Exp Brain Res
DOI 10.1007/s00221-014-3882-4

RESEARCH ARTICLE

Occupation-related long-term sensory training enhances roughness discrimination but not tactile acuity

S. Mueller · C. Winkelmann · F. Krause · M. Grunwald

Received: 13 November 2013 / Accepted: 16 February 2014

Abstract Extensive use of sensorimotor properties has been shown to lead to use-dependent plasticity in the human motor cortex as well as sensory areas. The sensory consequences of these cortical changes, however, remain widely unclear. We were interested whether job-related long-term haptic training is measurable in terms of changes in *haptic* perception (active touch exploration) in manual physiotherapists (PT). To that end, the haptic thresholds of PT (students and employed) and registered osteopathic manual therapists (OMT; PT with postgraduate specialization) were measured and compared to age- and sex-matched control groups. Additionally, tactile acuity (passive static touch) was assessed using grating domes. PT and OMT had superior mean haptic thresholds compared to the control group, suggesting an increase in sensitivity through use. An age-related decline in haptic perception capacity occurred only in the control group, suggesting that the job-related training of the manual therapist groups may have slowed their age-related decline. Contrary to our expectation, we found significantly poorer mean haptic threshold results in the PT student group than for the controls. No significant differences or changes in tactile acuity were found for any of the groups (students and professional). The present results demonstrate use-dependent plasticity in manual therapists. Furthermore, the results underline the known effect of a superior discrimination ability of haptic as opposed to tactile perception.

Keywords Use-dependent plasticity · Tactile spatial resolution · Haptic threshold · Sensory training · Osteopathic manual physiotherapists · Perceptual learning

S. Mueller · F. Krause · M. Grunwald (✉)
Haptic Research Laboratory, Medical Faculty, Paul-Flechsig-Institute for Brain Research, University of Leipzig, Johannisallee 34, 04103 Leipzig, Germany
e-mail: mgrun@medizin.uni-leipzig.de

C. Winkelmann
Department of Health and Social Services, Baden-Wuerttemberg Cooperative State University, Wilhelm Street 10, 89518 Heidenheim, Germany

Introduction

Several previous studies have shown that gains in tactile acuity may be achieved by healthy participants with the help of tactile training (e.g., Dinse et al. 2008; Sathian and Zangaladze 1997). These perceptual learning effects most often presented with a strong specificity for the type of task and stimulus (Dinse et al. 2008). The neuronal plasticity of the human primary sensory cortex has been studied extensively in experimental (e.g., Kalisch et al. 2008; Hoffken et al. 2007; Godde et al. 2000; Elbert et al. 1995) as well as clinical studies (e.g., Yang et al. 1994; Ramachandran et al. 1992).

Practical applications take place especially in the field of computer-aided surgery where regular haptic trainings are necessary to improve the haptic perception and motor abilities of the surgeons (Singapogu et al. 2013; Gosselin et al. 2013). Other relevant fields are, for example, veterinary medicine (training of palpation ability of the students, e.g., Baillie et al. 2003), recovery of somatosensory and haptic capacity in patients after stroke (e.g., Moseley and Wiech 2009; Patton et al. 2006), and the treatment for phantom limb pain (e.g., Flor and Diers 2009; Flor 2002; Flor et al. 2001). These trainings are mostly conducted for and with specific tasks and purposes as well.

But what about the other way around? Does activity-related or job-related haptic training result in a sharper perceptual power? One study showed that long-term haptic training in the form of professional piano playing resulted in better tactile spatial discrimination measured by a two-point discrimination experiment (Ragert et al. 2004). Another study, analyzing the tactile acuity of Tai Chi practitioners, found that even long-term training of attention focussing on the hands may be associated with a higher tactile acuity compared to a control group (Kerr et al. 2008). However, so far, there has been no attempt to assess whether job-related long-term haptic training is measurable in terms of a difference in *haptic* threshold.

Haptic perception occurs when a person is actively moving to explore 2D or 3D physical structures with either the fingers or other body parts. Experimental analyses have shown that healthy adults can detect an elevation as small as 1 µm on a most even surface with their fingertips during active haptic surface exploration (Louw et al. 2000, 2002). As opposed to this, tactile perception denotes any passive, static contact between a person and its surroundings. Tactile thresholds are considerably higher than their haptic counterparts with a discrimination sensitivity of on average 1 mm at the fingertips (Vanboven and Johnson 1994; Johnson and Phillips 1981).

In the present paper, first results will be presented using a new haptic threshold test (HST) setting, which allows the participants' eyes to remain open during the procedure. Previous experimental measurement attempts required the participants to be blindfolded or to hide behind a screen to prevent visibility of the stimuli and hands to prevent visual information from distorting the results. Covering the hands or eyes, however, may have an influence on haptic perception in itself. A recent study showed that the visibility of manual exploration movements (as is most often the case in daily life) may pose different cognitive demands than a blindfolded or covered task (Mueller et al. 2013).

Additionally, tactile acuity was measured using grating domes (Vanboven and Johnson 1994; Johnson and Phillips 1981) to allow a comparison with the results from the above-mentioned use-dependent plasticity studies.

To assess whether job-related long-term haptic training is measurable in terms of a difference in *haptic* threshold, the thresholds of physiotherapists (PT, students, and employed) and osteopathic manual therapists (OMT; PT with postgraduate specialization) were measured. The results of the manual therapist groups were compared to the results of age- and sex-matched control groups.

