AGE DIFFERENCES IN TACTILE PATTERN RECOGNITION
AT THE FINGERTIP

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3 Figures

1 Table

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ABSTRACT

Young (21-26 years, n=20) and Old (55-86 years, n=25) participants were tested for their ability to recognize raised letters (6-mm high, 1-mm relief) by touch. Spatial resolution thresholds were also measured with grating domes to derive an index of the degree of afferent innervation at the fingertip. Letter recognition in the young group was very consistent and highly accurate (mean, 86% correct), contrasting with the performance of the old group, which was more variable and comparatively low in accuracy (mean, 53% correct). In both groups, spatial resolution thresholds accounted for a substantial portion of the variance in the performance, suggesting a strong link between age-dependant variations in tactile innervation and recognition accuracy. The patterns of errors in the old group showed that an inability to encode internal elements specific to certain letters was at the source of most confusion among letters. Whether this inability reflected only deficient peripheral encoding mechanisms or some other alterations at the central level is discussed.

INTRODUCTION

Humans possess a very refined ability to perceive the spatial features of objects and surfaces by touch. This ability is particularly developed at the fingertip where the rich supply in mechanoreceptors affords great spatial resolution. In recent years, a new method has been introduced to assess spatial sensitivity to replace the more traditional, albeit flawed, two-point discrimination threshold (Johnson et al., 1994). This method developed by Van Boven, Johnson and colleagues (Van Boven et al., 1989; Van Boven et al., 1991) relies on the use of a set of small grating domes with equidistant groove and ridge widths (JVP domes). The domes are placed on the skin following one of two possible orientations (along or across the segment of skin), and the subjects are asked to report the perceived orientation. The finest grating whose orientations are reported reliably (75% correct) provides a threshold estimate of the limit of spatial resolution in the tested area. With this method, young persons typically exhibit spatial thresholds in the order of ~1-mm, a limit that corresponds closely to the theoretical resolution limit imposed by the density of mechanoreceptors supplying the fingertip, particularly the slowly adapting type I (SAI) associated with Merkel cells ($\sim 100/\text{cm}^2$), which are considered to be primary responsible for the encoding of spatial stimuli (Johnson et al., 2000). Grating resolution thresholds, therefore, provides a valid and objective index of afferent innervation, a notion that was corroborated in patients with sensory loss secondary to nerve injury in whom sensory recovery was paralleled by a return in the ability to report grating orientation (Van Boven and Johnson, 1994b).

In previous reports, we used the grating orientation task to characterize changes in spatial acuity in old persons. Our results showed that spatial resolution thresholds were often markedly

increased in persons aged over 60 years, with doubling and even tripling in the grating dimension required to get reliable reports of orientation (Tremblay et al., 2000; Tremblay et al., 2003). Without obvious confounding pathologies (e.g., diabetic neuropathy), the decline in spatial acuity was attributed primarily to an age-related loss in afferent innervation, an interpretation consistent with earlier reports of reductions in the number of mechanoreceptors supplying the glabrous skin in old persons (Cauna, 1965; Bruce, 1980). Yet, the possibility remains that alterations, beyond those affecting peripheral sensation, might also contribute to the observed decline in spatial acuity with aging. This possibility is further entertained by the observation that older individuals often display wide variations in their ability to perform spatial discriminations at the fingertip (Stevens and Choo, 1996; Stevens and Cruz, 1996; Tremblay et al., 2003), which suggests that individuals may present with different degrees of impairment at different levels, i.e., peripherally and/or centrally.

One strategy to address the question of whether impaired central processing may also contribute to poor spatial discriminations in old persons is to introduce stimuli of different complexity. As pointed out by Hsiao et al. (2002), perceiving the orientation of bars and grooves can be considered, by analogy with the visual system, as an initial (albeit important) step in the processing of more complex forms at the fingertip. These authors noted that orientation selectivity was an emerging property of neurons in the primary (SI) and secondary somatosensory (SII) areas, driven by the input of a population of SAI primary afferents. In theory, identification of fine complex patterns by touch, such as Braille symbols or embossed letters, would require additional processing since the spatial image of the pattern conveyed by the primary afferents needs to be transformed through successive stages to be eventually compared with previously stored images in working memory and finally classified as one pattern among a family of others

