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# Aging and the haptic perception of 3D surface shape

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**Abstract** Two experiments evaluated the ability of older and younger adults to perceive the three-dimensional (3D) shape of object surfaces from active touch (haptics). The ages of the older adults ranged from 64 to 84 years, while those of the younger adults ranged from 18 to 27 years. In Experiment 1, the participants haptically judged the shape of large (20 cm diameter) surfaces with an entire hand. In contrast, in Experiment 2, the participants explored the shape of small (5 cm diameter) surfaces with a single finger. The haptic surfaces varied in shape index (Koenderink, *Solid shape*, 1990; Koenderink, *Image and Vision Computing, 10*, 557–564, 1992) from −1.0 to +1.0 in steps of 0.25. For both types of surfaces (large and small), the participants were able to judge surface shape reliably. The older participants' judgments of surface shape were just as accurate and precise as those of the younger participants. The results of the current study demonstrate that while older adults do possess reductions in tactile sensitivity and acuity, they nevertheless can effectively perceive 3D surface shape from haptic exploration.

**Keywords** Aging · Shape perception · Haptics

Three-dimensional (3D) shape perception has been studied scientifically for hundreds of years. For example, the importance of binocular disparity and motion parallax for the perception of 3D shape was pointed out by Wheatstone (1838) and von Helmholtz (1867/1925), respectively. Over the past 170 years, most of the studies of 3D shape perception have been limited to explorations of visual shape perception. While haptics (active touch) is the only other modality by which human beings perceive 3D shape, its study has been relatively neglected. This began to change in the 1960s. In that decade, James Gibson and his students (notably James Caviness), pointed out the importance of haptics for the perception of solid object shape (Gibson, 1962, 1963, 1966). In these publications, Gibson referred to some clever experiments conducted in his laboratory: on any given trial in a typical experiment, a participant would haptically explore one of ten smoothly curved solid objects (which were collectively called "feelies") that they could not see and then indicate which of ten visible objects possessed the same 3D shape. Because the participants could make these cross-modal matching judgments with a relatively high degree of accuracy, Gibson believed that vision and haptics were essentially equivalent, at least with regards to shape. In referring to vision and haptics, he concluded (1962, p. 489) by saying "the equivalence of the two modes of perception for judgments of the object is such that differences got by one sense are equated to differences got by the other." Given the obvious importance of Gibson

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and Caviness's findings, it is very unfortunate that these experimental results (quantitative descriptions of data, graphs, statistics, etc.) were never published. If one wants to learn about the actual results of these seminal experiments, the only source is James Caviness's unpublished Master's thesis and unpublished Ph.D. dissertation (Caviness, 1962, 1964). In 2004, Norman, Norman, Clayton, Lianekhammy, and Zielke replicated Gibson and Caviness's haptic-visual cross-modal matching task with naturally shaped solid objects and found that Gibson's conclusions were basically correct: vision and haptics do share important similarities with regards to the perception of shape. Following Gibson in the 1980s and 1990s, systematic research into the haptic perception of objects increased. For example, Klatzky and Lederman (e.g., Klatzky, Lederman, & Metzger, 1985; Lederman & Klatzky, 1987; Lederman & Klatzky, 1990) conducted numerous studies of haptic exploration and object recognition, and Astrid Kappers and her colleagues began psychophysical experimentation upon the haptic perception of surface shape (e.g., Kappers, Koenderink, & Lichtenegger, 1994; Kappers, Koenderink, & te Pas, 1994).

Over the past decade, much has been learned about how increasing age affects the visual perception of 3D object shape. Although there are significant effects of age upon the stereoscopic perception of 3D shape (Norman, Dawson, & Butler, 2000; Norman, Crabtree, Herrmann, et al., 2006), these age-related changes are usually quantitative rather than qualitative in nature. For the most part, the stereoscopic systems of older observers function similarly to those of younger observers (Norman & Wiesemann, 2007; Norman, Norman, et al., 2008). The same cannot be said for the visual perception of 3D shape from motion. While older observers can perceive 3D shape from motion (Andersen & Atchley, 1995; Blake, Rizzo, & McEvoy, 2008; Norman, Bartholomew, & Burton, 2008; Norman, Clayton, Shular, & Thompson, 2004; Norman et al., 2000; Norman & Wiesemann, 2007), their ability to recover information about 3D shape from motion fails if the temporal correspondence of moving surface points is sufficiently disrupted (see Norman et al., 2000, 2004).

In contrast to the growing literature on aging and visual perception, few studies have examined the potential effects of aging upon the haptic perception of 3D shape. Two studies (Kleinman & Brodzinsky, 1978; Thompson, Axelrod, & Cohen, 1965) did examine aging and the haptic perception of two-dimensional (2D) shape. On any given trial in the Thompson et al. study, the younger and older participants haptically explored one of 24 2D objects; they were then required to select which of 26 visible objects possessed the same outline shape. Thompson et al. found relatively large effects of age. In one condition, for example, the younger participants' shape-matching performance was 62.1 percent higher than that of the older participants. The task employed by Kleinman and Brodzinsky was similar. On any given trial, the participants haptically explored a "standard stimulus" (a 2D polygonal figure) with their right hand, and simultaneously haptically explored either two, three, or four "comparison stimuli" with their left hand. The participants' task was to identify which of the comparison stimuli possessed the same outline shape as the standard. The results of Kleinman and Brodzinsky were similar to those of Thompson et al.: the younger participants' 2D shape-matching performance was 38.6 percent higher than that of the older participants.