Individual differences in haptic thresholds have been reported across all ages. Individual disposition, training, age, and diseases explain some variance and can alter the capacity of tactile as well as haptic perception (Wong et al. 2013; Dinse et al. 2008; Manning and Tremblay 2006; Vrethem et al. 2002; Grunwald et al. 2001; Norrsell et al. 2001). Comparisons of a physiotherapy student group (PT students) and an age-matched control group (CO young) were conducted to explore the individual differences in haptic thresholds due to individual disposition. Because of the limited amount of perceptual training experienced by the PT students up to the time of testing, our first Hypothesis is as follows: The participants of the two young groups will not differ in their haptic perception beyond the effects of age and education. Additionally, similar means of the student groups would indicate that the decision to study physiotherapy is not based on extraordinary haptic perception capacity and, therefore, that the results may not be biased by self-selection effects.

Based on the fact that without specific training, both haptic and tactile capacity deteriorate with age (Dinse et al. 2008; Kleibel et al. 2003), our second Hypothesis is as follows: The decline in haptic threshold and tactile acuity with age will be smaller in the OMT group and the PT group than in the control group (CO old). Furthermore, we expect to find differences in haptic thresholds depending on the status of training of the groups. The mean haptic threshold and tactile acuity of OMT should differ from those of PT and the control group with the highest thresholds in the osteopathic manual therapist group (Hypothesis 3).

Methods

Participants

Of all $N = 183$ participants, 163 were right-handed, 19 left-handed, and 1 ambidexter. The participants consisted of $n = 39$ physiotherapy students, $n = 25$ employed PT, and $n = 31$ OMT (PT with postgraduate specialization). The entire group of OMT consisted of trained PT who had completed an additional course of studies. The extra occupational studies were comprised of approximately 700 h of practical training and 700 h of theoretical and scientific principles. The participants had worked in the field for 1–10 years ($M = 5.42$, $SD = 3.34$) since their osteopathic manual training (postgraduate specialization). At the time of testing, 9 of the OMT worked another additional job. Additionally, $n = 44$ young students of other courses and $n = 44$ older adults of other vocations than the above were tested to form two control groups. The sex, age, and education ratios of all five groups are listed in Table 1. Education was defined as the sum of the number of school years (without repeated grades) and the number of years of the first completed higher education or training (standard period of study). The three older groups (PT, OMT, and Co old) as well as the two young groups (PT students and Co young) did not differ in age ($\chi^2_{old} = 0.155$, $p = .926$; $z_{young} = -0.528$; $p = .597$).

Table 1 Descriptive statistics

	PT students	PT	OMT	Co young	Co old
N	39	25	31	44	44
Sex (f/m)	27/12	22/3	19/12	24/20	29/15
Age *M* ± SD (min–max)	21.18 ± 1.82 (18–24)	40.88 ± 4.75 (34–50)	41.35 ± 4.12 (34–50)	21.36 ± 1.78 (18–24)	41.41 ± 4.85 (34–50)
Education *M* ± SD (min–max)	12.82 ± 1.32 (10–16)	13.92 ± 1.19 (12–15)	14.47 ± 1.66 (10–18)	14.11 ± 1.67 (10–18)	14.98 ± 1.73 (12–18)

PT physiotherapists; *OMT* physiotherapists who completed an osteopathic manual therapy training; *Co* control group; *M* mean; *SD* standard deviation; *f* female; *m* male

The participants were recruited from the following institutions: PT students were enrolled in the medical vocational school (Medizinische Berufsfachschule) of the local university clinic; professional PT were employed at the university clinic of Leipzig; OMT were registered manual therapists who were recruited via advertised bidding if they fit the criteria of 700 h practical postgraduate training. The participants of the control group were taken from a random community sample and rewarded 10 €/h.

All participants had normal or corrected to normal eyesight. Exclusion criteria were neurological and psychiatric disorders, as well as any known polyneuropathy or paresthesia of the hands. Our own pre-studies have shown that especially polyneuropathy caused by liver diseases and paresthesia of the hands of unspecified cause influence the individual haptic threshold measured with the HST.

All participants gave written informed consent. All procedures were in accordance with the Declaration of Helsinki and were approved by the Institutional Ethics Committees.

Experimental tests and procedures

The study was conducted in a quiet room without disturbances. To assess diseases that may cause polyneuropathy, a questionnaire was used. On average, the investigation lasted $M = 48.49$ min (SD = 12.47).

Haptic threshold test (HST)

The haptic threshold was measured with the above-mentioned HST. The test consists of 13 similar two-dimensional relief stimuli (parallel grooves and ridges; Fig. 1). Each stimulus is presented in a small round plastic box that is covered by an opaque PVC layer. Thus, neither the participant's eyes nor their hands have to be covered during the haptic exploration of the stimuli because the opaque PVC layer renders the palpable features invisible.

The difference between the 13 stimuli is the spacing of the ridges. The peak-to-peak spacing of the simplest stimulus (Haptic-Pad 1) amounts to 3 mm. With every pad, the peak-to-peak distance decreases by 200 µm. In Haptic-Pad number 2, it is, therefore, 2.8 mm, while the peak-to-peak distance in Pad No. 13 is only 0.6 mm. Due to the PVC layer that covers the stimuli, the palpable deformation differs from the physical spacing of the ridges. The separating PVC layer is 252 µm thick. Table 2 lists each peak-to-peak value and the corresponding elongation value of the PVC layer measured with an indenter point of 150 mN pressure.