symbols (Loomis, 1990; Vega-Bermudez et al., 1991). One therefore can imagine a situation where alterations at the central level may prevent tactile recognition of complex forms while discrimination of simple grating orientations would still be possible. Vega-Bermudez and Johnson (2002) examined this issue in patients with digit amputations to test whether cortical reorganization of sensory maps would affect tactile pattern recognition. The stimuli consisted of fingertip size raised capital letters that were scanned for identification. While the results failed to show differences between hands in the group of amputees, the data did reveal a decline in the recognition performance with age in both amputees and age-matched controls. This observation, however, was based on a limited number of subjects and most of them were middle-aged (45-55 year).

In the present study, we also elected to use embossed letters as stimuli to characterize complex pattern recognition at the fingertip in older adults. As stressed by Johnson et al. (1994), letter recognition offers several advantages over other tactile spatial tasks. First, the large numbers of possible alternatives ($n=26$) forces subjects to rely solely on spatial cues to perform correct identification, thereby reducing the likelihood that spurious cues might influence the performance. Second, the performance is little affected by variations in scanning velocity, in contact forces or by the mode of touch (e.g., active or passive, Vega-Bermudez et al., 1991). Third, letter recognition requires no special training and does not seem to be influenced by response bias associated with cognitive function (e.g., literacy aptitude or the frequency of letters in written language, Loomis, 1990; Vega-Bermudez et al., 1991). In characterizing the performance of our participants for letter recognition, we also sought to determine to what extent age-related changes in tactile afferent innervation, as reflected in grating resolution thresholds, influenced the ability to recognize complex patterns at the fingertip.

MATERIALS AND METHOD

Participants

Forty-five subjects were recruited for this study. All subjects provided informed consent before participation and the study's procedures were approved by the University Research Ethics Committee. One group consisted of young adults (n=20) recruited among the student population at the University of Ottawa, Health Sciences Campus. The second group consisted of older adults (n=25) aged between 55-86 years recruited through personal contacts and in collaboration with local community centers for retired persons in the area. To participate in this study, participants had to be in good health without antecedents of conditions likely to affect their performance in the tests (e.g., carpal tunnel syndrome, type I and type II diabetes, stroke, Parkinson's disease, severe hand arthritis, multiple sclerosis or severe dermatological conditions). In addition, all participants were screened for the presence of undiagnosed peripheral neuropathies using a graduated Rydel-Seiffer tuning fork to assess vibration sense. Rydel-Seiffer tuning forks carry calibrated weights on each arm, which allows for simple semi-quantitative estimation of vibration extinction threshold (Kastenbauer et al., 2004; Pestronk et al., 2004). Such thresholds have been shown to be valid and reliable indicators of sensory nerve function in the extremities (Kastenbauer et al., 2004; Pestronk et al., 2004). The test was always administered by one of the authors (HM), who is also a registered physiotherapist. Vibration sense was tested at two specific sites on the dominant upper extremity (i.e., styloid process of the ulna and dorsal aspect of the distal interphalangeal joint of the index finger) as prescribed in previous clinical studies ((Martina et al., 1998; Pestronk et al., 2004). Threshold values were subsequently compared to norms previously published (Martina et al., 1998). All participants exhibited threshold values

within the normal limits for their age group. The demographic characteristics of the participants are summarized in Table 1. Participants received a small honorarium for their participation.

Tactile stimuli

JVP domes (Stoelting Instruments; Wood Dale, IL) were used to derive spatial resolution thresholds. The domes consist of rectangular gratings cut into a convex surface (20-mm diameter) mounted on top of a cylindrical handle piece (30-mm length). Each dome is made up of equal-width grooves and ridges. The set is comprised of eight domes with groove widths of 3, 2, 1.5, 1.2, 1, 0.75, 0.50 and 0.35-mm. To account for the fact that thresholds sometimes exceed 3-mm in old persons (Tremblay et al., 2000; Tremblay et al 2003) custom domes with larger grooves (4.5, 4, 3.5, 2.5 mm) were added to the original set. These domes were made of similar material and had the same overall dimensions as those available commercially.

