touch sensitivity	Force feedback (for instance, vibration) should not be solely used; A user should be given a means to customize a system; Multimodal feedback methods (for instance, visual, sound, haptic feedbacks) should be available upon a user's request	Force feedback (for instance, vibration) should not be solely used because a user might have Carpal Tunnel Syndrome	4.5±0.9	4.2±0.9
A spherically shaped widget is difficult for a user to understand by touch in the real world	A virtual spherical widget should be avoided	The system should communicate with a user through concepts familiar to the user, rather than system-oriented ones; User interfaces should follow a user's real-world conventions, making information appear in a natural and logical order	2.4±0.5	2.9±0.9
The user's virtual pointer is approaching the boundary of the 3D virtual space	A system should generate vibration with speech sounds when a user's virtual pointer touches the boundary of the 3D virtual space	A combination of two different sensory modalities can increase a user's chance of being informed about a situation	3.8±0.9	4.1±0.3
A user wants to save time and efforts when finding a place or object in the 3D virtual space	There should be a search function; A user types a place to go or objects to find; A system then verbally or physically guides the user toward the target	A search function can save a user's time and effort	4.1±0.6	4.1±0.6
A user is likely to become confused as to the degree to which a slider (or a clock type) button is moved	A push type button should be used in the 3D virtual space because it is the most preferred design compared to others (a switch up/down button and a clock type button)	A push button shows only two statuses -on and off- making it easy for a user to understand the status	3.9±0.9	3.5±1.3
6. TOUCH - WORKSPACE SIZE				
A user's virtual pointer quite often touches a virtual menu bar by mistake; The menu bar interrupts the virtual pointer's movement; A user's virtual pointer results in a limited range of movement in the 3D virtual space	If a virtual menu bar is implemented, a user should be allowed to rearrange it in a way s/he thinks is more suitable and easy to navigate around in the 3D virtual space; S/he should be able to drag and drop it to change its position	A user will have enough space to navigate and not bump into the menu bar	4.4±1.0	3.5±1.2
A user gets lost and wanders away from a working area; The user has no idea of his or her location in the virtual space	A 3D virtual space should have a boundary	Graphic user interfaces have a container, that is, window; A sighted user is able to see the window through vision; A pointer's location is identified whether it is inside or outside of the window; Haptic user interfaces have a virtual boundary	4.1±0.6	4.3±0.5

Appendix A, continued

Condition	**Formulated need**	**Explanation**	**Degree of agreement**	
			Younger	**Older**
A user navigates in the 3D virtual space	Once a system is activated, it should provide a user with a chance to perceive a 3D virtual space size by guiding a user to touch, follow, and feel the boundary; A user should have force feedback (for example, vibration or locking a virtual pointer move)	In this way, a user's space perception will be enhanced; Space perception provides cues, such as depth and distance, that are important for movement and orientation to the environment; As a result, the user becomes aware of the relative position of his / her virtual pointer	3.8±0.9	4.0±0.8
A virtual space is large; A user keeps moving to find a certain object	A small-sized virtual space should be provided to a user	It is a challenge for a user to locate objects in the large virtual space.	3.5±1.1	3.3±0.8
7. Vision - Icons				
Widgets in the 3D virtual space are arranged to be overlapped so that multiple objects look like a single object	Virtual widgets should not all be arranged on the same sagittal plane (parallel to the midline of body)	There are two identical widgets; If a widget is located right behind another widget, a user gets confused and considers them as a single widget	2.8±1.1	3.7±1.0
Widgets in the 3D virtual space share the same color or a combination of less distinctive colors	The color should be changeable to black and white, yellow on black, and inverted brightness	The clarity of contents presented in the 3D virtual space generally contributes to a user's easier viewing and reduced eyestrain	4.3±1.0*	3.3±1.2*
Small widgets are difficult for a user to detect	Extremely small widgets should be avoided	Making widgets easy to detect is critical to user interface designs	3.3±1.3	4.3±0.5
8. Vision / Audition - Icons				
While a user tries to find a certain virtual widget (menu or other objects in the virtual space), there is a possibility that the user fails to locate it; However, a user may desire to continue looking instead of going back to a reference point	A system should be able to scan any virtual widgets (for instance, user interface components and any other objects) near a user's virtual pointer and update the user on their locations (for instance, overview)	Unless a user wants to get back to a reference point, s/he prefers to keep moving around to find a target	4.4±0.5	4.1±0.6
9. Vision / Audition - Menus				
A user should trigger an event	Shortcut keys on a keyboard should be set as primary tools to control or play with content in the 3D virtual space instead of manipulating menus on a screen	A computer keyboard is easy for a user with visual impairments to operate rather than menus on a screen	3.2±1.2	3.5±0.7
A user is not good at spelling	A system should provide a spelling checker	A spelling checker flags words in a search box that are not spelled correctly	4.1±0.7	3.6±1.1

Appendix A, continued

Condition	Formulated need	Explanation	Degree of agreement	
			Younger	Older
10. Vision / Audition - Pointers				
A user controls a system's input device (such as mouse) that is associated with a virtual pointer; It is not easy for a user to follow a fast move of a 3D virtual pointer on the screen	A user should be allowed to adjust a 3D virtual pointer speed	Adjusting the virtual pointer speed is a necessity for certain users; If s/he wants to play a fast-paced application with a lot of dynamic movements, a faster pointer speed is desired; Sometimes, s/he plays with a delicate move	4.5±0.7	3.8±1.2
11. Vision / Audition - Windows				
A boundary is less noticeable; A user is likely to miss the boundary in the 3D virtual space; His / her virtual pointer moves through it and s/he gets lost; S/he likes to be informed visually before bumping into the virtual boundary	A 3D virtual space should have a boundary with colorful spots	Color helps a user to easily recognize the boundary	3.3±1.3	3.0±1.2
Text or an image is presented to a user; However, the sentence is too long to be shown in a given space, or the image is too big to fit in the virtual working area	The whole widget or text should be shown within a working space; It should be ensured that, even if the image of a widget (or text) is magnified, the entire image (sentence) should be shown within the working space; For example, written information is presented in short sentences instead of one long sentence	The whole image or sentence will enhance a user's understanding	4.1±0.7	4.1±0.6
A user does not want to enlarge all components in the 3D virtual space but a specific components (or area)	An e-magnifier (partial enlargement) with a color enhancement function should be available.	A user can carefully observe a given environment	3.9±0.9	4.0±0.5