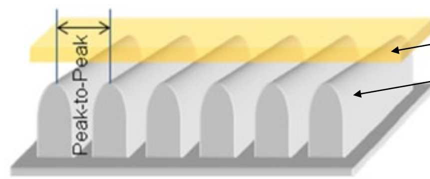

Fig. 1 Schematic picture of the construction of the stimuli: Parallel grooves and ridges of equal spacing were covered by an opaque plastic layer

Table 2 Technical plastic deformation gauge of the separating PVC layer

Haptic-Pad number	Peak-to-peak value in mm	Elongation value in µm[a]
1	3.0	54.71
2	2.8	45.62
3	2.6	39.40
4	2.4	26.11
5	2.2	25.57
6	2.0	23.42
7	1.8	15.23
8	1.6	12.22
9	1.4	10.69
10	1.2	8.25
11	1.0	7.14
12	0.8	6.48
13	0.6	2.16

[a] Mean elongation values in micrometers of the PVC layer for each haptic stimulus pad measured with a force of 150 mN applied by an perpendicular indenter tip

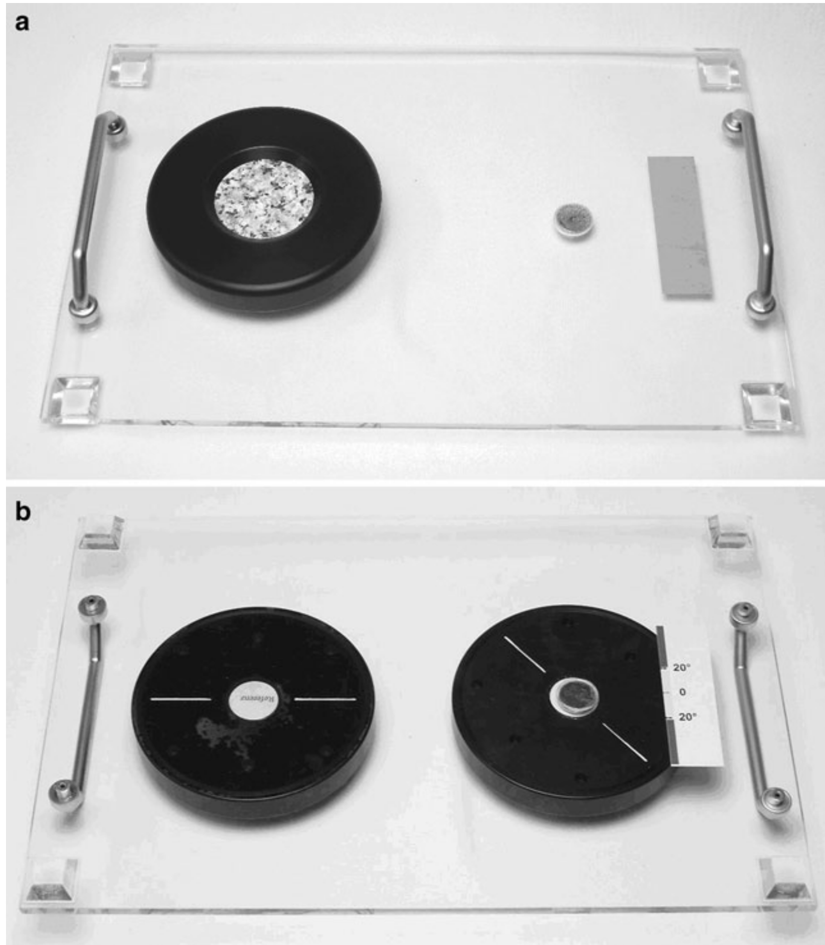

Fig. 2 **a** Front side of the test board with fixated reference pad. **b** Reverse side of the test board with fixed reference pad (*left*) and a threshold pad with its alignment outside the 20° marking (*right*)

These measures present a good estimation of the palpable thresholds. The retest reliability of the HST in a random sample was $r = .845$, $p < .0001$. Face validity and content validity are high. Discriminant validity, as indicated by the low correlation (nonsignificant) of grating domes and HST ($r = -.390$, $p = .150$), is given.

The participants were seated at a table with the test board in front of them (Fig. 2a). A reference pad with a peak-to-peak value of 7 mm was firmly attached to the test board with its grooves and ridges in a horizontal orientation. The task of the participants was to explore each stimulus and to bring it into an equally horizontal orientation by rotating the Haptic-Pad. No time limit was given, and the participants were free to use any fingers they preferred and to switch between fingers during exploration. The stimulus field had room for up to four fingers (four of one hand or two from each hand) or two thumbs. On the back of each Haptic-Pad is a white line to indicate the horizontal orientation of the stimulus (Fig. 2b). On the back of the test board is a division scale that marks an area of 20° above and below the horizontal line (0°). Those Haptic-Pads that were oriented horizontally, with the white line within the ±20° area, were marked as recognized. Orientations outside of the ±20° area (like in Fig. 2b) were marked as wrong/not recognized. To solve the task, each subject completed three iterations beginning with the simplest pad and ending with the most difficult. The haptic threshold is indicated by that Haptic-Pad with the smallest groove distance, which was recognized correctly at least twice.