The stimuli for the letter recognition task consisted of embossed capital letters (1-mm relief, 6-mm high, 0.5-mm stroke width) raised from a uniform background made of flexible nylon plates. The letters (sans serif, Stewardson font) were first produced by printing series of characters at high resolution (1200 dpi) on a laser printer. Then, photography negatives were produced from the print out. These negatives were subsequently used as templates to produce the embossed letters by exposing nylon plates to UV light. For testing, each individual letter was cut out from the plate and glued on top of a small wooden block (2.5-cm³) using double sided adhesive tape. During testing, the block itself was inserted into a cavity cut into a larger piece of high density Styrofoam, which formed a rectangular base (5-cm x 4-cm, 0.7-cm thick) to ensure proper stabilization during scanning. The letters' dimensions were based on previous reports in

human observers on the high legibility of characters 6-mm high (Johnson and Phillips, 1981; Vega-Bermudez et al., 1991).

Grating resolution threshold

The procedure for testing with JVP domes has been described in details elsewhere (Tremblay et al., 2000; Tremblay et al., 2003). Briefly, participants were seated in a quiet room at an examination table with the dominant hand in supination resting on light padding. The center of the pulp of the dominant index finger was marked using an erasable ink marker to ensure consistent placement of the domes. Before testing, participants were provided with practice trials with large grooves (young, 3-mm dome; old, 4-mm dome). In addition, a visual aid demonstrating the two possible orientations (along or across) was always placed near the subject to help with the discrimination throughout the testing period. Feedback was provided during practice trials but not during formal testing. To reduce testing time, a range of five grating widths was pre-selected to be administered in each age group to account for the difference in acuity with age (young: 0.75, 1.0, 1.2, 1.5 and 2.0-mm domes; old, 1.2, 1.5, 2.0, 2.5 and 3.0-mm domes). Larger or smaller grating dimensions were added to this pre-determined set, if necessary, to adjust for individual performance. For formal testing, vision of the hand was prevented by covering the distal portion of the forearm with a box. In each trial, the examiner gently pressed (force, ~60-80 g) the dome against the skin of the distal finger pad in either one of the two prescribed orientations, i.e., along or across the longitudinal axis of the finger. Participants were required to report the perceived orientation of the grating. In each block of 50 trials, the two orientations were applied following a predetermined random sequence and both were equally probable within a block. Testing always began with presentation of the largest dome (young, 2.0-

mm; old, 3.0-mm) and proceeded sequentially until the smallest dome was presented. Grating resolution threshold were determined by computing for each participant the minimal grating width whose orientation could be discriminated with a probability of 75%, via interpolation of performance values just above and below the 75% level (Van Boven and Johnson, 1994a).

Letter recognition

After completion of the grating orientation task, participants were tested for letter recognition, with a 10-15 minutes pause between the two sessions. Participants were seated comfortably at the same examination table. Each testing session was preceded by a period of familiarization with the stimuli, lasting ~15 minutes, wherein participants were invited to inspect visually, then tactually, each of the 26 letters. They were asked to attend to specific details of each letter, for example the horizontal bar in the letter «H» or the tail with the letter Q distinguishing it from the O. Then, practice trials with visual and verbal feedback were performed with presentation of a range of letter from low confusion probability (e.g., I) to high confusion probability (e.g., Q often mistaken for O). After proper training, the recognition performance was tested with the hand hid from view. Each of the 26 letters was presented three times according to a predetermined random sequence for a total of 78 presentations. In each trial, the examiner held the base holding the block with the letter firmly in place while the participants scanned with the tip of the dominant index finger. Participants reported the letter's identity by speaking out loud. No constraints were imposed on the scanning strategy or in terms of time limits to perform the task. The response was recorded on a data sheet for later analysis. Performance in the task was determined by computing for each participant the overall percentage of correct identification across the 78 letter presentations (i.e., $\text{performance} = N_{\text{correct}}/78 \times 100$). A

semi-quantitative analysis was also performed to look at patterns of confusion between pairs of letters (e.g., how often “A” was called “R” and vice-versa). To this end, a stimulus-response matrix (i.e., 26 X 26 matrix) was constructed in each age group by compiling the number of times each letter stimulus (S_i) provoked a given (R_j) response (Loomis, 1982; Vega-Bermudez et al., 1991).