Very few studies of aging and haptic 3D shape perception have been conducted, but the results obtained to date are quite different from those of Thompson et al. (1965) and Kleinman and Brodzinsky (1978). In their studies, Ballesteros and Reales (2004) and Ballesteros, Reales, Mayas, and Heller (2008) investigated aging and haptic priming. In an initial "study phase," younger and (healthy) older participants were allowed to haptically explore a variety of common 3D objects (e.g., vegetables, tools, etc.) for 10 s each. In a later "test phase," the participants were presented with both "old" (objects they had previously felt) and "new" (objects that they did not feel in the study phase) objects. The participants' task was to haptically explore and then name each object. The results in both studies demonstrated the existence of haptic priming (i.e., the latencies needed to name the objects were reduced for the "old" items). Furthermore, the magnitudes of the obtained haptic priming were similar for both the younger and (healthy) older participants. The studies of Ballesteros and colleagues indicate that older adults can effectively recognize/name objects using their sense of active touch. The only existing study to investigate aging and the haptic ability to discriminate differences in 3D object shape was conducted by Norman, Crabtree, Norman, et al. (2006). In their Experiment 1, older and younger participants haptically explored two naturally shaped 3D objects (bell peppers) on any given trial. The participants' task was to indicate whether the haptically explored objects possessed the "same shape" or had "different shapes." The results showed that there was no difference in shape discrimination performance between the younger and older participants.

From the results of Ballesteros and Reales (2004), Ballesteros et al. (2008), and Norman, Crabtree, Norman, et al. (2006), it is clear that older adults can reliably identify objects and discriminate whether two particular objects possess the same or different 3D shapes using their sense of active touch. However, this is all we know at present. We do not know, for example, how accurately older adults can perceive the 3D shape of single objects. Can older adults accurately perceive 3D surface shape from haptics? If they can, are there differences in the precision of older and younger participants’ judgments? The purpose of the current set of experiments was to remedy this lack of information and answer such questions: In Experiment 1, participants haptically explored large surfaces with an entire hand, while they explored small surfaces with a single finger in Experiment 2.

## Experiment 1

### Method

*Apparatus* The random assignment of experimental conditions across trials and the collection of the participants' responses were performed by an Apple iMac computer. The computer was also used to graphically depict the response scale (Fig. 1) employed by the participants in making their judgments of surface shape.

*Experimental stimuli* The 18 stimulus objects were created by a computer-controlled milling machine, and were first used by Kappers, Koenderink, and Lichtenegger (1994). The objects were composed of polyurethane foam that was impregnated with synthetic resin. To the participants, the object surfaces felt like beech wood. All of the objects possessed a circular flat base, with a diameter of 20 cm. The upper surface of the objects was smoothly curved: across the 18 objects, it varied in both shape (9 levels) and curvedness (2 levels). The specific shape index values (e.g., see Koenderink, 1990; Koenderink & van Doorn, 1992) ranged from −1.0 to +1.0 in increments of 0.25: −1.0, −0.75, −0.5, −0.25, 0, 0.25, 0.5, 0.75, and 1.0. A graphical depiction of the nine surface shapes is presented in Fig. 1. One set of the nine differently shaped objects possessed a curvedness of 2 $m^{-1}$ (radius of curvature was 0.5 m), while the other set of objects possessed a much smaller curvedness of 0.25 $m^{-1}$ (radius of curvature was 4 m). A photograph of 2 of the 18 objects is shown in Fig. 2. Figure 3 shows an object with a participant's hand for comparison.

*Procedure* A single object was presented on any given trial; it was not visible to the participant. The participants reached behind a curtain and haptically explored the shape of each curved surface with one hand; they were free to rotate the object with their other hand. The participants were given 30 s to haptically explore the shape of each object's upper surface; they were not allowed to systematically investigate the outer edge or "corner." Following the haptic exploration of each object, the participants' task was to adjust the position of a movable pointer (using the left and right arrow keys on the computer keyboard) along the scale shown in Fig. 1 in order to indicate the perceived surface shape. The participants were naïve and were thus unaware of the actual shape index values used in the experiment. Each participant estimated the shape of 72 objects in a single block of trials (9 surface shapes × 2 magnitudes of surface curvedness × 4 repetitions). No feedback was given until the conclusion of the experiment.

In addition to judging haptic surface shape, the participants were asked to perform the Moberg pick-up test (e.g., see Dellon, 1981; Moberg, 1958, 1962). The pick-up test is a test of both manual dexterity and tactile sensitivity, and has been used in previous investigations of aging (e.g., Desrosiers, Hébert, Bravo, & Dutil, 1996; Norman, Crabtree, Norman et al., 2006; Norman, Norman, Swindle, Jennings, & Bartholomew, 2009). In performing this test, a participant picks up 12 small common objects (e.g., a coin, flat-head screw, wing nut, hex nut, key, paper clip, nail, or washer) one at a time and places them into a small box. The cumulative time needed to pick up all of the objects is recorded. The participant performs this task with vision and without vision. In the absence of vision, the participant must rely on tactile information to detect, pick up, and manipulate the objects.