Tactile threshold: grating domes (GOT)

The participants' tactile acuity [grating orientation threshold (GOT)] was measured with grating domes (Stoelting Co., Wood Dale, IL; Vanboven and Johnson 1994; Johnson and Phillips 1981) of equal groove and ridge widths (0.35, 0.5, 0.75, 1.0, 1.2, 1.5, 2.0, and 3.0 mm). The tactile threshold was measured only in the three older groups (PT, OMT, and Co old). The grating domes were administered according to the test manual: Each grating dome was applied 20 times for 1 s to the ventral side of the distal part of the first finger. After each application, the participants were required to indicate the orientation of the grooves that were randomly varied between longitudinally and across the finger axis. The administration of the test began with the widest grating of 3.0 mm and terminated by that grating dome at which the performance was less than 75 % correct. The grating width at which the performance would be exactly 75 % correct (the GOT) was then calculated with the help of an established formula.

Data analysis

To analyze the data, statistics software SPSS 20.0 was used. Standard Pearson's correlations and linear regression models were used to assess the relationships of continuous variables. Group comparisons were conducted using Mann–Whitney *U* tests (two groups) and one-way ANOVA (three groups).

Results

Hypothesis 1: Variation between individuals

The mean haptic value students of physiotherapy obtained was threshold number 9 ($M = 9.00$; SD = 1.75). That equals a mean haptic threshold of 10.69 µm (see Table 2). As expected, strong individual differences occurred. The individual results varied between threshold pad number 4 (26.11 µm; low sensitivity) and threshold pad number 11 (7.14 µm; high sensitivity). As postulated, no correlation existed between haptic threshold and age for this group of test participants ($r = -.008$, $p = .226$).

As opposed to that, the mean haptic value obtained by the participants of the young control group was threshold pad number 11 ($M = 10.50$; SD = 1.17). That equals a mean haptic threshold of approximately 7.14 µm (see Table 2). As in the physiotherapy student group, individual differences occurred. However, the results varied between threshold pad 8 (12.22 µm; moderate sensitivity) and threshold pad 13 (2.16 µm; very high sensitivity), only.

Therefore, the students of physiotherapy systematically obtained lower threshold values than the participants in the young control group ($z = -4.105$; $p < .001$; Fig. 3). According to Hypothesis 3, this group difference should not persist beyond age and education. To exclude the possible influence of education, all participants with an education higher than 13 years were removed from the analysis. The remaining two groups had the same age and education ($z_{\text{education}} = -0.382$; $p = .770$; $M_{\text{Co}} = 12.35$; SD = 0.75; $n = 20$; $M_{\text{PT}} = 12.38$; SD = 0.78; $n = 34$). Contrary to Hypothesis 3, however, the significant difference in haptic threshold remained, even though there was a marked decline in the difference ($z_{\text{HST}} = -2.468$, $p < .05$; $M_{\text{Co}} = 10.05$; SD = 1.73; $M_{\text{PT}} = 8.82$; SD = 1.83).

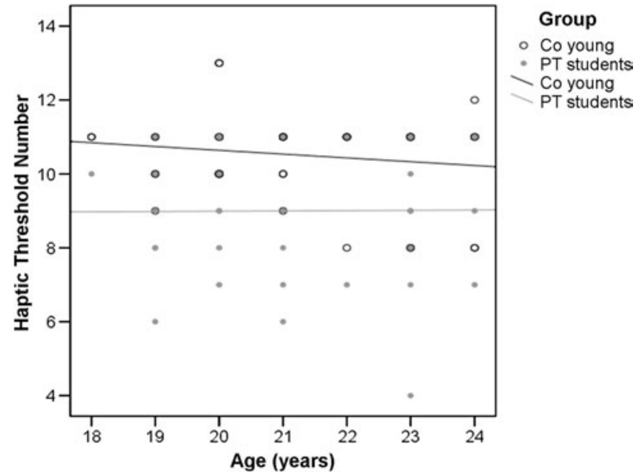

Fig. 3 Students of physiotherapy systematically obtained lower threshold values than the participants in the young control group. The *scatter plot* shows the haptic threshold values of both groups sorted by age. The *two lines* indicate the mean values

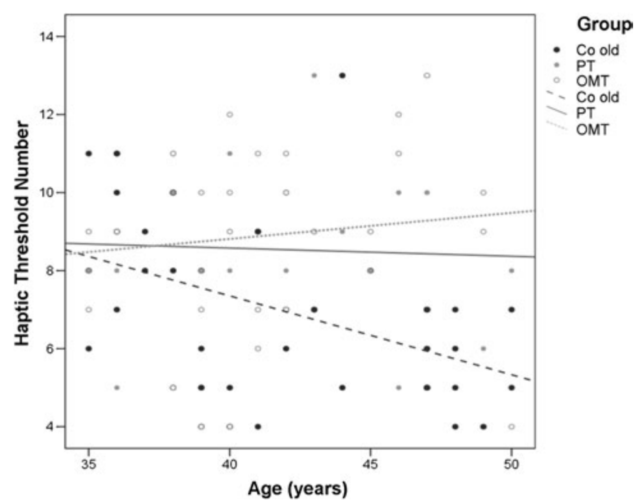

Fig. 4 Diagram shows age and haptic threshold of all older participants. The *three lines* represent the slopes of the linear regression models for each group. *PT* physiotherapists; *OMT* physiotherapists who completed an osteopathic manual therapy training; *Co* control group