Data analysis

An analysis of variance (ANOVA) was performed in each group with grating resolution thresholds as co-variates and “Gender” as a between-subjects factor to determine their influence on recognition rates. The threshold for significance was set at $p < 0.05$. All the statistical analyses were performed with SPSS v. 12.0 for Windows. The graphics were prepared with SPSS v. 12.0.0 and GraphPad Prism v. 4.0 for Windows (GraphPad Software, San Diego, CA, USA, <http://www.graphpad.com>).

RESULTS

Overall performance and confusion patterns

All participants, with one exception, completed the testing. The one subject who did not complete consisted of a 68 years old woman who was unable to perform the letter recognition task due to time constraints. Thus, the final analysis included 24 subjects in the old group and 20 subjects in the young group. Individual performance scores in the letter recognition task, along with corresponding resolution threshold values determined from the grating orientation task, are illustrated in Figure 1A. As expected, older individuals displayed much greater variability in their performance in the two spatial tasks as compared to young participants. Despite this variability, the general decline in spatial acuity associated with age was really apparent in the old group with grating resolution thresholds being twice as large, on average, as those determined in the young group (2.5 ± 0.4 mm vs. 1.2 ± 0.3 mm, respectively). The decline in performance with age was also clearly apparent in the letter recognition task. In this task, young participants clearly outperformed the older ones by a factor of 1.5 (i.e., mean hit rate, 86 ± 9 % vs. 53 ± 20 %, respectively). As shown in Figure 1B, there was a close association between age and poor recognition in the old group. Yet, and in spite of their lower accuracy, the overall performance of older participants was still well above what one could expect from simple random guessing (i.e., 4% (1/26), chance level).

The difference in performance for letter recognition between the two groups can be further appreciated by looking at the confusion matrices displayed in Figure 2 (A and B). Inspection of the diagonal lines formed by numbers traced in bold (i.e., # hits) shows that young participants were very accurate in their reports (Figure 2A). When confusion did occur, it followed a very distinctive pattern with confusion appearing between specific pairs of letters, i.e., those for which

the mean confusion rate exceeded 8% and identified with boxes in the matrix. The most frequent confusion pair was between M and N (mean confusion rate, 25%), which were often confused one for the other. Both letters were also often mistaken with H. The other pairs of confusion were formed by the BD, RA and YV couples. As evident in Figure 2B, the performance of older participants was characterized by multiple pairs of confusion. In fact, in the old group, more than 10 pairs of confusion were identified; the most frequent being again the MN pair and its interaction with H. Besides the “MNH” trio, the following pairs were also associated with high confusion rates: GC, DO, EK, JI, KR, PI, RA, TY, SZ, VY and XZ.

Another way to contrast the performance of the two groups is to look at individual letters. In the young group, the majority of letters (19/26, SVKTDPYAEWXCUIJLQGO) were associated with high recognition rates (i.e., $\geq 85\%$ correct), leaving only few letters (5/26, NHBRZF) with fair recognition rates (i.e., 60-80% correct,) and only one letter (M) with a poor recognition rate (33% correct). In the old group, the distribution was somewhat the reverse image with the majority of letters (i.e., 18/26, MRFHNSVEXBKPZDYAG) being associated with poor to very poor recognition (i.e., 30-57% correct). Another small group of letters (6/26, TWUCLJQ) led to fair recognition rates (60-82%, correct), leaving only two letters (O and I) with recognition rates $> 85\%$ correct.

Impact of spatial resolution thresholds on letter recognition

In the young group, spatial resolution thresholds, as determined from the grating orientation task, accounted for a very substantial proportion of the variance in letter recognition. In fact, this factor alone accounted for $> 40\%$ of the total variance in the performance ($F_{1, 19}=12.3, p=0.003$), gender having no significant effect ($F_{1, 19} = 2.2, p=0.16$). In the old group, the same factor

accounted for one-third of the variance ($F_{1, 23} = 9.2$, $p = 0.006$) in the recognition performance. A small “Gender” effect ($F_{1, 23} = 5.1$, $p = 0.04$) was also noted in this group, owing to the difference in recognition rates between men and women ($60.6 \pm 14.8\%$ vs. $50.4 \pm 21.5\%$, respectively). To further illustrate the impact of spatial resolution thresholds on letter recognition, individual performance values from all participants have been plotted against corresponding thresholds in Figure 3. It can be seen that grating resolution thresholds were indeed strong predictors of the recognition performance. In this Figure, threshold values have been regrouped into arbitrary categories (vertical lines) just to illustrate the fact that those participants with fine spatial acuity (mostly young) were also those that excelled in identifying letters by touch and vice-versa for those with poor acuity.