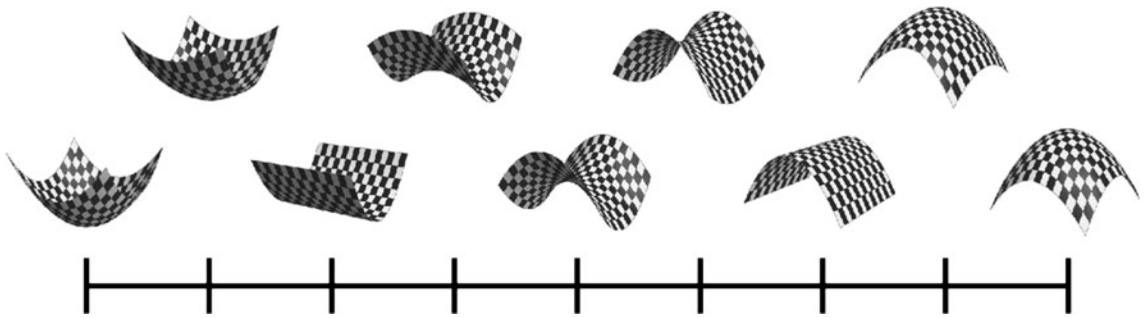

**Fig. 1** A graphical depiction of the types of curved surfaces used in the experiment. The surfaces are arranged by shape index, which ranges from −1.0 (concave hemisphere) at the far left to +1.0 (convex hemisphere) at the far right. Concave and convex cylinders possess shape index values of negative and positive 0.5, respectively, while a symmetric "saddle" is represented by a shape index value of zero. Shape index values with a magnitude between 0.5 and 1.0 represent various ellipsoids, while values with a magnitude between zero and 0.5 represent asymmetric "saddles." For more information about shape index, see Koenderink (1990) or Koenderink and van Doorn (1992)

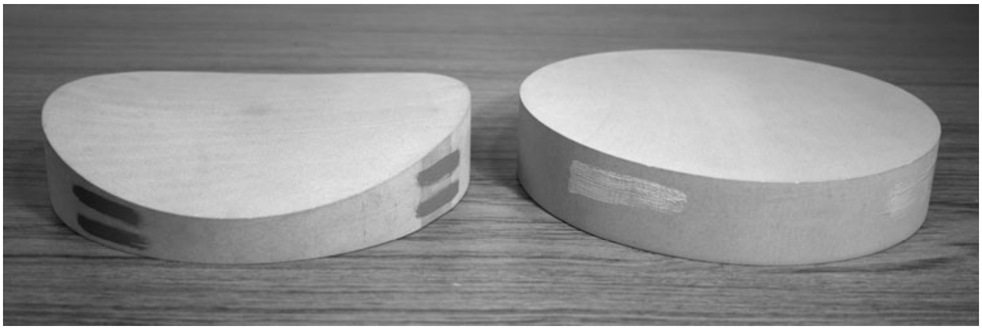

**Fig. 2** Photographs of two of the stimulus objects. Both of these objects are symmetrical "saddles" (i.e., shape index equals zero). The object on the left possesses a curvedness of 2.0 $m^{-1}$, while the object on the right is much flatter and possesses a curvedness of 0.25 $m^{-1}$

The time needed to pick up the objects is consistently shorter when vision is allowed and becomes longer when only tactile information is available. Our participants performed the Moberg pick-up test twice; we used their best performance in the resulting analyses.

*Participants* Twenty adults participated in the experiment. Ten of the participants were 64 years of age or older (mean age was 71.6 years, SD = 6.4; ages ranged from 64 to 84 years), while another 10 participants were 25 years of age or younger (mean age was 22.9 years, SD = 2.0; ages ranged from 18 to 25 years).

## Results and discussion

Various aspects of the results are shown in Figs. 4, 5, 6 and 7. Figure 4 plots the participants' perceived surface shapes as a function of the actual surface shapes. The results demonstrate that both the younger and older participants could reliably perform the shape estimation task, even for the surfaces with the least curvature. The average slopes of the best-fitting regression lines were 0.84 and 0.37 for the 2.0 $m^{-1}$ and 0.25 $m^{-1}$ surfaces, respectively. A three-way analysis of variance (ANOVA; one between-subjects factor: age, and two within-subjects factors: shape and curvedness) was conducted upon the participants' perceived surface shapes. The ANOVA revealed that there was no significant effect of age (or age-related interaction) upon the accuracy of the participants' responses (e.g., the main effect, F(1, 18) = 1.9, $p = .19$). While there were significant main effects of surface shape (F(8, 144) = 163.4, $p < .0001$, $\eta^2 = 0.90$) and surface curvedness (F(1, 18) = 15.8, $p < .001$, $\eta^2 = 0.47$), the surface shape × curvedness interaction was also significant (F(8, 144) = 27.2, $p < .0001$, $\eta^2 = 0.60$). This shape × curvedness interaction can be seen in the results shown in Fig. 4: the effect of the actual shape variations upon the participants' judged shapes depended heavily upon the magnitude of the surface curvedness.