Hypothesis 2: Differential age-related decline depending on training

To evaluate the influence of age in all three adult groups (PT, OMT, and control group old), the data were analyzed by means of linear regression models. In the control group, a significant part of the variance in individual haptic thresholds was explained by the age of the participants ($r = .434$; $F(1, 42) = 9.764$, $p < .005$; Fig. 4). Accordingly, 18.8 % of the variance in haptic thresholds was explained by the age differences of the participants. This signifies a medium

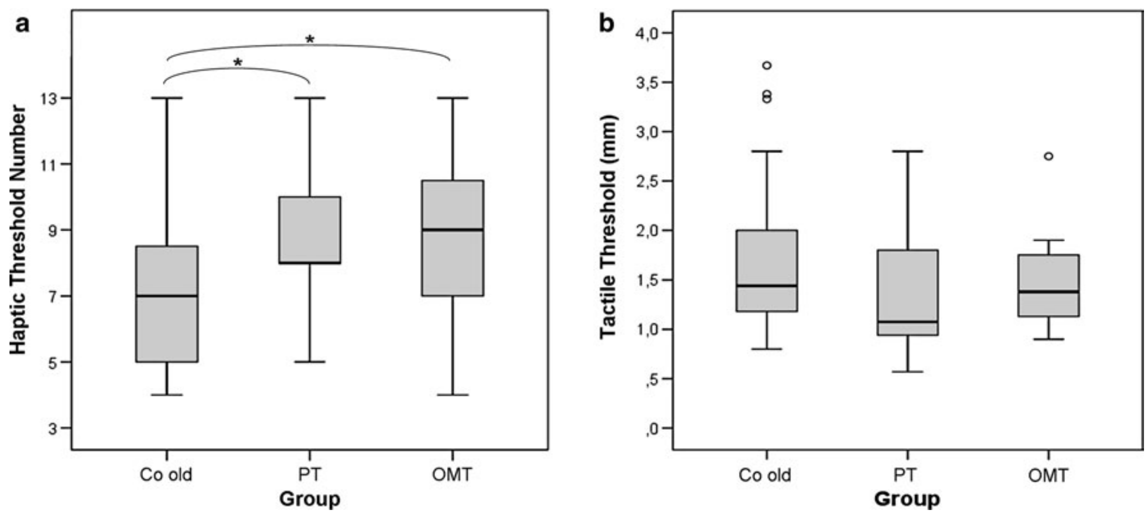

Fig. 5 **a** Box plots depict the median and distribution of the haptic thresholds per group. The *asterisks* indicate significant differences. **b** Box plots show the distribution of tactile thresholds of the three groups. The *little circles* mark outlier values. There were no mean differences between the groups. *PT* physiotherapists; *OMT* physiotherapists who completed an osteopathic manual therapy training; *Co* control group

effect size. Therefore, age significantly predicted the haptic threshold ($b = -0.933$, $p < .005$) with the haptic threshold declining one point every 5 years in the control group.

The linear regression model for the PT group, however, did not predict any significant associations ($r = .054$; $F(1, 23) = 0.068$; $b = -0.141$, $p = .796$). Neither did the regression model for the OMT group ($r = .114$; $F(1, 29) = 0.379$; $b = 0.193$, $p = .543$).

To assess whether the difference between the regression slopes of the three groups was significant, an ANCOVA was calculated. The interaction effect of age and group was significant ($F(1,3) = 6.832$, $p < .001$). Therefore, the three slopes differed significantly with an association of age and haptic threshold present only in the control group. In both therapeutic groups, the haptic threshold was not influenced by age.

Concerning tactile acuity, the linear regression models revealed no significant associations with age in any of the groups. Age was not associated with tactile acuity in the control group ($r = .239$; $F(1, 36) = 2.176$, $b = 1.684$, $p = .149$), nor in the PT group ($r = .612$; $F(1, 8) = 4.778$, $b = 3.676$, $p = .060$) and neither in the OMT group ($r = .281$; $F(1, 29) = 2.488$, $b = 2.938$, $p = .126$).

Hypothesis 3: Mean differences in haptic thresholds but not in tactile thresholds

Analyses showed significant differences between the mean haptic thresholds of the control group and the two therapeutic groups, however (one-way ANOVA: $F(2, 97) = 7.27$, $p < .005$). Post hoc analyses using the Scheffé post hoc criterion for significance indicated that the PT and OMT groups significantly reached higher haptic threshold levels than the control group ($M_{HST\_Co} = 7.07$, SD = 2.26; $M_{HST\_PT} = 8.56$, SD = 1.83; $M_{HST\_OMT} = 8.90$, SD = 2.43)—partially confirming Hypothesis 2 (Fig. 5a).

Contrary to Hypothesis 2, however, a one-way ANOVA revealed no significant differences between the tactile thresholds of the three groups ($F(2, 76) = 2.89$, $p = .062$; $M_{tactil\_Co} = 1.73$, SD = 0.72; $M_{tactile\_PT} = 1.31$, SD = 0.69; $M_{tactile\_OMT} = 1.45$, SD = 0.39; Fig. 5b).