DISCUSSION

In the present study, we examined age differences in the ability to recognize complex patterns by touch, using embossed letters as stimuli. We found that young adults clearly outperformed older adults in this task in terms of recognition accuracy. We also found that spatial resolution thresholds, as reflected in the ability to resolve simple gratings, had a major impact on letter recognition in the two age groups.

Before considering the factors that may have limited the ability of older participants to recognize patterns by touch, it is critical to ascertain that their performance was not affected by pre-existing conditions interfering with tactile perception. As stated earlier, to address this potential confounding issue, all our participants, young and old, were carefully screened before testing to check their sensory status and detect those with potential unreported deficits. In addition, the fact that all our old participants were community-dwelling individuals, who were

relatively well-educated, leaves no reason *a priori* to think that their ability to make judgments about letter stimuli was affected. Besides, as stated before, cognitive bias has little influence on letter recognition by touch (Loomis, 1982). Another potential confounding issue is whether the task conditions were optimal to allow pattern recognition without undue difficulties. This issue is important given that our main objective was to test supra-threshold perceptual abilities and not to assess the limits of sensory function. However, one needs to recognize that tactile identification of raised patterns is an inherently difficult task for observers, since one has to extract geometric information about the touched pattern using contour exploration; a process which is slow and demanding by nature (Lederman and Klatzky, 1997). Yet, when performed under optimal conditions, human observers can excel in this task (e.g. Braille readers). In this respect, the performance of our group of young adult is very telling with the vast majority of them (15/20) exhibiting recognition accuracy > 80% correct. This contrasts with the large inter-individual differences reported (e.g., 30-86% hit rates) in previous studies using characters of comparable dimensions (Johnson and Phillips, 1981; Loomis, 1981a; Loomis, 1982; Phillips et al., 1983). These earlier reports, however, were often based on a limited number of subjects and involved no prior training, which may explain the greater variability between subjects. In addition, participants were often constrained to perform within certain time limits or to use one mode of touch over another (e.g., active vs. passive). In the present study, we strived to provide optimal conditions for tactile recognition by providing participants with proper training prior to testing, imposing no restrictions on the exploration strategy or time limits and using characters of highly legible dimensions. The fact that these task conditions led to such a high performance in the young group argues against the possibility that the observed age difference in performance was simply the result of the task being too stringent for old persons. Finally, one has to address the

common assumption that age-related changes in the skin properties, after a lifetime exposure to physical and thermal stress, would account for the decline in tactile acuity seen in old persons. In fact, this and other related assumptions (e.g., decrease in blood flow in the extremities) about tactile aging proved to be wrong after careful examination in observational studies (Stevens et al., 2003; Vega-Bermudez and Johnson, 2004).

Which factors, then, could have limited the ability of older adults to perform letter recognition by touch? As stated earlier, one factor that comes to mind immediately is the age-related reduction in tactile innervation, and its impact on spatial acuity in older persons, as we (Tremblay et al., 2000; Tremblay et al., 2003) and others (Stevens and Patterson, 1995; Stevens and Choo, 1996) have reported. Evidently, identification of raised patterns with the fingers requires proper encoding of the stimulus features at the periphery. As noted earlier, the SAI afferent system is considered to be largely responsible for this spatial encoding, owing to its high sensitivity to edges and curvatures (Johnson et al., 2000; Johnson, 2001). In fact, neurophysiological experiments have shown that raised patterns presented across the monkey's finger pad evoke structured activity in SAI afferents, yielding an "isomorphic" image of the scanned stimuli (Phillips et al., 1988). Yet, even in the high resolution image produced in the SAI afferent discharge, representation of internal horizontal elements (e.g. bar in the letter H) tends to be less accurate as compared to contour elements (Phillips et al., 1988). According to Vega-Bermudez et al. (1991), these distortions in the response of SAI afferents to spatial stimuli accounted for many of the asymmetries (e.g., why B is often mistaken for D, but not the reverse) noticed in the reports of naive observers when presented with letter stimuli and helped explain why certain characters (e.g., N and H) had abnormally high rates of false alarm. Interestingly, many of the asymmetries reported in the study of Vega-Bermudez et al. (1991) were also

