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The Effects of Aging on Haptic 2D Shape Recognition

Krista E. Overvliet, J. Wagemans, and Ralf T. Krampe
University of Leuven (KU Leuven)

We use the image-mediation model (Klatzky & Lederman, 1987) as a framework to investigate potential sources of adult age differences in the haptic recognition of two-dimensional (2D) shapes. This model states that the low-resolution, temporally sequential, haptic input is translated into a visual image, which is then reperceived through the visual processors, before it is matched against a long-term memory representation and named. In three experiments we tested groups of 12 older (mean age 73.11) and three groups of 12 young adults (mean age 22.80) each. In Experiment 1 we confirm age-related differences in haptic 2D shape recognition, and we show the typical age × complexity interaction. In Experiment 2 we show that if we facilitate the visual translation process, age differences become smaller, but only with simple shapes and not with the more complex everyday objects. In Experiment 3 we target the last step in the model (matching and naming) for complex stimuli. We found that age differences in exploration time were considerably reduced when this component process was facilitated by providing a category name. We conclude that the image-mediation model can explain adult-age differences in haptic recognition, particularly if the role of working memory in forming the transient visual image is considered. Our findings suggest that sensorimotor skills thought to rely on peripheral processes for the most part are critically constrained by age-related changes in central processing capacity in later adulthood.

Keywords: aging, touch, haptics, shape recognition, working memory

Experimental aging research has traditionally followed a distinction between "peripheral" sensorimotor and "central" cognitive processes. This distinction is supported by the modularity of the human brain and findings that adult age differences tend to be pronounced in tasks challenging central processes engaging prefrontal regions (West, 1996) than visual perception tasks challenging occipital regions, which undergo less dramatic neural changes during adulthood (Raz & Rodrigue, 2006). In recent years aging researchers have become aware that sensorimotor and cognitive processes are more intrinsically related in later adulthood (Lindenberger & Baltes, 1994; Woollacott & Shumway-Cook, 2002). One implication of these findings is that understanding adult-age development of skills heavily resting on sensorimotor processes requires careful consideration of cognitive processes. In this article we investigate age-related changes in such a skill, haptic perception and recognition of shapes. Specifically, we aim to determine the contribution of different peripheral and central stages of processing to age-related differences in haptically recognizing objects from two-dimensional (2D) shapes (raised line drawings).

Haptics is the sense of "active touch," it combines two sources of sensory information: touch (tactile input on the skin) and proprioception (the sense of the position of your body and body parts in space and relative to each other; e.g., Overvliet, Azañon, & Soto-Faraco, 2011). In order to recognize an object by touch we have to move our tactile sensors around that object in order to pick up detailed tactile information about its shape and surface properties (Lederman & Klatzky, 1987). Although the tactile sense is necessary in order to follow the line and pick up details of the shape (e.g., angle between two lines; Levy, Bourgeon, & Chapman, 2007), proprioceptive input is also important for recognition of tangible 2D shapes (Magee & Kennedy, 1980). It is proprioception, which provides information about the spatiotemporal trajectory that corresponds to the overall outline of the shape.

The "image-mediation model" (Klatzky & Lederman, 1987) aims to explain the haptic recognition of 2D shapes and it offers a framework that guides our investigation of age-related changes. According to the model (see Figure 1 for a graphical representation) the low-resolution, temporally sequential, haptic input is translated into a visual image, which is then reperceived through the visual processors. Subsequently the visual image is interpreted by matching it with long-term memory representations that would also contain the name of the object depicted by the shape. Experimental evidence for this model, and specifically for the need for visual translation came from a study by Lederman, Klatzky, Chataway, and Summers (1990). They asked participants to explore and name raised line drawings. Several results of these experiments provided strong support for the hypothesis that participants indeed relied on visual imagery processes to do the task. First, both

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Krista E. Overvliet, J. Wagemans, and Ralf T. Krampe, Laboratory of Experimental Psychology, University of Leuven (KU Leuven), Leuven, Belgium.

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Correspondence concerning this article should be addressed to K. E. Overvliet, Laboratory of Experimental Psychology, University of Leuven (KU Leuven), Tiensestraat 102 (Box 3711), B-3000 LEUVEN, Belgium. E-mail: krista.overvliet@gmail.com

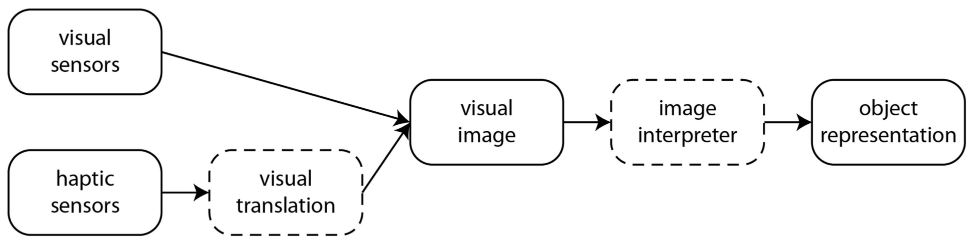

Figure 1. Schematic representation of the image-mediation model. Adapted from *The Intelligent Hand* (p. 129) by R. L. Klatzky and S. J. Lederman, in *The Psychology of Learning and Motivation,* 1987, New York: Academic Press.

imaging difficulty and vividness ratings were strongly correlated with RTs and accuracy. Second, congenitally blind had poorer performance than the normally sighted, and early blind were better than sighted. Third, the line drawings in their study contained three-dimensional (3D) structure, a clear visual pictorial cue. Fourth, and last, participants with a high ability to use mental imagery took less time to respond and were more accurate. Evidence for the last step in the image-mediation model, the naming of the object representations, came from a study by Heller, Calcatera, Burson, and Tyler (1996). These authors found that providing categorical information improves recognition of 2D haptic line drawings.

Together these findings strongly support the image-mediation model as a framework for haptic 2D shape recognition and they also open several routes for investigating differences between adult age groups. The initial stage of the image-mediation model is already a potential locus of age-related decline. This stage involves the finger pad touching a surface or an edge and moving around to pick up information about its shape (contour following, Lederman & Klatzky, 1987). The innervation of touch receptors in the skin of older adults is lower than in young adults, as measured by two-point discrimination on the finger pad (van Nes et al., 2008; Wickremaratchi & Llewelyn, 2006). It is, therefore, not surprising that older adults are less accurate than young adults in identifying small tactile shapes, for example, old fashioned type writer letters (Manning & Tremblay, 2006). However, studies assessing recognition of natural, real objects (at their real size) after exploration through active touch found no age-related differences in recognition *accuracy*, although older adults were typically *slower* at performing the tasks (e.g., Ballesteros & Reales, 2004). Likewise, older adults' were as accurate as young adults in 3D surface shape perception of objects (Norman et al., 2011), in a 3D shape discrimination task with natural objects (Norman et al., 2006) and in haptic search (Anema, Overvliet, Smeets, Brenner, & Dijkerman, 2011). Moreover, a recent study by Sebastián, Reales, and Ballesteros (2011) even showed no age-related differences in haptic performance (exploration times and accuracy), but despite that they found differences between the age groups in the amount of cognitive resources that was used. A study by Cole, Rotella, and Harper (1998) points in a similar direction: Here participants were instructed to grasp and lift a metal sphere with vision allowed or blocked. Although older participants took more time than young participants, the authors concluded that there was no evidence that the peripheral tactile deficits associated with participants' age had impaired their ability to complete the task. A recent study by Kalisch, Kattenstroth, Kowalewski, Tegenthoff, and Dinse (2012) indeed showed that cognitive capacity has a larger influence on haptic performance on a block recognition task compared with tactile acuity. In conclusion, peripheral sensory deficits in the elderly are unlikely to provide complete accounts for age-related differences on these tasks. However, they may still have a relatively small contribution to complex tasks like recognizing an object through touch. They, therefore, need to be considered and their influence must be controlled for in experimental paradigms as much as possible.