A small correlation of HST and GOT across all groups was found ($r = -.342$, $p < .001$). The size of the correlation decreased somewhat after age was added as a covariate but it remained significant ($r = -.285$, $p < .005$). In other words, for each haptic threshold, approximately the same range of variation in tactile thresholds occurred with a slight shift of the means (see Fig. 6).

Nine of the 31 OMT had completed yet another training for an other profession since completing the osteopathic manual training and were working both jobs. These two groups did not differ in age ($z = -1.44$, $p = .149$), tactile acuity ($z = -1.22$, $p = .223$), or haptic threshold ($z = -0.42$, $p = .675$).

There was no correlation of time since the osteopathic manual training was completed and haptic threshold ($r = .099$, $p = .611$) or tactile acuity ($r = .043$, $p = .823$) after controlling for age.

Discussion

The aim of the present study was to identify possible effects of occupation and age on the haptic perception of manual

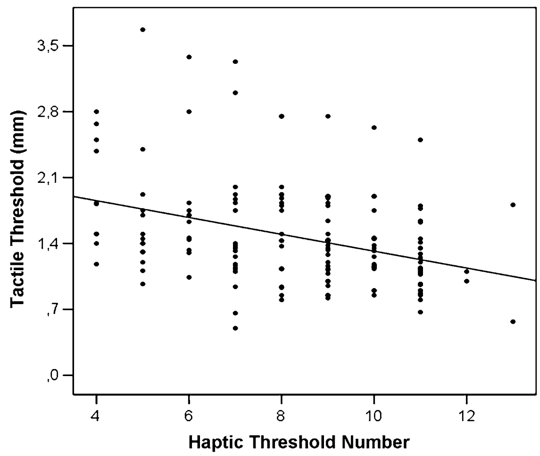

Fig. 6 Scatter plot of tactile and haptic thresholds for all participants. The *line* shows the small correlation (not significant) between HST and GOT

therapists as well as to determine individual differences in haptic perception across all groups (manual therapists as well as control groups). Long-term occupation-related haptic training in manual therapists was found to have an effect on the haptic threshold but not on tactile acuity. Individual differences in the haptic threshold were found across all groups—independently of age and occupation. Of special interest are the differences between individuals of the young participant groups (PT students and young control group; Hypothesis 1). Their results varied between haptic threshold number 4 (low sensitivity) and number 11 (high sensitivity) in the PT students group and between 8 (medium sensitivity) and 13 (very high sensitivity) in the young control group. The, therefore, somewhat surprising result of a group difference in mean haptic threshold of PT students and the age-matched young control group (with the PT students showing a poorer threshold) remained even after education was entered as a covariate: After all participants with more than 13 years of education were excluded from the analysis, the group difference remained significant as well as unsolved. Links between intelligence and tactile perception (Li et al. 1998; Stankov et al. 2001) as well as vision and audition have been reported before. Tactile perception has also been linked to academic performance (Boll et al. 1978). Furthermore, intelligence has been shown to predict educational level (Strenze 2007). Therefore, a possible association of education (as an indicator of intelligence) and sensation seemed logical. However, the analysis remains exploratory.

As required, the two groups did not differ in age and there was no correlation of age and haptic threshold for both groups. Future studies should aim to identify the underlying variables of both the variation between individuals and the mean differences between the young groups. Possible variables may be systematic variation of skin thickness and finger size (Peters et al. 2009), intelligence (as opposed to education), or degree of stimulation during early childhood (toys and human interactions). Also, individual differences in skin surface friction (between the finger and PVC layer of the HST) may be a relevant factor to be controlled in future studies. Possibly, physical activity and/or smoking may be relevant because they influence peripheral blood flow, which may in turn influence perceptual limits. Previous studies that measured intensity of exercise and smoking did not find an influence on tactile acuity (Kerr et al. 2008; Stevens et al. 2003); however, haptic perception was not assessed in these studies. The systematic difference between PT students and control group, as well as the strong variation between individuals, furthermore raise questions about the training of the PT students. Possibly, a haptic training throughout their studies should be considered or more emphasis put on it. Since the present study was conducted cross-sectionally, it is unforeseeable whether the young participants will develop in a comparable way as the tested professional manual therapists. It is possible that the haptic thresholds of the participants in the young control group may decline rapidly with age way below the mean threshold of the PT students group due to the lack of occupation-related training, while the mean haptic threshold of the PT students remains much the same. While this is mere speculation, this process would mirror the trend found for the employed sample.

Differences in the tactile and haptic perception of individuals of the same age have been reported before (Wong et al. 2013; Montague 1978; Escalona 1953). Insights from infant research suggest that differences in sensory discrimination and processing are not congenital. Their development seems to be strongly influenced by the amount and frequency of haptic and tactile stimulation. With additional training of the less sensitive participants, a relevant increase in their perceptual capacity should, therefore, be possible. Previous findings show that participants with poorer initial capability show greater gain through training (Wong et al. 2013).