**Fig. 3** A photograph of a stimulus object (symmetrical saddle), with a participant's hand for comparison

For each individual participant, Pearson *r* values were obtained by correlating the participants' perceived surface shapes with the actual surface shapes. The $r^2$ values (see Fig. 5) show that for the more curved surfaces, more than 80 percent of the variance in the participants’ perceived shapes can be accounted for by variations in actual shape. This proportion of variance accounted for dropped to less than 25 percent for the less curved surfaces. These $r^2$ values also constitute a useful measure of the overall precision of the participants' judgments (e.g., see Norman, Crabtree, Bartholomew, & Ferrell, 2009). If the participants' judgments are precise (little variation across repeated judgments for the same experimental stimuli), then the individual judgments will cluster tightly about the regression line and the resulting $r^2$ values will be relatively high. In contrast, if the participants' judgments are less precise (more variable), the resulting $r^2$ values will be lower. The results shown in Fig. 5 indicate that while the magnitude of surface curvedness has large effects upon the overall precision of the participants’ judgments (F(1, 18) = 178.6, $p < .0001$, $\eta^2 = 0.91$), age does not (main effect: F(1, 18) = 1.3, $p = .26$; age × surface curvedness interaction: F(1, 18) = 0.8, $p = .39$).

In their study, Kappers, Koenderink, and Lichtenegger (1994) found that the shape and curvedness of object surfaces had significant effects upon the variability of the participants' judgments across repeated trials. A similar effect also occurred in the current experiment. Figure 6 plots the standard deviation of our participants' repeated judgments for single conditions as a function of both surface shape and curvedness. While there were significant main effects of both surface shape (F(8, 144) = 3.0, $p < .004$, $\eta^2 = 0.14$) and

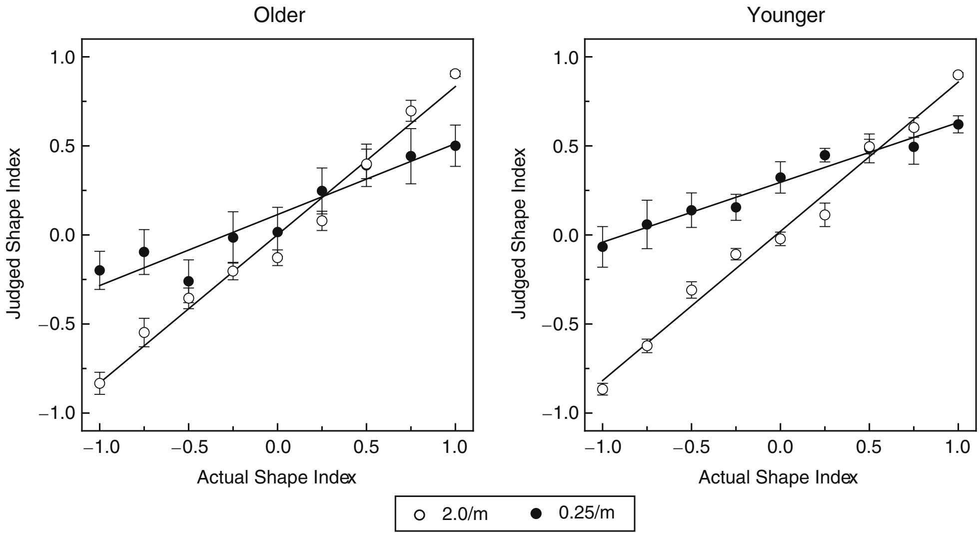

**Fig. 4** Experimental results. The younger (*right panel*) and older (*left panel*) participants' perceived shape index values are plotted as a function of the actual shape index values. The *filled circles* indicate results for the less curved surfaces (0.25 m$^{-1}$), while the *open circles* indicate results for the more curved surfaces (2.0 m$^{-1}$). The *error bars* indicate ±1 SE

curvedness (F(1, 18) = 44.9, $p < .0001$, $\eta^2 = 0.71$), there was, in addition, a significant shape × curvedness interaction (F(8, 144) = 2.2, $p < .04$, $\eta^2 = 0.11$). As can be seen in Fig. 6, the participants were much more variable in their judgments across repeated trials when the surfaces possessed less curvature. As the interaction indicates, the effect of shape, while significant, was different for the 0.25 m$^{-1}$ and 2.0 m$^{-1}$ surfaces. For the less curved surfaces, the standard deviations were lower for the convex surfaces and were higher for the concave surfaces. For the more curved surfaces, the standard deviations were lower for the symmetrically curved surfaces (concave hemisphere, convex hemisphere, and symmetrical saddle) and were higher for the asymmetrically curved surfaces.

While performing the surface shape estimation task, the participants would sometimes exhibit a "reversal." That is, a convex object, such as a cylinder, would be presented and haptically explored. The participant would then indicate that the perceived surface curvature was concave. Or the opposite would occur: the actual surface was concave, but the perceived surface was convex. A response was only considered to be a reversal when the stimulus surface was entirely convex or concave (because symmetric and asymmetric saddles contain both convex and concave curvatures). These perceptual reversals occurred on 17 percent of relevant trials for the 0.25 m$^{-1}$ surfaces, but occurred on only 0.8 percent of trials for the 2.0 m$^{-1}$ surfaces. Once again, the older and younger participants exhibited the same pattern of behavior: there was neither a main effect of age on the frequency of reversals (F(1, 18) = 0.1, $p = .72$) nor an age × surface curvedness interaction (F(1, 18) = 0.4, $p = .53$).