In the present study we investigate differences between older and young adults in haptic 2D shape recognition and we determine the contributions of different processing steps postulated by the image-mediation model proposed by Klatzky and Lederman (1987). Past research has shown that healthy older adults are indeed less accurate in haptic 2D shape recognition compared with young adults (Kleinman & Brodzinsky, 1978; Thompson, Axelrod, & Cohen, 1965). Two key components of the Klatzky and Lederman model go beyond peripheral, somatosensory processes, namely the translation of haptic information into a visual image and the matching with long-term memory representations. Both components arguably involve extensive central processes, which make them candidates for age-related decline and potential sources of age by task complexity interactions. Although visual perception can be based on all shape information available simultaneously and the visual image is provided "directly" (i.e., without transformations between modalities), haptic exploration involves a gradual build-up of representations from sequentially perceived features. The visual image resulting from transformation will almost certainly differ in quality from a "direct" visual image and this difference can be assumed to be larger for more complex shapes. Once the visual image of the object is available, it has to be matched with existing memory representations prior to naming. Without being explicit the image-mediation model basically assumes these processes to be similar for visual and haptic perception. Nonetheless, related search, comparison, and retrieval operations are known to be age-sensitive (e.g., Hodgson & Ellis, 1998; see for a review: Johnson, Paivio, & Clark, 1996), a disadvantage that will be aggravated by reduced information resulting from the visual transformation process.

An important aspect of the recognition of haptic 2D shapes is that they need to be explored sequentially, which involves quite a large working memory load: The formation of a complete image requires considerable simultaneous storage and processing because new information must be rapidly analyzed, and integrated with prior knowledge. As the exploration continues one has to keep the ready explored areas in working memory so that a complete picture can be synthesized. Moreover, the visuospatial scratchpad, the part of working memory that involves a temporary storage or online cache for visual and spatial information (Logie & Pearson, 1997) is suggested to play a role in visual imagery and is, therefore, important for the second step in the image mediation model. As aging commences it is well known that visuospatial working memory capacity is going down (Paz, Mayas, & Ballesteros, 2007). In the third step of the model, object recognition, working memory is also an important factor. One has to keep the possible options in working memory so that recognition is facilitated. Thus, by investigating the different stages of the image mediation model, we investigate different aspects of working memory. This is likely to be done in working memory. As soon as working memory declines with age, these stages are all going to be affected, and by investigating the recognition of haptic 2D shapes step by step, as we do in the current article, we can shed some more light on the importance of several different sub processes in working memory in relation to aging.

In a first step (Experiment 1) we validate our experimental paradigm by confirming negative age-related changes and age by stimulus complexity interactions in the recognition of two types of raised line drawings simple, geometrical shapes and complex, everyday objects. Along these lines we also consider stimulus-specific measures of complexity (Attneave, 1957) like compactness (the ratio between circumference and area of a line drawing) and the number of line intersections in the drawings. In a second step (Experiment 2 and 3) we scrutinize age-related performance deficits at the level of two component processes in the image-mediation model, namely translation of haptic input into a visual image and object naming. Our approach was to provide experimental manipulations that allow participants to circumvent a certain step in the haptic object recognition process or at least enhance processing at this stage considerably. Our rationale was that age-sensitive components should reveal themselves through a reduction of negative age-effects. In Experiment 2 we target the visual translation of haptic information process by contrasting haptic exploration with a visual "peek hole" task in the same participants. In Experiment 3 we provided participants with an object category along with the stimulus thereby reducing the search space for the object matching and facilitating retrieval of the memory representation. Throughout the experiments we aimed to control the contribution of peripheral sensory factors by using suprathreshold stimuli and by determining post hoc correlations between task performance and marker variables.

Experiment 1

Method

Participants. Participants were recruited from the participant pool of our lab. Twelve young (four male and eight female) and 12 healthy older (six male and six female) adults participated in this study on a voluntary basis; they were paid 8 euros per hour of participation. Sample characteristics and marker variables, related to cognitive status, working memory, and tactile sensitivity are shown in Table 1. These marker variables were mainly used as inclusion criteria (a description of each test can be found in the Appendix). At the beginning of the experiment, participants signed an informed consent. The study was approved by the local ethical committee.

Apparatus and stimuli. The stimuli were 30 2D tangible shapes (raised-line drawings), made with A3-sized Zy-Tex2 Swell paper® (Zychem Ltd., Cheshire, United Kingdom). This size is shown to generate higher accuracy rates as compared to other sizes (Wijntjes, van Lienen, Verstijnen, & Kappers, 2008). The lines in the drawings had a width of 2 mm and a height of approximately 0.5 mm. We divided the stimuli in two sets: a set consisting of simple shapes (simple set, Figure 2a) and a set consisting of shapes

Table 1
Sample Characteristics, Group Means and SDs (in Parentheses) for the Screening Tests of the all Experiments: Mini Mental State Examination (MMSE), Digital Span (DS), Digital Symbol Substitution (DSS), Activities of Daily Living (ADL), Instrumental Activities of Daily Living (IADL), Tactile Sensitivity Test, Proprioception Test, Spatial Memory, Vividness of Visual Imagery Questionnaire (VVIQ)

	Experiment 1		Experiment 2		Experiment 3	
	Young mean (*SD*)	Older mean (*SD*)	Young mean (*SD*)	Older mean (*SD*)	Young mean (*SD*)	Older mean (*SD*)
Age	23.58 (1.08)	73.92 (2.87)*	23.08 (1.31)	73.00 (3.19)*	21.75 (1.22)	72.42 (3.48)*
Years of education	17.58 (1.08)	15.90 (1.42)	17.08 (1.31)	14.56 (1.49)	15.75 (1.22)	15.92 (.82)
MMSE score	.	28.75 (1.06)	.	29.33 (1.07)	.	29.67 (.65)
SS score (scaled)	12.50 (.88)	12.17 (.53)	14.92 (.84)	11.00 (.60)*	11.00 (.54)	12.17 (.59)
DS score (scaled)	12.41 (.66)	11.75 (1.30)	11.92 (.58)	10.83 (.30)	13.17 (1.21)	12.75 (.66)
ADL	.	7.17 (0.29)	.	8.00 (0.00)	.	8.00 (0.00)
IADL	.	6.17 (0.29)	.	7.00 (0.00)	.	6.83 (0.58)
Tactile sensitivity	4.88 (0.09)	4.56 (0.33)*	4.84 (0.20)	4.29 (0.43)*	4.81 (0.09)	4.49 (0.35)*
Proprioception	.	14.00 (0.00)	.	12.75 (0.97)	.	14.00 (0.00)
VVIQ	43.08 (11.61)	32.20 (8.64)*	34.45 (9.43)	26.58 (9.65)*	38.00 (9.05)	30.08 (7.64)*

Note. Young participants did not take the MMSE, ADL, IADL and Proprioception test. * Indicates a significant difference ($p < .05$) in means between the two groups. A description of each screening test and significant correlations of the tests with exploration time and accuracy can be found in the appendix. SD = standard deviation; MMSE = mini mental state exam; SS = symbol substitution; DS = digit span; ADL = activities of daily living; IADL = instrumental activities of daily living; VVIQ = vividness of visual imagery questionnaire; * = significantly different between groups.