observed in the performance of our participants, regardless of their age. For instance, the following pairs of letters: BD, MH, NH, RA were all associated with asymmetric response patterns in the two groups. Such an observation brings further support to the suggestion that tactile pattern recognition is highly dependent on the quality of the spatial encoding evoked in the SAI afferent discharge. In fact, examination of error patterns produced by older participants confirms that an inability to represent internal horizontal elements was indeed a major source of confusion between several pairs of letters (e.g., AK, CG, DO, PI, RA, VY and YT, see Figure 2B). The issue is to determine whether this inability was entirely attributable to peripheral mechanisms, owing to the inevitable loss of mechanoreceptors with age, or to some other age-related alterations further down in the processing stream. As suggested by Loomis (1981b), even if all critical information about a stimulus pattern was to reach the SI cortex, recognition may still fail due to factors acting at higher levels and interfering with the perceptual integration process.

In support of the primary importance of peripheral mechanisms, we found that grating resolution thresholds exerted a major influence on letter recognition accuracy in both age groups. This finding reiterates the conclusion of Johnson and Phillips (1981) and that of the two tasks, grating orientation discrimination and tactile letter recognition, rely on common coding neural mechanisms and are equally valid measures of tactile spatial resolution. Since grating resolution thresholds at the fingertip reflect the density of innervation, we can conclude that age-dependant variations in the number of functional receptors at the tip of the index finger were certainly a major factor for the recognition performance. Interestingly, the influence of grating resolution thresholds was particularly large in the young group, where it accounted for 40% of the variance in performance. Such a high correlation between grating resolution and letter recognition was also found by Vega-Bermudez and Johnson (2001), who examined differences in acuity between

digits in young persons. In a recent study, the same authors (Vega-Bermudez and Johnson 2004) investigated whether variations in the skin mechanics could account for differences in tactile spatial acuity. Their results showed that the degree of skin conformance to applied stimuli (grating domes in this case) accounted for a substantial proportion of the variance (~50%) in spatial acuity in young adults; whereas its impact was negligible in old adults. They concluded that skin conformance was likely a key factor in determining spatial acuity in young adults, whereas neural factors seemed far more important in older persons. In keeping with this conclusion, we suggest that the high accuracy performance of the young group was largely the result of their ability to produce high-fidelity spatial images of the scanned stimuli, owing to a high degree of skin conformance coupled with a dense SAI afferent innervation at the fingertip. These high-fidelity spatial images could then be relayed up to the SI cortex with a minimal loss of information and go through the successive stages to be transformed for comparison with templates of characters stored in memory. Also in keeping with Vega-Bermudez and Johnson (2004) conclusion, we suggest that the performance of the old group largely reflected alterations at the neural level affecting not only the quality of spatial encoding at the periphery but also possibly some other processes at higher levels.

In fact, our observations showed that old participants could be classified into two broad categories on the basis of their ability to resolve simple gratings, i.e., those (13/24) with “poor” acuity thresholds (range, 2.7-3 mm) and those (11/24) with “fair” acuity thresholds (range, 1.6-2.4 mm); all this relative to thresholds measured in the young group. It is important to emphasize that these two categories did not necessarily reflect age differences, although those with “poor” acuity tended to be older (mean age, 70 ± 7 years) than those with “fair” acuity (64 ± 9 years); the difference was not significant ($t=1.08$, $p=0.08$). Given that participants that exhibited poor spatial