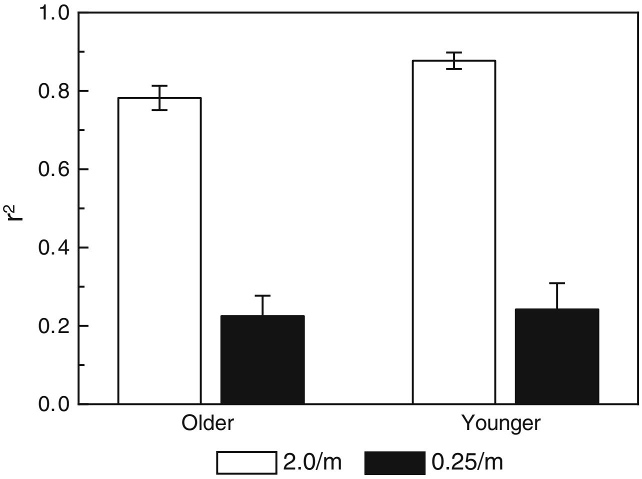

**Fig. 5** Experimental results. The younger and older participants' $r^2$ values are plotted for the less curved surfaces (*filled bars*) and more curved surfaces (*open bars*). The *error bars* indicate ±1 SE

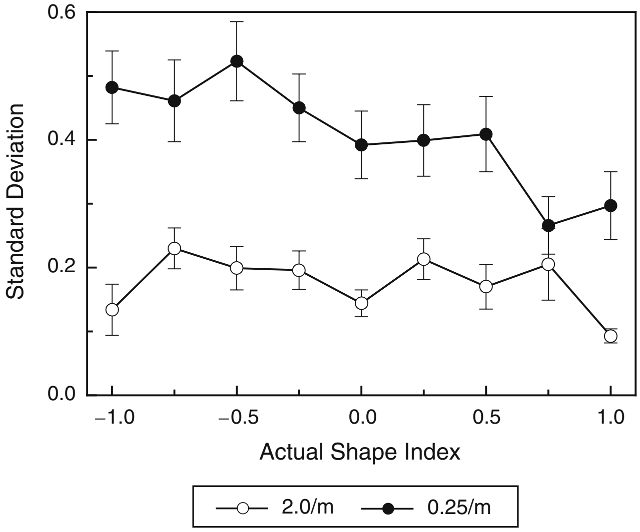

**Fig. 6** Experimental results. The participants' standard deviation values (variability across repeated judgments) are plotted for the less curved surfaces (*filled circles*) and more curved surfaces (*open circles*). The *error bars* indicate ±1 SE

Because the participants judged the shape of each object's surface four times, there is the possibility of practice effects (i.e., learning). In considering this issue, we calculated the magnitude of the participants' errors (deviations of judged shape from the actual shape) across the four repeated trials. While there was no overall effect of practice (F(3, 54) = 0.3, *p* = .84) or age (F(1, 18) = 1.2, *p* = .28), the age × replications interaction was significant (F(3, 54) = 2.84, *p* < .05). This interaction was caused by the fact that while the younger participants performed similarly across all four repetitions of a given object surface, the older participants' performance improved slightly over time (the older participants' errors decreased by 13.4 percent from the second repeated trial to the third; this improved performance was maintained during the fourth repeated trial). Other improvements in tactile 3D shape perception as a result of increasing experience have been obtained in past investigations (see Norman, Clayton, Norman, & Crabtree, 2008).

The results of the Moberg pick-up test are depicted in Fig. 7. An ANOVA conducted upon the results shown in Fig. 7 revealed that the age × vision/no-vision interaction was significant (F(1, 18) = 15.6, *p* < .001, $\eta^2 = 0.46$). The interaction occurred because while the older and younger participants' cumulative pick-up times were very similar when vision was allowed, they were quite different when the participants depended entirely upon tactile input. The almost identical pick-up times in the vision condition demonstrates that the older and younger participants possessed similar manual dexterity: i.e., it was possible for the older participants to pick up, manipulate, and transport the small objects at essentially the same rates as the younger participants. However, when vision was removed and the participants were required to use their sense of touch to detect and pick up the small objects, the results were quite different. In this case, the older participants had much more difficulty than the younger participants in tactually detecting the objects. The older participants would sometimes touch one of the small objects (e.g., the paperclip) and not pick it up (because they had not felt it). When this occurred (failure to detect an object after coming into tactile contact with it), the older participants would continue to search. During this additional search, the older participants would sometimes touch an object multiple times before finally detecting it and picking it up — this age-related difficulty in tactile detection is reflected in the longer cumulative pick-up times obtained in the no-vision condition for the older participants (compare the two filled bars in Fig. 7).

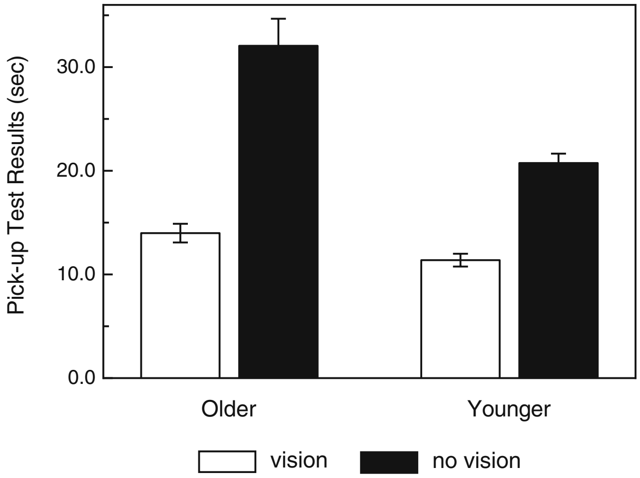

**Fig. 7** Experimental results. The results of the Moberg pick-up test are plotted for the younger and older participants. The cumulative pick-up times for the with- and without-vision conditions are indicated by the *light* and *dark* bars, respectively. The *error bars* indicate ±one SE