The superior haptic performances of PT and OMT (less age-related decline in haptic perception, Hypothesis 2 and higher haptic thresholds, Hypothesis 3) are also an indication of perceptual learning and use-dependent plasticity. Wong et al. (2013) argued that individual everyday life differs in the amount of necessity and opportunities it provides for tactile perceptual learning and that individuals differ in the amount of reliance on touch. They propose that the variance of individual tactile acuity, which is not explained by age and receptor density/finger size, results from differences in everyday tactile perceptual learning. A similar explanation may apply to the group differences in haptic thresholds of the older groups. In the same line, an explanation for the lack of differences in the tactile acuity of the manual therapist groups and the control group may be that their occupation does not provide much more tactile stimulation (passive touch) than occupational settings of other people. As opposed to this, haptic activities are a relevant part of their work. However, the effects of the occupation-related haptic training did not generalize enough to result in significant group differences in tactile acuity.

Similar to previous findings, there seemed to be a limit to perceptual learning. There was no significant difference in haptic threshold of the PT and OMT group, even though the persons of the OMT group underwent 700 h of perceptual training during their additional course of studies. Wong et al. (2013) reported an increase in correlation between GOT and finger size and a decrease in individual variability after training. They interpreted this finding as an indication for a limit to tactile learning set by finger size. In the present sample, finger size was not measured. However, future studies may evaluate whether finger size poses as a relevant factor in haptic perception as well. Most likely is that the necessity to move the fingers during haptic exploration would render this factor ineffective because the density of mechanoreceptors of the skin would no longer be of primary relevance. The type of sensory information that receptors are most sensitive for is more relevant in haptic perception. In our case, it is most likely that Vater–Pacini corpuscles play a relevant role in the detection and discrimination of the test specifities of the HST (Libouton et al. 2012; Halata and Baumann 2008; Johnson and Hsiao 1992). They are most sensitive to vibratory information between 40 and 1,000 Hz (Drenckhahn and Zenker 1994), which is most likely the kind of sensory input that occurs when a fingertip is moved across parallel grooves. The reason why the difference between PT and OMT did not reach significance remains unknown. Possibly, more training may be necessary to achieve even bigger increases in haptic thresholds or maybe the age-related decline prevented a sharper learning curve. Prior studies have shown that the age-related decline in haptic perception ability may be diminished by training but not stopped altogether (Dinse et al. 2008; Kleibel et al. 2003).

These results emphasize the higher sensitivity and specificity of the HST to measure and evaluate a haptic perception threshold. If nothing else, the results underline the known effect of a superior perceptual discriminability of haptic as opposed to tactile perception (Grunwald 2008; Louw et al. 2000; Vanboven and Johnson 1994). While the smallest groove width of the grating domes is 0.35 mm, the palpable elongation values of the HST range between 55 and 2 μm. It is known that haptic perception requires a more complex cortical integration process with an involvement of receptors of several more locations than tactile perception. Besides skin receptors also receptors of tendons, muscles and joints are involved during haptic perception (Hsiao and Yau 2008; Halata and Baumann 2008). Analogously, the results of a recent study support the well-discussed fact that for the detection of vibratory information resulting from haptic surface exploration with the fingertip, not only the receptors and nerves of the fingertips are involved but that receptors and afferents of the hands and arm play an important role as well (Libouton et al. 2012). The authors measured roughness discrimination ability by asking the participants to move their fingertips across two textured surfaces and to decide which one was the rougher one. The participant groups consisted of different persons with different types of nerve damage (carpal tunnel syndrome, median nerve section, and a control group with anesthetic ring bloc). They measured passive tactile acuity as described above as well. All three groups showed significant reduction in tactile acuity but intact roughness discrimination ability.

Fast adapting Pacinian corpuscles may have special relevance for the detection of vibratory information (and, therefore, for the handling of the HST, as mentioned above). They can be found in muscle tissue, in cutis and subcutis, connective tissue (in tendons and around ligaments), in the periosteum, and in interosseous membranes (Mountcastle 2005; Drenckhahn and Zenker 1994). Pacinian corpuscles are so sensitive they readily detect and transmit even very small vibrations of the body tissue (Hunt 1961). Additionally, slowly adapting Merkel cells and medium fast adapting Meissner's corpuscles are involved with the detection of vibration (Hsiao and Yau 2008; Bensmaia and Hollins 2003, 2005; Johnson and Hsiao 1992). Therefore, since all these tissues contain highly sensitive receptor afferents able to encode vibrations, vibrations generated at the fingertip by surface exploration may spread proximally through the tissue of the finger toward the hand and arm (Libouton et al. 2012). In future studies, results from tactile frequency discrimination tasks or vibration threshold tests should be correlated with HST results to gain further insights into the demands posed by the HST.

In summary, the results stress the fact that a differentiation between tactile and haptic perception may be necessary and that adequate denominations and tests need to be used. The results of the present study underline that tactile and haptic tests should not be used interchangeably and that the expected results as well as neural mechanisms may not be the same (Libouton et al. 2010, 2012). The correlation between GOT and HST was merely 13.4 % in the present study, with some participants who reached high haptic thresholds hardly recognizing the easiest grating domes and vice versa. Additionally, the group differences were not detected by the GOT.

The results of the present study suggest that besides an increase in haptic threshold through job-related training (better results of the OMT and PT groups compared to the control group), it may also antagonize the usual age-related decline in haptic perception of otherwise healthy persons. The acquired perceptual capacity proved to be highly generalized, which is reflected in its measurability with the HST. That means, that the daily training of employed PT and registered OMT has lead to an embedding of the perceptual ability in somatosensory association areas with activity modulations in the partial cortex, which makes it generally accessible (Wong et al. 2013; Dinse et al. 2008). Therefore, the present results demonstrate use-dependent plasticity in manual therapists. Future studies should evaluate the question to what magnitude an increase in haptic threshold (as opposed to tactile acuity) is possible and what its limits are.