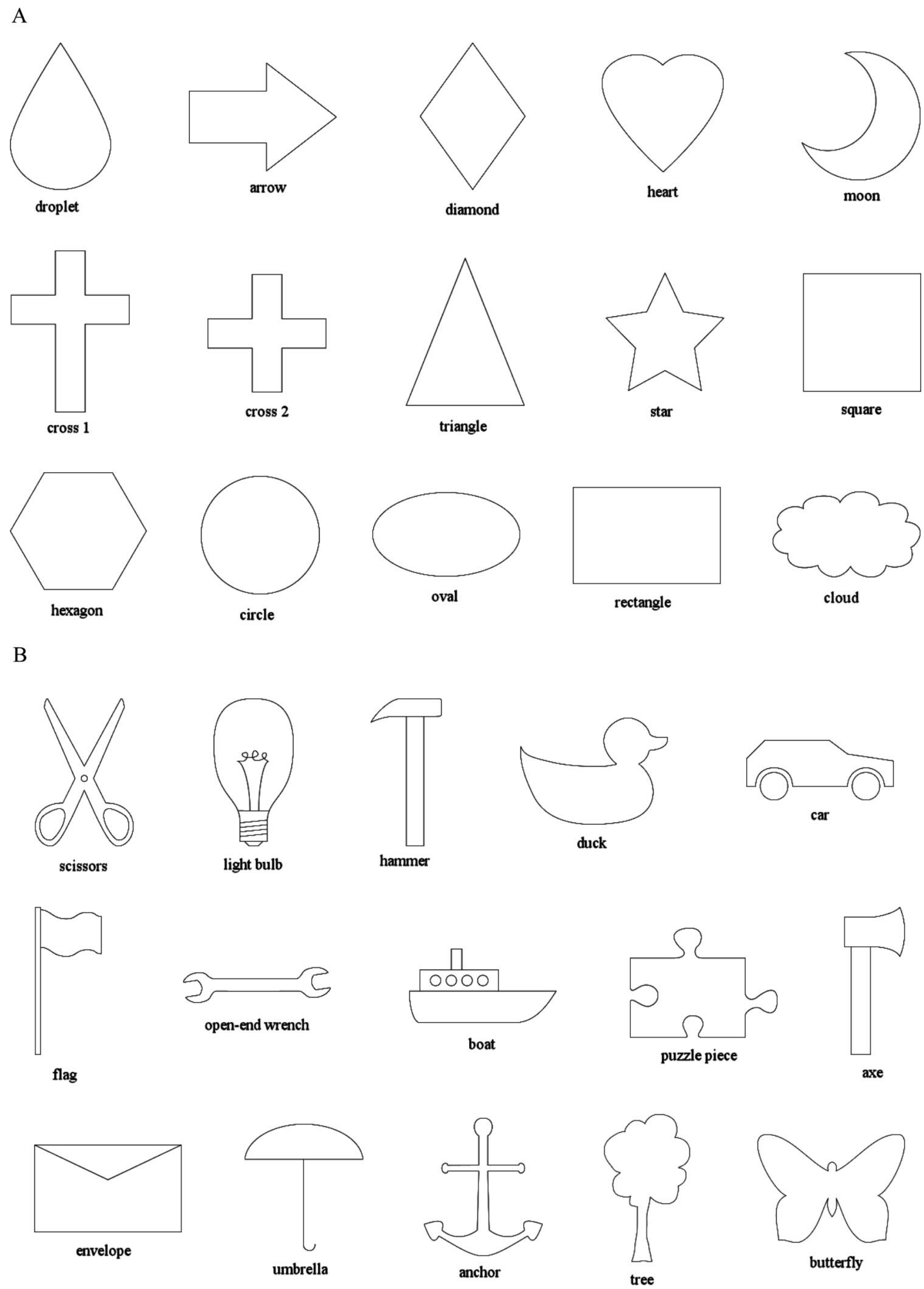

Figure 2. (A). The set of simple shaped stimuli. (B) The set of everyday objects.

of everyday objects (complex set, Figure 2b), each containing 15 different stimuli. All 15 pictures of the complex set were adopted, with permission, from the set used by Wijntjes, van Lienen, Verstijnen, and Kappers (2008). Each stimulus' size was defined according to its best fit to the A3 paper either in portrait or landscape. The largest dimension of the stimuli was always between 26.6 and 33.2 cm.

For all stimuli we calculated the complexity based on three different measures: the number of line crossings (defined as the number of places where two or more line segments come together), global symmetry (whether or not the outline of the contour is symmetrical), and a compactness measure. We calculated the compactness according to the definition of Segaert, Nygård, and Wagemans (2009): area of a contour divided by the area of a circle with a perimeter matching the contour length. Accordingly, the most compact contour (a circle) has a compactness value of 1, whereas a score of 0 equals infinitely low compactness (an infinitely complex contour).

Procedure. Participants were blindfolded and their task was to explore and name the raised-line drawings. They were free in the way they explored the stimuli. Although there was no time limitation, participants were instructed to be as fast and accurate as possible. If they were not sure about their answer they could continue to explore the stimulus until they were confident about their answer. If they had no idea which object the line drawing represented, they were asked to guess.

Before starting with the actual experiment, participants completed two practice trials with raised line drawings of everyday objects. The 30 experimental trials were divided in two blocks of 15: one block with simple shapes and one block with everyday objects. Participants were told which type of stimulus they would be presented with. The two blocks of trials were counterbalanced across participants and the stimuli within a block were presented in a randomized order. In each trial, the index finger of the dominant hand was placed at the starting position of the stimulus, which was at the bottom of the line drawing (either in the middle or one of the sides, depending on the shape of the stimulus; always at the same location for each stimulus). After a starting signal they could start exploring the stimulus, and as soon as they gave an answer the exploration time was recorded. The experimenter wrote down the answer that was given by the participant. Besides correct answers, any synonyms of these answers were also accepted as correct. For example, when participants named the diamond "parallelogram," we considered this correct. However, no feedback on accuracy was given during the course of the experiment. For each trial the experimenter marked which of the following exploration strategies were used by the participant: (a) using one hand, (b) using two hands: one is stationary and the other one is moving, and (c) using two hands: both are moving (Wijntjes et al., 2008). If two or three of the strategies were present in a trial we counted them all two or three. The participants were not informed about these strategies, and were not aware that the experimenter took note of them.

Analysis. Data analyses were done with Matlab R2008a, and statistical tests with SPSS version 19. To calculate average exploration times we used correct trials only. In order to normalize the exploration times we took the logarithm (log10) of each individual trial and averaged for each participant. Before averaging over participants, we took the antilog of the mean logarithmic exploration times. We also used these values for the ANOVAs and *t* tests. We used this normalization in all three experiments in this study. Post hoc comparisons were done as *t* tests with Bonferroni corrections applied for multiple comparisons. We applied Levene's test for violations of the equal variances assumptions and degrees of freedom were adjusted when necessary.