## Experiment 2

The results of Experiment 1 demonstrated that older adults can reliably make haptic judgments about 3D surface shape. There was no effect of age upon either the accuracy or precision of the participants' judgments. This good haptic performance for the older participants contrasts with the well-documented decline in tactile acuity that occurs with increasing age (e.g., Norman, Crabtree, Norman, et al., 2006; Stevens, 1992; Vega-Bermudez & Johnson, 2004; Woodward, 1993). Perhaps our older participants performed well in Experiment 1 because they haptically explored the curved surfaces using an entire hand (and thus had multiple, redundant, sources of tactile input from the five fingers and palm). In contrast, tactile acuity is measured at single locations, for example, at a single fingertip. It is conceivable that the older adults' ability to haptically perceive surface shape would deteriorate if they were limited to the use of a single finger. The purpose of Experiment 2 was to examine this possibility.

### Method

*Apparatus* The apparatus was the same as that used in Experiment 1.

*Experimental stimuli* The nine stimulus objects possessed the same surface shapes as those used in Experiment 1 (i.e., the shape indices varied from −1.0 to +1.0 in steps of 0.25). The major difference between the objects used in this experiment and the previous Experiment 1 was size: while the objects used in the previous experiment possessed a diameter of 20 cm, the current objects had a much smaller diameter of 5 cm (and were haptically explored by a single fingertip, see Fig. 8). The objects had cylindrical sides and a curved top, which was defined by the positions and

**Fig. 8** A photograph of a stimulus object, as used in Experiment 2 (a symmetrical "saddle" with a shape index of zero). The participant holds the object with one hand while haptically exploring its upper surface with the other hand's index finger

orientations of 3,062 connected triangular facets. The objects were composed of plastic and were printed using a Dimension Elite 3D Printer (Stratasys, Inc.). While the nine stimulus objects varied in surface shape, they all possessed a curvedness of 8 $m^{-1}$. While higher than the curvedness values employed in Experiment 1, 8 $m^{-1}$ is much smaller than that of typical handheld objects (e.g., a baseball, which fits comfortably in one hand, has a curvature magnitude of 27.4 $m^{-1}$). The value of 8 $m^{-1}$ was chosen following pilot experimentation, which revealed that this magnitude of curvedness for the smaller objects led to a precision of shape estimation that was intermediate between those obtained with the two sets (i.e., 2 curvednesses) of large objects used in Experiment 1.

*Procedure* The basic procedure and task was identical to that used in Experiment 1: on any given trial, each participant would hold a stimulus object with one hand and haptically explore the object's curved upper surface with the index finger of their other hand. The participants could feel, but not see, the stimulus objects, because of an occluding curtain. Once again, the participants were given 30 s to haptically explore each object's curved upper surface. The participants made their estimations of surface shape using the same scale that was employed in Experiment 1. Each participant made four judgments of surface shape for each of the nine stimulus objects, resulting in a total of 36 trials. The order of presentation of the stimulus objects was completely random. All participants were naïve and had no knowledge of the specific surface shapes used in the experiment.

In addition to measuring the participants' ability to haptically judge surface shape (which was the primary goal of the experiment), we also evaluated the participants' tactile acuity using tactile gratings (JVP Domes, e.g., see Bleyenheuft & Thonnard, 2007; Sathian, Zangaladze, Hoffman, & Grafton, 1997; Van Boven & Johnson, 1994). JVP domes (Stoelting, Inc.) are small hemispherical plastic domes that contain linear grooves (and ridges) of particular widths. We used a set of tactile gratings where the groove widths ranged from 5 to 0.75 mm (in particular, 5, 4, 3, 2, 1.5, 1.2, 1.0, & 0.75 mm). The tactile gratings were manually applied to the distal fingerpad of each participant's dominant index finger (the same finger that was used in the haptic shape task). The participants' task was to judge (without vision) whether the grooves were either aligned parallel or perpendicular to the long axis of their finger. For each groove width, 40 trials were conducted, where the actual orientation of the grating (parallel vs. perpendicular) was determined at random. Testing began for the younger participants at a groove width of 3.0 mm, and continued (with successive blocks of trials using smaller groove widths) until their orientation discrimination performance dropped below threshold levels (d' of 1.35, see Van Boven & Johnson, 1994). Because aging has been shown to significantly reduce tactile acuity (e.g., Norman, Crabtree, Norman, et al., 2006; Stevens, 1992; Vega-Bermudez & Johnson, 2004; Woodward, 1993), larger initial groove widths (e.g., 4 or 5 mm) were used for the older participants.

*Participants* The participants were 16 naïve adults, none of whom had participated in Experiment 1. Eight of the participants were 64 years of age or older (mean age was 71.8 years, SD = 5.7; ages ranged from 64 to 83 years), while the remaining eight participants were 27 years of age or younger (mean age was 21.0 years, SD = 3.2; ages ranged from 18 to 27 years). One potential younger participant was excluded, because her tactile acuity performance was exceptionally poor — her threshold was more than 3.5 standard deviations higher than the average of the other younger participants.