acuity were also those that had the lowest recognition rates (mean 46% correct) while being amongst the oldest old in the group (see Figure 1B), we suggest that the main factor limiting their performance was indeed their inability to resolve spatial details of the touched letters at the periphery. In this group of older participants, the marked elevation of spatial resolution thresholds suggests a substantial decline in the number of functional receptors supplying the distal finger pad with advancing age, a decline that likely affected all populations of receptors including the Merkel cells associated with SAI afferents. Thus, it is easy to suspect that the spatial image encoded in the discharge of SAI afferents was already significantly degraded at the periphery to compromise severely character recognition right at the outset. Of course, this suggestion does not exclude the possibility that additional alterations might have been present at the central level, but these were likely occulted given the level of sensory degradation at the periphery. In the group of older participants with “fair” acuity, the interpretation appears less straightforward. While this group was certainly more successful at recognizing letters than the previous one (63% vs. 49% correct, respectively), their performance still fell short in comparison to that of the young group (86%, correct). It is tempting to suggest that the performance of this subset of participants may have represented an intermediate stage between the two extremes, that is, the old subjects where faulty peripheral encoding was the main limiting factor and young subjects where peripheral encoding was optimal with minimal loss of information at all successive stages. At this intermediate stage, the quality of the spatial image encoded in the afferent discharge was surely affected, but maybe not to a point as to obliterate completely the possibility of recognition at later stages. In fact, there is evidence that older adults can sometimes outperform younger ones when working under conditions of sensory degradation (e.g. visual recognition at different levels of blurring), presumably through compensation by top-down

mechanisms (Scialfa, 2002). Then, why did recognition fail if critical information about the touched letter was able to reach the SI cortex? As mentioned earlier and following Loomis's suggestion (Loomis, 1990), recognition might have been compromised by factors affecting the ability to either transform, store or compare the touched stimulus throughout the successive stages of the perceptual integration process. Given that older adults often exhibited high interference effects in tasks relying on selective attention either in the visual (Gazzaley et al., 2005) or tactile modality (Valeriani et al., 2003), it is easy to conceive that a failure to register centrally the sparse inputs generated from successive contacts with the pattern might have affected the quality of the central representation, leading to increasing risks of confusion between letters of similar shapes. Similarly, impairments in working memory might also have affected the ability of older participants to retain and retrieve high-fidelity templates of all the 26 characters for effective comparison with the scanned stimulus. The fact that old participants often displayed very long response times in trying to report letters' identity, although this outcome was not strictly monitored in this study, would certainly be consistent with the possibility that recognition may have failed in some instances due to failure in working memory process. We are currently investigating this issue in our lab to compare differences in response times between young and old subjects in hopes of better delineating the factors that affect pattern recognition in normal aging.

Conclusion

The present study has revealed major differences in the ability of young and old healthy adults to recognize complex patterns, such as raised letters, at the fingertip. The patterns of errors produced in the old groups indicate that an inability to encode critical spatial features of the

touched letters, notably internal elements specific to many characters (e.g., the bar in H or in G) is a major source of confusion in the reports of old persons, leading to a substantial decline in accuracy. While this faulty spatial encoding is most likely of peripheral origin, owing to age-related reductions in afferent innervation at the fingertip, we suggest that in certain instances central alterations may also impair pattern recognition, especially when spatial acuity is relatively preserved.

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Table 1. Demographic characteristics of the participants

	Young (n=20)	Old (n=24)
Age (years, mean $\pm$ S.D.)	23.5 $\pm$ 1.5	67.2 $\pm$ 8.6
Dominance (n)		
Right/Left	20/0	23/2
Gender (n)		
Male/Female	6/14	7/17
Vibration threshold ^a (mode and range)		
Distal phalanx	8 (7-8)	8 (6-8)
Ulna	7.5 (7-8)	7 (6-8)

^a Thresholds were determined with the graduated Rydel-Seiffer tuning fork. All threshold values were equal to, or exceeded, the norms established for the upper extremity (<40 years, threshold $\geq$ 6.0; 41-85 years, threshold $\geq$ 6.5). Note that one subject of in the old group (female, 68 years old) was dismissed because testing was incomplete, leaving 24/25 subjects for the final analysis.

FIGURE LEGENDS

Figure 1. A. Distribution of spatial resolution thresholds (circle symbols) and letter recognition scores (triangle symbols) for the two groups of participants. Each horizontal line across the distribution represents the mean. Note the large difference in both threshold values and accuracy scores between young and old participants. B. Distribution of letter recognition scores as a function of age in the old group. Note the strong association between older age and poor letter recognition.