Results and Discussion

Mean exploration times for each condition are shown in Figure 3A. A mixed-model ANOVA with stimulus complexity as within-subjects factor and age group as between-subjects factor showed a significant main effect for age group, $F(1, 22) = 26.32$, $p < .0001$, $\eta^2_{\text{-p}} = .55$, and stimulus complexity (simple shapes vs. everyday objects), $F(1, 22) = 33.85$, $p < .0001$, $\eta^2_{\text{-p}} = .61$, as well as a significant interaction of the two factors, $F(1, 22) = 5.14$, $p < .05$, $\eta^2_{\text{-p}} = .19$. Post hoc comparisons showed that simple shapes were recognized faster than everyday objects in both age groups, $ts(11) > 4.11$, $ps < .01$. Young participants were faster than older adults for both types of shapes, $ts(22) > 3.72$, $ps < .01$.

Results for recognition accuracy mirrored those for exploration times and are shown in Figure 3b. A mixed-model ANOVA on proportions correct with complexity as within-subjects and age group as between-subjects factors yielded main effects of age, $F(1, 22) =$

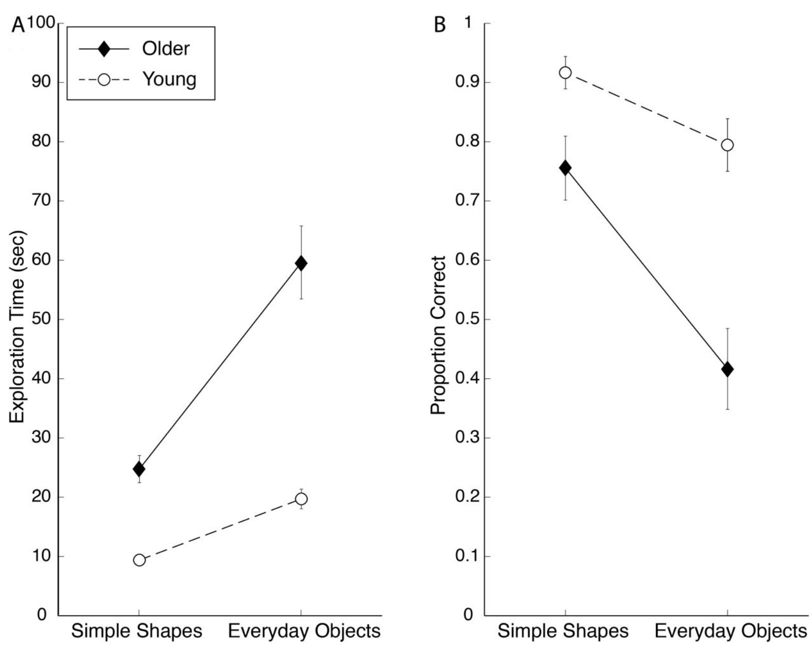

Figure 3. Results of Experiment 1. (A) Mean exploration time and standard errors of correct trials for both older and young group for simple and complex stimuli; (B) Proportion correct and standard errors for both older and young group for simple and complex stimuli.

18.69, $p < .0001$, $\eta^2_p = .46$, and complexity, $F(1, 22) = 41.94$, $p < .0001$, $\eta^2_p = .66$, as well as a significant interaction, $F(1, 22) = 9.26$, $p < .01$, $\eta^2_p = .30$. Both groups recognized more simple shapes than everyday objects, $ts(11) > 2.60$, $ps < .025$, and young participants recognized more stimuli in both tasks, $ts(22) > 2.66$, $ps < .025$, with a greater advantage in the more complex condition.

To test whether the differences between young and older adults in exploration time and accuracy could be the result of different exploration strategies that participants applied, we compared the frequencies of the use of the three predefined strategies as described in the procedure section (see Figure 4 for a graphical representation). A mixed-model ANOVA with within-subjects factors strategy and stimulus complexity and between-subjects factor age group showed main effects for strategy, $F(2, 44) = 115.92$, $p < .0001$, $\eta^2_p = .84$, stimulus complexity, $F(1, 22) = 26.34$, $p < .0001$, $\eta^2_p = .55$, and an interaction between these two, $F(2, 44) = 14.45$, $p < .0001$, $\eta^2_p = .40$. No effects related to age group turned out significant. Post hoc comparisons revealed that the second strategy (one hand stationary on the stimulus, the other hand moving) was used more often for everyday objects than for exploring simple shapes, $t(11) = 3.08$, $p < .01$. No other differences among strategies were significant. The experimenters also observed that symmetric stimuli and symmetric parts of stimuli were frequently explored with both hands simultaneously. Asymmetric stimuli or parts were typically mainly explored with one hand only (using either of two unimanual strategies). Note that simple shapes are more symmetric than everyday objects, which most likely contributed to the reported strategy effect. Moreover, unimanual strategies seemed to be used more often on everyday objects to gather more information about details of the drawings. These observations held for the young and older adults. Thus, young and older adults were highly similar in how they explored different types of shapes ruling out strategy differences as an account for observed age effects in exploration time and accuracy.

To further scrutinize the relation between different aspects of stimulus complexity and participants' exploration times, we conducted linear regressions on each individual's data of each participant with complexity measures (compactness, number of line crossings, and global symmetry) as independent variables. Besides higher intercepts, we found reliably steeper slopes for older adults compared with young adults in all three measures indicated that their exploration times were more heavily influenced by stimulus complexity than those of young adults, $t(22) = 3.67$, $p < .001$, $t(22 = 2.17$, $p < .05$ and $t(22) = 4.27$, $p < .001$, for compactness, number of line crossings, and global symmetry, respectively).

In sum, we obtained reliable differences between the two types of stimuli for exploration time as well as recognition accuracy in both age groups. Regression of exploration times on three different complexity measures at the level of individuals further validated our experimental procedures. As predicted, older adults took more time and they were also less accurate than young adults and this was true for both types of stimuli. We also demonstrated the typical age x task complexity interaction, which we corroborated at the level of age differences in slopes with continuous measures of complexity. In Experiments 2 and 3 we consider different phases of the 2D shape recognition process as loci for the demonstrated age-related differences in performance.

Experiment 2

In Experiment 2 we investigated the contribution of the presumed haptic-visual transformation to age-related differences in