## Results and discussion

The results of the shape estimation task for the younger and older participants are shown in Fig. 9. It is clear from these results that younger and older participants can both reliably judge the surface shape of small objects using a single fingertip. Indeed, the older and younger participants' judgments of surface shape were equally accurate. There was no significant main effect of age ($F(1, 14) = 0.05$, $p = .83$), nor was there a significant age × shape interaction ($F(8, 112) = 1.19$, $p = .31$). There was, however, a strong effect of surface shape upon the participants' judgments ($F(8, 112) = 113.2$, $p < .0001$, $\eta^2 = 0.89$). In agreement with the results of Experiment 1, there was no significant difference in the precision of the younger and older participants' judgments of surface shape (i.e., no significant

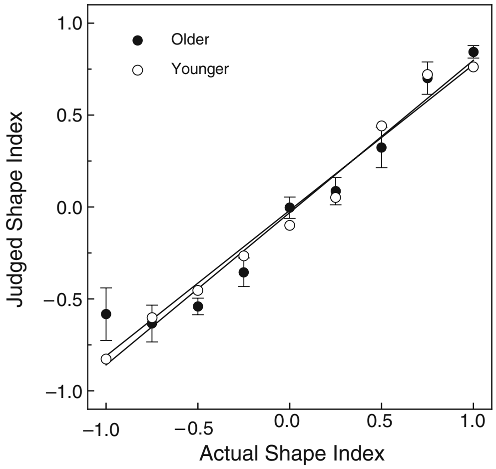

**Fig. 9** Experimental results (Haptic Shape Perception). The younger and older participants' perceived shape index values are plotted as a function of the actual shape index values. The *filled circles* indicate results for the older participants, while the *open circles* indicate results for the younger participants. The *error bars* indicate ±1 SE. The *solid lines* indicate the best-fitting regression lines

difference in $r^2$ values, t(14) = −0.87, $p$ = .4, two-tailed). The mean $r^2$ values for the older and younger participants were 0.68 and 0.77, respectively. Although there was no statistically significant age-related difference in precision, we decided to investigate this issue further, because the younger participants' $r^2$ values were 13.2 percent higher than those of the older participants. Given the difference in $r^2$ values that we obtained (0.09 = 0.77 − 0.68) and the variability across individual participants, a power analysis revealed that we would need a total of 222 participants (111 older and 111 younger participants) to have a 90 percent chance of detecting a difference in precision this small. It is thus conceivable that with enough participants, a statistically significant age-related difference in precision could be obtained. However, these results also indicate that even if increasing age does affect the precision of haptic shape estimation, this effect is very small relative to the amount of individual variability that occurs across participants.

The overall results of the current experiment were quite similar to those of Experiment 1 (e.g., compare Figs. 4 and 9); however, some differences were observed. Unlike Experiment 1 (see Fig. 6), the variability (standard deviation) of the participants' repeated judgments in the current experiment was not significantly affected by surface shape (F(8, 112) = 1.56, $p$ = .14). Also unlike Experiment 1, there were no significant effects of practice [i.e., no significant main effect of practice (F(3, 42) = 0.4, $p$ = .74) and no age × repetitions interaction (F(3, 42) = 0.6, $p$ = .62)].

The results for the tactile acuity task (see Fig. 10) were quite different than those obtained for the surface shape estimation task. For this task, there was a sizeable effect of age (t(14) = 4.74, $p$ = .0003). The older participants needed an average groove width (of the tactile gratings) of 2.99 mm for threshold orientation discrimination, while the younger participants needed a groove width that was 59 percent smaller (1.23 mm). From these results, it is clear that aging adversely affects performance for some tactile tasks, but not others. Tactile acuity is strongly affected by aging, but the ability to haptically judge surface shape is preserved.

Since the participants completed both tactile tasks, we wanted to determine whether there is any systematic relationship between the accuracy of surface shape estimation and the participants' tactile acuity. When plotting and correlating a participant's judged shapes with the actual stimulus shapes, accurate performance occurs when the participant's data fall along a line with a slope of 1.0 and when the best-fitting regression line has a y-intercept of zero. There are thus two convenient parameters by which we can evaluate the accuracy (or inaccuracy) of any given participant's shape judgments (slope and y-intercept). Because our older participants possessed a wide variety of tactile acuities, we correlated the older participants' grating orientation discrimination thresholds with the slope and y-intercept values obtained from a regression analysis of their surface shape judgments. The results of this analysis showed that there was almost no relationship between the performances obtained for these two tactile tasks. For example, the $r^2$ value for the relationship between the older participants' grating orientation discrimination thresholds and their y-intercepts was 0.281: thus, only 28.1 percent of the variance in the accuracy of shape estimation (when assessed using y-intercepts) can be accounted for by variations in the participants' tactile acuity. The $r^2$ value for the relationship between the older participants' grating orientation discrimination thresholds and their slopes was an even smaller 0.012: thus, only 1.2 percent of the variance in the accuracy of shape estimation (when