Figure 2. Pooled confusion matrices computed for the two groups of participants. Each corresponding row and column represents the number of times the stimulus letter S_i evoked the response R_j . For instance, the letter R was reported as an A 10 times in the young group. The numbers in the right column indicate the number of times each letter stimulus was presented in each group (i.e., 3 times $\times$ n subjects). Boxes inside the matrix represent letter pairs whose mean confusion rates exceeded 8% (i.e., higher than random guessing). For example, in the old group, the mean confusion rate of CG was 17% (i.e., $> 8\%$) on the basis that C was called G 18% of the trials and G was called C 16% of the trials. Note the multiple pairs of confusion that characterized the performance of the old group.

Figure 3. Distribution of all individual scores in letter recognition as a function of spatial resolution thresholds measured at the tip of the index finger. Vertical lines have been drawn to arbitrarily to regroup spatial thresholds into broad categories to illustrate the association between variations in spatial acuity and the recognition performance. A regression line was fitted into the data to further demonstrate the strength of the relationship between the two variables, as evident in the high r^2 value.

A

B

A. Young group (n=20)

A. Young group (n=20)										Response																										R
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z										
A	56																	4										60								
B		45							2									1					1					60								
C			57					3																				60								
D				11																								60								
E					54											6												60								
F		2				56		1										1										60								
G		1				2	50				1					2				3	1							60								
H							60																					60								
I								39			2			8	9									1	1			60								
J									59	1																		60								
K								2	58																			60								
L											52									1	1				2			60								
M			1			1	2					59																60								
N													20	22										2				60								
O									16			1																60								
P									12					8	37									2		1		60								
Q																60												60								
R		1				2					1						54	1	1									60								
S																		59										60								
T																			46	1								60								
U																				51					1		3	60								
V																					53							60								
W																						57	2					60								
X																							51			8		60								
Y																								1	56			60								
Z																										56		60								
																											55	60								
																												46	60							
Total	66	53	58	65	59	54	68	66	63	60	60	59	40	72	66	57	60	56	58	57	57	57	61	69	70	49	1560									

B. Old group (n=24)

		Response																													
		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	<i>n</i>			
Stimulus	A	40	2			2			3		2	10			4				5					1	2		1	72			
	B	2	31	1	7	2	2	2		6	2	1	2	1			6			1	1				1		2	2	72		
	C			51															5	1	1				1				72		
	D		3		36		1	1	13										1	1			4				1		72		
	E		7	2	1	28	1	4		1	1	9				1		3	7	3						1		1	72		
	F	2	4	3		6	22	1	1			3	2					9	6	4	2	1				1	3	2	72		
	G		2	12	1	2	2	43				1	1				1		2	2		1			1		1		72		
	H	1			1	1				24		1	3	1					1	1	1	1	1		6	3	1		72		
	I	1	1						63		3											1						1		72	
	J						1		1	11	58													1						72	
	K		1	3		5	9	2				31	1		3			1	1	9	1			1	1		1	2		72	
	L	2		1		1		5			3	1		53					2							1	1	2		72	
	M				1				20			4				21	15		1	3			1		3	2		1		72	
	N	1					1		16			4			11	25		2					2	2	4	2	1	1		72	
	O											1					67	1	1	1		1								72	
	P		2		1		3	1		13	4		2		2			32		2	1	5				2	1	1		72	
	Q				1			1				2					5		59	2			1							72	
	R	10	7				4	1			3	2	6	3		5		1		21	2	1	1	1		1			1	72	
	S		2		1	2	3	4			1	9	2				1	3	1	2	26		1	1	2	5			6		72
	T		1		2				1	3			1				2		1			45						10	2		72
	U	1			1			2	2		2		2		1	2	1		2				50	4	3			1		72	
	V		1		1	1						4	1	1	3		5			1	1		5	27	1		18			72	
	W	1				1			3			2	1	2	3		1	1	1			4	2	48	1			1		72	
	X		2				1					8		2	5				3	3			2	8	30	2	6			72	
	Y	1	1		3	5		1	4		1	1		1				3			11		4			36				72	
	Z		2		6	3	3		1	1	1	1	1						1	7	1				8	2	35			72	
Total		61	70	73	59	58	60	83	76	107	86	97	70	52	83	95	73	74	73	50	69	72	45	81	59	82	64	1872