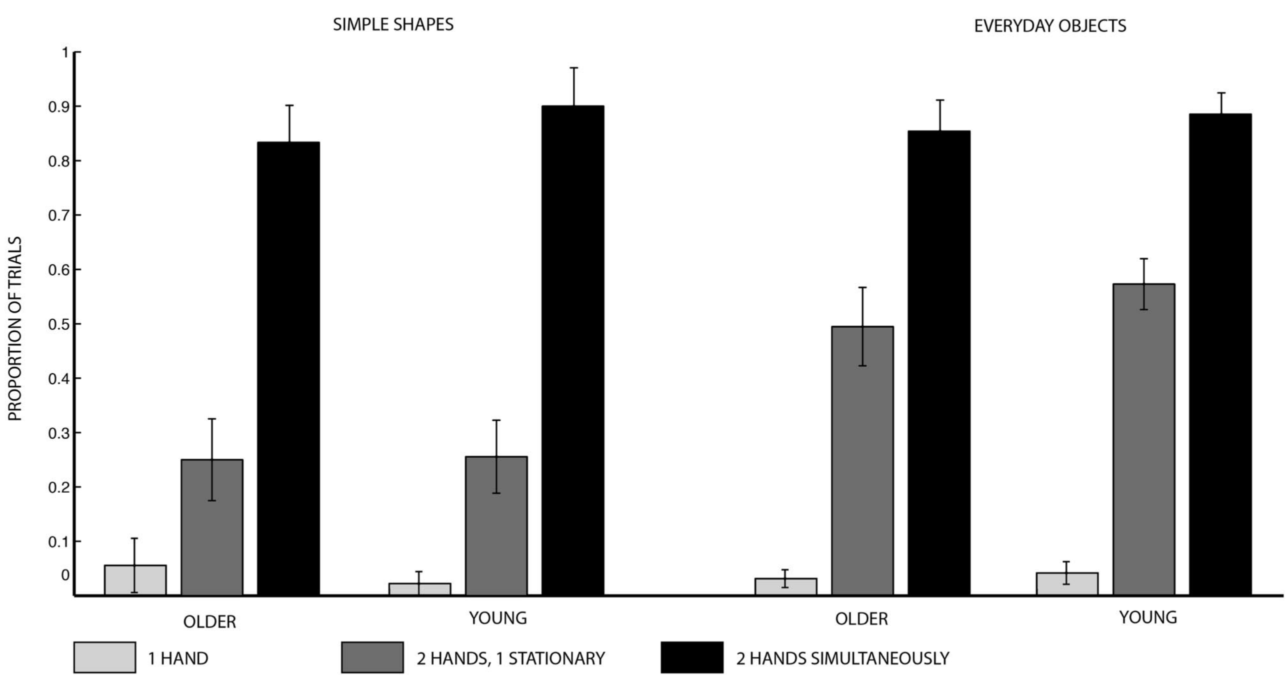

Figure 4. Exploration strategies used by the participants. Bars represent proportion of trials in which this strategy is used. If two or more strategies were used in a trial, they were included in the proportions of both strategies. The error bars represent the standard error of the mean.

haptic 2D shape recognition. To do so, we alleviated this process by letting participants explore the stimuli visually in half of the trials, albeit in the same sequential manner as during haptic exploration. If transformation and visual mediation are age-sensitive processes contributing to the observed group differences in performance, we predict our manipulation to produce a three-way interaction between age, complexity, and exploration modality with the longest durations time for older adults' haptic exploration of everyday objects. The shortest exploration times are thus expected to be found for simple shapes, young adults, and visual exploration.

Method

Methods used for Experiment 2 were largely identical with Experiment 1 and we only describe the differences in the following.

Participants. For the second experiment, new participants were recruited using our lab's participant pool. Twelve young (four male and eight female) and 12 healthy older (four male and eight female) adults participated on a voluntary basis. Results of the screening tests and other sample characteristics for both groups (young and older adults) are shown in Table 1.

Apparatus and stimuli. We used the same stimuli as we used in the first experiment. We divided the stimuli for each participant in four groups defined by exploration mode (visual or tactile exploration) and complexity (simple shapes and everyday objects). To create these groups and make visual and tactile stimuli comparable with each other, we first ordered the stimuli in five groups of difficulty, based on the results of Experiment 1. For each participant, we then randomly assigned half of the stimuli of each difficulty level to the visual and the other half to the tactile group, also keeping the number of simple shapes and everyday objects the same. The stimuli in the visual condition were the same swell paper stimuli that were used in the haptic condition.

Procedure. For the tactile conditions, the same procedure was used as in the first experiment, except that the exploration mode was now restricted to using the index finger of the dominant hand, to make the results readily comparable to the visual condition. Note that this strategy was used the least in Experiment 1, which may lead to an increase in exploration times. The procedure in the visual condition was largely the same as in the tactile conditions, except that instead of using their finger pad to explore the stimulus, they now used a large black sheet of cardboard with an oval shaped peek hole in the middle. The peek hole roughly matched the size of the participant's finger, which could be 14, 16, or 18 mm wide. The participants could move the sheet of cardboard, which was placed directly on top of the stimulus, with their hands so they could explore the stimulus by looking through the peek hole, the proprioceptive input of the hand moving the sheet was similar as in the tactile condition. The stimuli were presented in four blocks, counterbalanced for complexity and exploration modality (visual or tactile). After all four blocks, participants were visually shown all stimuli and were asked to name them to verify whether all participants recognized all stimuli (which was indeed the case).

Results and Discussion

The mean exploration times and standard errors are displayed in Figure 5A. A mixed-model ANOVA on the mean exploration times with modality and complexity as within-subjects factors and age as a between-subjects factor showed significant main effects for age, $F(1, 22) = 47.21$, $p < .0001$, $\eta^2_{\text{p}} = .68$, modality, $F(1, 22) = 11.18$, $p < .01$, $\eta^2_{\text{p}} = .34$ and complexity, $F(1, 22) =$

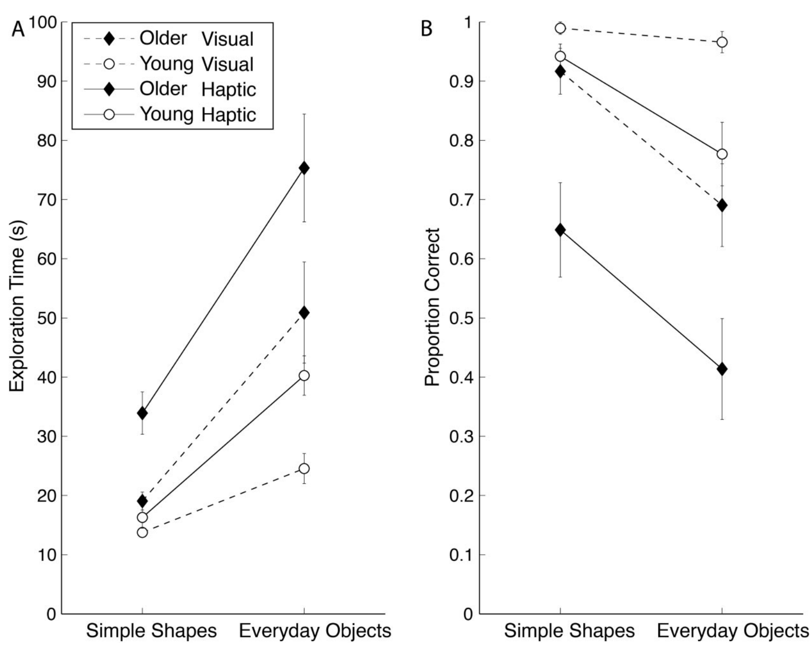

Figure 5. Results of Experiment 2. (A) Mean exploration time and standard errors of correct trials for both older and young group for simple shapes and everyday objects; (B) Proportion correct and standard errors for both older and young group for simple shapes and everyday objects.