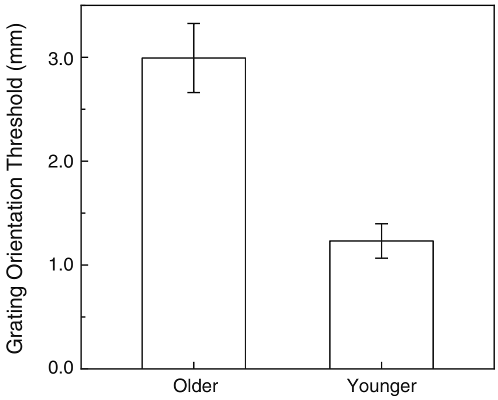

**Fig. 10** Experimental results (Tactile Acuity). The participants' grating orientation thresholds are plotted separately for each age group. The *error bars* indicate ±one SE

assessed using slopes) can be accounted for by variations in the participants' tactile acuity. While tactile sensation is obviously needed to perceive 3D shape, it also seems clear that one cannot predict how any given person will perform on haptic surface shape estimation given a knowledge of their tactile acuity.

## General discussion

The results of the current experiments replicate and extend those of Kappers, Koenderink, and Lichtenegger (1994). As in their study, we found that variations in curvedness had strong effects upon both the accuracy (Fig. 4) and precision (Fig. 6) of participants' judgments of haptic surface shape. In addition, Kappers et al. found that their participants' standard deviations (for repeated judgments) were higher for concave surfaces and lower for convex surfaces — the same pattern of results was obtained for the 0.25 $m^{-1}$ surfaces in Experiment 1 (see Fig. 6). In the earlier study, those authors reported occasional instances of perceptual "reversals" where the participants were able to perceive the "shape," but nevertheless made errors regarding the direction of curvature (i.e., the actual surface was convex, but the response was concave, or vice-versa, e.g., see Figs. 4c and 6c of Kappers et al.). Our participants also exhibited perceptual reversals. On average, our participants produced reversals on 17 percent of the relevant trials for the less curved surfaces, but produced similar reversals on only 0.8 percent of the trials for the more curved surfaces. It is clear that this difficulty in distinguishing convex from concave primarily occurs in the most difficult circumstances (i.e., when the surfaces have minimal curvature, e.g., see the right object in Fig. 2).

While the basic findings of the current study replicate those of Kappers, Koenderink, and Lichtenegger (1994), they extend the earlier results in a number of important ways. Most of all, the current results are important, because they demonstrate that older adults (even as old as 84 years) can haptically perceive 3D surface shape with the same level of accuracy and precision as 18-27-year-old adults (Figs. 4, 5, and 9). The current results (of Experiment 2) are also important, because they show that accurate and precise shape estimation occurs for small surfaces explored with a single fingertip. In addition, the current results demonstrate that the earlier findings of Kappers et al. are robust and occur for a larger and completely naïve sample of participants.

Past research has shown that aging has uneven effects upon sensory and perceptual abilities. For example, aging greatly disrupts performance on many different motion-related visual tasks, such as motion detection and the perception of stimulus shape, direction, and speed (Andersen & Ni, 2008; Atchley & Andersen, 1998; Bennett, Sekuler, & Sekuler, 2007; Bidwell, Holzman, & Chen, 2006; Billino, Bremmer, & Gegenfurtner, 2008; Buckingham, Whitaker, & Banford, 1987; Gilmore, Wenk, Naylor, & Stuve, 1992; Norman, Ross, Hawkes, & Long, 2003; Raghuram, Lakshminarayanan, & Khanna, 2005; Sekuler, Hutman, & Owsley, 1980; Snowden & Kavanagh, 2006; Trick & Silverman, 1991). These motion-related effects of age are not small. Norman et al. (2003), for example, found that their older observers' thresholds for speed discrimination were, on average, 58.7 percent higher than those of the younger observers. Aging has also been demonstrated to have detrimental effects upon tactile sensory tasks. Besides the reductions in tactile sensitivity found in the Moberg pickup test (Experiment 1) and tactile acuity (Experiment 2), aging has also been shown to reliably produce reductions in performance for a variety of tactile tasks involving (1) the detection of pressure (Kenshalo, 1986; Thornbury & Mistretta, 1981), (2) the detection of vibration (Kenshalo, 1986; Verrillo, 1980), and (3) tactile letter recognition (Vega-Bermudez & Johnson, 2002).

In agreement with past research, the results of the current experiments document the existence of age-related reductions in performance for tactile sensory tasks (tactile sensitivity in Experiment 1 and tactile acuity in Experiment 2). The same experiments also indicate, however, that older adults can effectively use haptic exploration to perceive the surface shape of objects (e.g., Figs. 4 and 9). Older adults can also effectively discriminate (Norman, Crabtree, Norman, et al., 2006) and recognize (Ballesteros & Reales, 2004; Ballesteros et al., 2008) solid objects using haptics. At this point it is important to remember that haptics involve the *active* exploration of objects, and thus utilizes motor and proprioceptive (kinesthetic) information, as well as tactile (cutaneous) input, to support the judgment of object shape (see Bell, 1833, pp. 178, 192–193; Lederman & Klatzky, 1987, 1990; Révész, 1950, pp. 92–101). As an example of the effectiveness of active exploration, Gibson (1962) showed that the active (haptic) manipulation of objects led to much higher shape recognition performance than the performance that resulted from simple (passive) tactile input. The results of the current study demonstrate that despite the existence of age-related reductions in tactile acuity, older adults can haptically perceive 3D surface shape in a manner that is essentially identical to that observed in young adults.

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