81.77, $p < .0001$, $\eta^2_{p} = .79$, as well as a significant interaction effect between complexity and age, $F(1, 22) = 10.39$, $p < .01$, $\eta^2_{p} = .32$. This indicates that older adults are slower than young adults. Participants recognize visual stimuli faster than tactile stimuli and simple shapes faster than everyday objects. The difference between simple shapes and everyday objects is larger in the group of older adults than it is in the group of young adults. However, this effect was the same for both visual and tactile exploration modes. We may, therefore, conclude that image mediation is not the largest contributing factor toward the age-related differences in 2D shape recognition as found in Experiment 1. No three-way interaction was found, $F(1, 22) = .79$, $p = .38$, $\eta^2_{p} = .04$, the achieved (post hoc) power for the three way interaction was rather small (0.39). Reasonable chances to detect this three way interaction with a sufficient power of 0.80 we would have had needed at least 64 participants per age group. Although this number of participants could be obtained in principle, we believe that there is one other important reason, why we did not find a three-way interaction that deems sample enlargement a nonoptimal solution. We noticed that when older adults had explored complex everyday shapes for longer than 150 seconds they occasionally became frustrated, had problems focusing their attention on the task, and sometimes gave up, despite continued encouragement. Arguably, the exploration times we report for the complex condition underestimate "real" time demands, which limited our chances of finding the three-way interaction. A more realistic perspective seems to be that several older adults had reached the asymptote level of performance with complex items, that is to say, adding extra exploration time no longer outweighed the efforts of maintaining information in working memory already assembled.

Thus, following this reasoning, in order to test whether we find age x modality interactions if we do not take the complexity factor into account, we conducted two separate ANOVAs on the simple shapes and the everyday objects, respectively. The ANOVA on the everyday objects revealed main effects for age, $F(1, 22) = 30.30$, $p < .0001$, $\eta^2_{p} = .58$, and modality, $F(1, 22) = 7.23$, $p < .05$, $\eta^2_{p} = .25$, but no interaction between age and modality. Interestingly, however, an ANOVA for the simple stimuli not only revealed a main effect for age, $F(1, 22) = 23.68$, $p < .0001$, $\eta^2_{p} = .52$, and modality, $F(1, 22) = 18.76$, $p < .0001$, $\eta^2_{p} = .46$, but also an interaction, $F(1, 22) = 9.40$, $p < .01$, $\eta^2_{p} = .30$. Post hoc paired samples t tests for the simple stimuli showed that in the older group of participants, the mean exploration time in the visual-simple condition was lower than in the tactile-simple condition, $t(11) = 4.06$, $p < .01$, yet for the young group this was not significantly different. Independent samples t tests show that older adults are slower in both the visual and tactile condition as compared with the young adults, $ts(22) > 3.05$, $ps < .01$.

The results for the mean proportion correct and standard errors are shown in Figure 5B and point in the same direction as the results for the exploration times. A mixed-model ANOVA on the mean proportions correct with modality and complexity as within-subjects factors and age as between-subjects factor showed significant main effects for age, $F(1, 22) = 20.06$, $p < .0001$, $\eta^2_{p} = .48$, modality, $F(1, 22) = 27.56$, $p < .0001$, $\eta^2_{p} = .56$, and complexity, $F(1, 22) = 47.06$, $p < .0001$, $\eta^2_{p} = .68$, as well as a significant interaction effect between complexity and age, $F(1, 22) = 8.29$, $p < .01$, $\eta^2_{p} = .27$. No three-way interaction was found, $F(1, 22) = 1.35$, $p = .26$, $\eta^2_{p} = .06$. An ANOVA on a subset of the data (the everyday objects) revealed main effects for age, $F(1, 22) = 21.27$, $p < .0001$, $\eta^2_{p} = .49$, and modality, $F(1, 22) = 18.24$, $p < .0001$, $\eta^2_{p} = .45$, and no interaction. For the simple shapes, again the ANOVA revealed main effects for age, $F(1, 22) = 12.80$, $p < .01$, $\eta^2_{p} = .37$, and modality, $F(1, 22) = 15.77$, $p < .01$, $\eta^2_{p} = .42$, and a significant interaction, $F(1, 22) = 7.79$, $p < .05$, $\eta^2_{p} = .26$. Post hoc paired samples t tests explored this interaction and showed that the older group of participants recognized more stimuli in the visual-simple condition than in the tactile-simple condition, $t(11) = 3.48$, $p < .01$, for the young adults this was not the case. Independent samples t test showed a difference between older and young adults for tactually explored stimuli, $t(12.41) = 3.56$, $p < .01$, but not for visually explored.

In sum, we replicated negative age effects for exploration times and recognition accuracy obtained in Experiment 1. For simple shapes, both exploration times and proportions correct showed a reduction of negative age differences in the condition where visual mediation was alleviated. The absence of the three-way interaction shows that our manipulation to alleviate visual mediation did not yield pronounced benefits when more complex stimuli had to be processed. Nonetheless, significant improvements in performances on complex everyday objects in the peek hole condition implicate visual mediation as a component process in haptic recognition in both groups. It is likely that additional processes are limiting the performance of older adults at this level, and that our manipulation can only compensate so much for negative age effects at later levels when complex objects must be recognized. One candidate along these lines is matching the object with a representation in long-term memory, the final step of the image-mediation model. We investigated its contribution in Experiment 3.

Experiment 3

The third and last step in the image mediation model concerns object recognition. A large component of object recognition is matching the object with a representation in long-term memory. In Experiment 3 we provided participants with an object category along with the stimulus thereby reducing the search space for the object matching and facilitating retrieval of the memory representation.

Method

Methods used for Experiment 3 were largely identical with Experiment 1 and we only describe the differences in the following.

Participants. For the third experiment, 24 new participants were recruited using our lab's participant pool. Twelve young (three male and nine female) and 12 healthy older (six male and six female) adults participated on a voluntary basis. The same screening tests as in the first experiment were used. Sample characteristics can be found in Table 1.

Apparatus and stimuli. Only 2D representations of everyday objects were used in Experiment 3. We created a new stimulus set that consisted of 30 everyday objects (including seven drawings that were part of the stimulus set in Experiment 1). We selected 30 stimuli (see Table 2), which were recognized well by six young adults (accuracy > .33) in a pilot study with a total of 45 stimuli, and which we could easily classify in the following categories:

Table 2
Characteristics of the Stimulus Set in Experiment 3

Stimulus	Category	Stimulus set	Typicality (mean (SD))
Lamp	Furniture	S & V	0.66 (0.27)
Table	Furniture	S & V	0.97 (0.08)
Bicycle	Transport	S & V	0.89 (0.22)
Car	Transport	W et al.	0.98 (0.05)
Truck	Transport	S & V	0.86 (0.19)
Boat	Transport	W et al.	0.87 (0.15)
Scissors	Kitchen utensils	W et al.	0.71 (0.24)
Bottle	Kitchen utensils	S & V	0.68 (0.28)
Fork	Kitchen utensils	S & V	0.88 (0.19)
Wine glass	Kitchen utensils	S & V	0.80 (0.17)
Apple	Fruit	S & V	0.98 (0.05)
Banana	Fruit	S & V	0.98 (0.05)
Cherry	Fruit	S & V	0.91 (0.19)
Pear	Fruit	S & V	0.98 (0.05)
Chicken	Animals	S & V	0.93 (0.12)
Horse	Animals	S & V	0.94 (0.16)
Dog	Animals	S & V	0.95 (0.15)
Bird	Animals	S & V	0.89 (0.14)
Duck	Animals	S & V	0.88 (0.17)
Butterfly	Animals	W et al.	0.85 (0.15)
Giraffe	Animals	S & V	0.93 (0.16)
Rabbit	Animals	S & V	0.93 (0.12)
Hat	Clothing	S & V	0.93 (0.12)
Sock	Clothing	S & V	0.81 (0.18)
Pants	Clothing	S & V	0.90 (0.14)
Boot	Clothing	S & V	0.98 (0.05)
Hammer	Tools	W et al.	0.88 (0.12)
Axe	Tools	W et al.	0.96 (0.15)
Wrench	Tools	W et al.	0.95 (0.10)
Screwdriver	Tools	S & V	0.96 (0.08)

Note. The first column shows the correct answer for that stimulus, the second column the category it belongs to. The third column shows the origin of the stimulus: S & V = Outlines of the original Snodgrass and Vanderwart (1980) set and W et al. = from the set used by Wijntjes, Van Lienen, Verstijnen, and Kappers (2008). The last column shows the results of the typicality questionnaire on a scale from 0 to 1, where 1 is the maximum value 1 for typicality.

furniture, transport, kitchen utensils, fruit, animals, clothing, and tools. This resulted in the use of seven stimuli of the set of Wijntjes et al. (Wijntjes et al., 2008) and 23 outline versions of stimuli from the Snodgrass and Vanderwart (1980) set as used by Wagemans et al. (2008). Typicality ratings of all stimuli were high (> .66). For Experiment 3 we created two lists for each participant making sure that each stimulus appeared equally often in the category cue and in the control condition.

Procedure. Again roughly the same procedure as in the first experiment was used, except for the following. In half of the trials a category name was mentioned before the start of the trial. The trials were blocked for category condition (category vs. no category). To keep the total experiment within manageable time, we restricted the maximum exploration time to 150 seconds. In the first two experiments we already showed that nearly all the correct answers were given within 150 seconds (98.46% in Experiment 1 and 97.55% in Experiment 2). We asked the participants after completion of the experiment, to name the stimuli while they were presented visually, and again all participants recognized all line drawings. After completion of the experiment, the participants were asked to fill out a typicality questionnaire, in which all 30 stimuli had to be rated on a scale from 1 to 7 how well it fitted to the given category name. We rescaled the values of this scale to a 0 to 1 scale, where 1 is the maximum value for typicality. The results of this questionnaire show an average typicality score of 0.89 ± 0.02 (range 0.68–0.98).

Results and Discussion

Mean exploration times for the older and young groups are displayed in Figure 6A. A mixed-model ANOVA on mean exploration times with category (cue provided or not) as within-subjects variable and age group as between-subjects variable showed reliable effects for age group, $F(1, 19) = 12.40$, $p < .01$, $\eta^2_{\text{-p}} = .40$, and category, $F(1, 19) = 31.70$, $p < .0001$, $\eta^2_{\text{-p}} = .63$, and an interaction between these two factors, $F(1, 19) = 7.37$, $p < .05$, $\eta^2_{\text{-p}} = .28$. In line with Experiment 1 post hoc *t* tests showed that older adults were slower in exploring stimuli than young adults, $t(19) = 4.48$, $p < .001$, when no category cue was provided. However, when a category was given before exploration differences between category were no longer significant, $t(21) = 1.71$, $p = .10$. Additional post hoc *t* tests revealed that older, $t(8) = 5.15$, $p < .001$, as well as young adults, $t(11) = 2.36$, $p = .04$, reliably shortened their exploration times when a cue was provided compared with the control condition. The corresponding mixed-model ANOVA on the mean proportions correct (means in Figure 6B) showed significant main effects for age group, $F(1, 22) = 32.13$, $p < .0001$, $\eta^2_{\text{-p}} = .59$ and category, $F(1, 22) = 30.17$, $p < .0001$, $\eta^2_{\text{-p}} = .58$, but no interaction. Although older adults were again slower and less accurate than young adults, providing category cues clearly benefitted older adults' exploration times, which were close to those of young adults for successfully recognized items.

General Discussion

In the current study we investigated differences between young and older adults in haptic 2D shape recognition. Our goal was to determine the contributions of different component processes in the image-mediation model (Klatzky & Lederman, 1987) to age differences. In Experiment 1 we replicated previously reported (Kleinman & Brodzinsky, 1978; Thompson et al., 1965) age-related performance declines in speed and accuracy of recognition for 2D representations of simple shapes and everyday objects. Moreover, we demonstrated the typical age-complexity interaction, with more complex stimuli yielding larger differences between the two age groups. In Experiment 2 we investigated whether visual mediation was a factor contributing to age-related decline by comparing haptic exploration with a sequential visual inspection through a moving peek hole. Our manipulation did indeed reduce differences between age groups. However, the effect was limited to the simple shapes and age differences in complex everyday objects were similar to the haptic exploration condition. Finally, in Experiment 3 we investigated the role of the final stage in the model, the matching of the transient visual image with long-term memory representations of the object. Our manipulation of providing a category cue for half of the objects prior to exploration had the desired effect by reducing age differences in exploration time for recognized everyday objects to nonsignificance. However, overall negative age differences in recognition accuracy remained similar to the control condition.

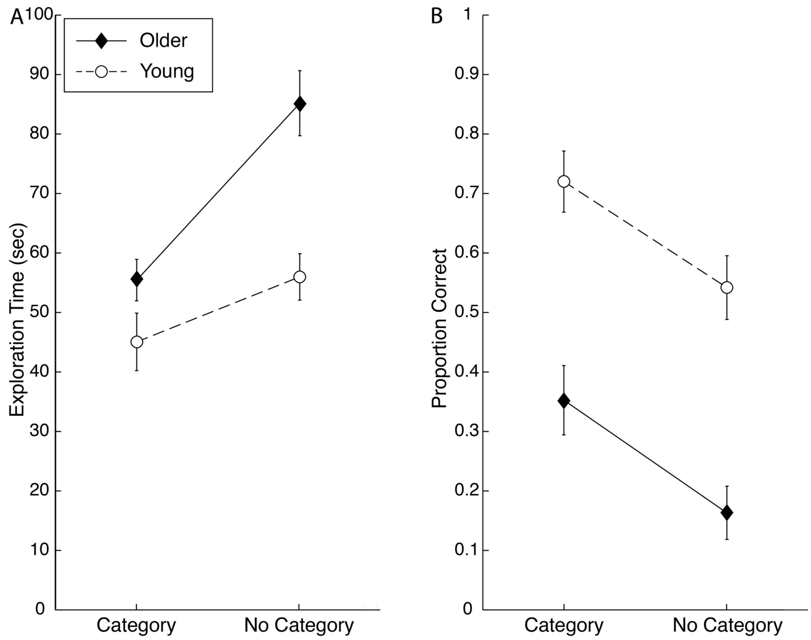

Figure 6. Results of Experiment 3. (A) Mean exploration time and standard errors of correct trials for both older and young group for category and no category blocks; (B) Proportion correct and standard errors for both older and young group for category and no category blocks.

The manipulations motivated by the image mediation model yielded the expected effects in young as well as older adults, a pattern of results well supporting the framework as such. At the same time, a consideration of pattern of age and age by task complexity effects we obtained can inform extensions and specifications of the model. A key finding in this respect is the (partly unexpected) outcome of Experiment 2: Although performance in the visual inspection condition was better in both age groups and for both stimulus conditions, benefits in terms of a reduction of age differences were limited to the simple shapes. In our view this proves that transformation of haptic to mediating visual representations is an age-sensitive process, but also that there is an additional bottleneck in recognition of the more complex everyday objects. Older adults may have reached the asymptote level of performance with these complex items: Adding extra exploration times ($>$ 150 s) no longer outweighed the efforts of maintaining information in working memory already assembled. Moreover, it has been shown that tactile working memory capacity is even more limited than visual working memory (Bliss & Hamalainen, 2005) and we have no reason to assume that related age differences are smaller for abstract stimuli.

We deliberately kept the sequential exploration aspect similar in the haptic and the visual peek hole conditions in Experiment 2. This means that participants encountered features successively, had to interpret them (e.g., edge, crossing), keep them in working memory, and integrate them into a recognizable visual representation as they went along. Presumably working memory load increases with the number of features while it decreases for more salient features and more familiar objects. In line with this reasoning, our analysis of item complexity (Experiment 1) showed that everyday objects contained more details than simple shapes and exploration times were reliably correlated with compactness, number of intersections and global symmetry. Importantly, our analysis of individual complexity-exploration time slopes showed that differences between older and young adults systematically increased with stimulus complexity.

These considerations imply that quality and richness (in terms of salient features integrated) of the mediating visual images will probably differ between young and older adults if complex objects must be recognized. As a result, the final stage in the image mediation model, the matching of visual representations and long-term memory contents for object recognition is more likely to fail. This perspective also provides an account for the near-absence of age effects in exploration times for successfully recognized items in Experiment 3: Note that the category cue was always provided before exploration commenced. We assume that participants adopted "generate-test" or "confirmation strategies" in which they deliberately generated certain feature-cues representative of this category and then derived the precise object as they went along: For instance, when the category transportation was given, participants may have looked for a handle bar, to narrow down the options to bicycles. Such strategies efficiently constrain the search space and reduce working memory load. Similarly, a study by Norman et al. (2006) showed improved performance for older adults in a haptic recognition task when memory load was reduced. In this study, participants had to match a haptically explored natural shape to a set of six or 12 visual representations of natural shapes. Although the exploration time was the same in both conditions, the difference in accuracy between older and younger adults diminished when the set of visual representations contained fewer items.

The critical role of the search space for the recognition of objects helps to evaluate the practical implications of the observed age-differences. In real-life, older people typically know what to search for and which other objects compete for their attention. Under such circumstances negative age effects may not be as large as those we observed in our Experiments 1 and 2. Indeed, as already mentioned in the introduction, there is quite some evidence that there are no age-related differences in accuracy for haptic recognition or matching of 3D objects or shapes (Ballesteros & Reales, 2004; Norman et al., 2006; Norman et al., 2011), which are more likely to be encountered on a daily basis. However, one has to note that exploration times for haptic 3D objects are much shorter and thus, working memory load lower, as compared with the 2D representations that were used in the current study. Moreover, it is well established that when people are trained in a certain task, or are even expert in the task domain, they show little or no age-related performance decrements despite normal age-related declines in (e.g., Krampe, 2002). As far as we know, there are currently no studies that investigated the role of specialized knowledge in the context of expertise or training on haptic 2D shape recognition.

Although we did a basic screening of our participants for proprioceptive and tactile functioning, a set of specific, and more elaborate tests, like a detailed limb position sense test (e.g., Dukelow et al., 2010), would have been desirable. If we could control the peripheral factors in more detail, we could make stronger conclusions about the role of central processes on haptic 2D shape recognition tasks. Although peripheral processes undergo less dramatic neural changes as aging commences as compared to central processes (Kalisch et al., 2012; Raz & Rodrigue, 2006), future research should take more detailed peripheral tests into consideration.

In conclusion, we found further support for the image-mediation model and its explanatory power for the age-related differences we observed. We argue that age-related working memory limitations critically constrained the visual image formation process and the quality of the representation to be matched with long-term memory contents. Future research should be directed at specifying the role of haptic working memory and knowledge about haptic object characteristics at different phases of image mediation and shape recognition.

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Appendix

Screening Test Descriptions

Symbol Substitution (SS), also called Digit Symbol-Coding, is a subscale of the Wechsler Adult Intelligence Scale III (WAIS-III) and measures processing speed. The participant is asked to match the right symbol with the right number using a key. He/she has 2 minutes to complete as many pairs as possible. The final score is the total number of correctly matched pairs, with 133 as a maximum. Scores can be normalized according to the age of the participant, which we did in our study (Kaufman & Lichtenberger, 1999).

The Digit Span (DS) is another subtest of the WAIS-III, used to assess a person's memory span. The participant is asked to repeat a certain amount of numbers read out aloud by the experimenter, either in the same (DS Forward) or reversed order (DS Backward). The test starts with two sequences of two numbers. If one or both sequences are repeated correctly, an extra digit is added. For both the forward and backward test, the scores consist of the number of correctly repeated sequences. The Digit Span Total is the sum of the latter two final scores, with 30 being the maximum score. Scores can again be normalized according to the age of the participant, which we did in our study (Kaufman & Lichtenberger, 1999).

Tactile sensitivity was assessed using the Touch-Test® Sensory Evaluator Kit. This kit contains handles with monofilaments (Von Frey hairs) in various sizes, ranging from 2.83 (target force of 0.07 gr) to 6.65 (target force of 300 gr). Tapping the Sensory Evaluators against the skin till they bend, asserts a certain amount of target force. This force is applied four times on various predetermined locations for both hands. The participant is asked to indicate whenever he or she feels something. If he/she does not feel the smallest pressure, a Sensory Evaluator with a larger target force is applied next. The maximum score is 5 for each hand, indicating a high tactile sensitivity, the detectability of a 0.07 g filament. We calculated the mean score over the two hands.

Proprioception: We used two tasks to assess the participants' proprioception. First, the experimenter asked them to close their eyes and raise one of both hands with the index finger extended. The experimenter then moved this finger either upwards or downwards for four consecutive times. The participants had to indicate the direction of the finger. Once completed, the same procedure was repeated with the other hand. Next, the experimenter asked the participants to stretch one arm and try to touch their nose with the index finger. This was also repeated for the other arm and index finger. For both tasks each attempt equaled one point. The maximum score was therefore 14.

The Vividness of Visual Imagery Questionnaire (VVIQ) consists of 16 items in groups of four. Each group of items asks the participants to imagine a certain kind of situation (e.g. a visit to the store) and focuses specifically on certain details within that situation (e.g. paying for groceries). The participant is asked to rate the vividness of the image in his or her mind along a 5-point scale. Higher scores reflect a lower vividness (Marks, 1973).

The Mini-mental State Examination (MMSE) or Folstein test consists of a 30-point questionnaire test and is used for detecting cognitive impairment. It analyzes functions such as arithmetic, memory, and orientation in time and place. Scores higher than or equal to 25 points are considered effectively normal. Other scores indicate severe (9 points or less), moderate (10 to 20 points), or mild (21 to 24 points) cognitive impairment (Mungas, 1991). Low to very low scores are associated with dementia (Folstein, Folstein, & McHugh, 1975).

The Activities of Daily Living (ADL) and the Instrumental Activities of Daily Living (IADL) are two questionnaires that examine how (in)dependent the person is in performing certain daily activities as using the telephone, bathing, dressing, toileting, and transferring. Low scores suggest dependence. Maximum scores are 8 and 7 respectively (Katz, Ford, Moskowitz, Jackson, & Jaffe, 1963; Lawton & Brody, 1969).

Although we mainly used these marker variables as inclusion/exclusion criteria, we correlated the screening test scores to the exploration time and accuracy of both groups of participants separately. Because no one-to-one relation of exploration time or accuracy to one of the tests was found we cannot conclude that one of these tests is measuring the critical underlying factor that defines the difference between young and older adults.

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