Acknowledgments The authors would like to thank Mrs. cand. psych. Laura Harms, Mrs. Kirsten Heitmueller, and Mr. cand. psych. Matthias Moeder for their support in the acquisition of the data. We would also like to thank the Medizinischen Berufsfachschule, Leipzig, (especially Mrs. Zenker), and the University Clinic of Leipzig AöR for their support during the realization of the study. This research project was supported in part by the Deutsche Forschungsinitiative Eßstörungen (DFE e.V.) and the Haptik-Forschungszentrum. Neither had influence on the preparation of the article nor the conduct of the research.

Conflict of interest None.

References

Baillie S, Crossan A, Reid S, Brewster S (2003) Preliminary development and evaluation of a bovine rectal palpation simulator for training veterinary students. Cattle Pract 11:101–106

Bensmaia SJ, Hollins M (2003) The vibrations of texture. Somatosens Mot Res 20:33–43

Bensmaia SJ, Hollins M (2005) Pacinian representations of fine surface texture. Percept Psychophys 67:842–854

Boll TJ, Richards H, Berent S (1978) Tactile-perceptual functioning and academic performance in brain-impaired and unimpaired children. Percept Mot Skills 47:491–495

Dinse HR, Wilimzig C, Kalisch T (2008) Learning effects in haptic perception. In: Grunwald M (ed) Human haptic perception: basics and applications. Birkhäuser, Basel, pp 165–182

Drenckhahn D, Zenker WEd (1994) Benninghoff Makroskopische Anatomie, Embryologie und Histologie des Menschen, vol 2. Urban & Schwarzenberg, München

Elbert T, Pantev C, Wienbruch C, Rockstroh B, Taub E (1995) Increased cortical representation of the fingers of the left hand in string players. Science 270:305–307

Escalona S (1953) Emotional development in the first year of life. In: Senn MJE (ed) Problems of infancy and childhood. Josiah Macy, Jr. Foundation, New York

Flor H (2002) Phantom-limb pain: characteristics, causes, and treatment. Lancet Neurol 1:182–189

Flor H, Diers M (2009) Sensorimotor training and cortical reorganization. Neurorehabilitation 25:19–27

Flor H, Denke C, Schaefer M, Grusser S (2001) Effect of sensory discrimination training on cortical reorganisation and phantom limb pain. Lancet 357:1763–1764

Godde B, Stauffenberg B, Spengler F, Dinse HR (2000) Tactile coactivation-induced changes in spatial discrimination performance. J Neurosci 20:1597–1604

Gosselin F, Bouchigny S, Megard C, Taha F, Delcampe P, d'Hauthuille C (2013) Haptic systems for training sensorimotor skills: a use case in surgery. Robot Auton Syst 61:380–389

Grunwald M (ed) (2008) Human haptic perception. Birkhäuser, Basel

Grunwald M, Ettrich C, Assmann B, Dahne A, Krause W, Busse F, Gertz HJ (2001) Deficits in haptic perception and right parietal theta power changes in patients with anorexia nervosa before and after weight gain. Int J Eat Disord 29:417–428

Halata Z, Baumann KI (2008) Anatomy of receptors. In: Grunwald M (ed) Human haptic perception. Birkhäuser, Basel, pp 85–92

Hoffken O, Veit M, Knossalla F, Lissek S, Bliem B, Ragert P, Dinse HR, Tegenthoff M (2007) Sustained increase of somatosensory cortex excitability by tactile coactivation studied by paired median nerve stimulation in humans, correlates with perceptual gain. J Physiol-Lond 584:463–471

Hsiao S, Yau J (2008) Neural basis of haptic perception. In: Grunwald M (ed) Human haptic perception. Birkhäuser, Basel, pp 103–112

Hunt CC (1961) On the nature of vibration receptors in the hind limb of the cat. J Physiol 155:175–186

Johnson KO, Hsiao SS (1992) Neural mechanisms of tactual form and texture-perception. Annu Rev Neurosci 15:227–250

Johnson KO, Phillips JR (1981) Tactile spatial-resolution. 1. 2-point discrimination, gap detection, grating resolution, and letter recognition. J Neurophysiol 46:1177–1191

Kalisch T, Tegenthoff M, Dinse HR (2008) Improvement of sensorimotor functions in old age by passive sensory stimulation. Clin Interv Aging 3:673–690

Kerr CE, Shaw JR, Wasserman RH, Chen VW, Kanojia A, Bayer T, Kelley JM (2008) Tactile acuity in experienced tai chi practitioners: evidence for use dependent plasticity as an effect of sensory-attentional training. Exp Brain Res 188:317–322

Kleibel N, Ragert P, Kalisch T, Böhmer G, Tegenthoff M, Dinse HR (2003) Tactile discrimination learning in seniors evidence for reversibility of age-related changes. Soc Neurosci Abs 29(172):14

Li SC, Jordanova M, Lindenberger U (1998) From good senses to good sense: a link between tactile information processing and intelligence. Intelligence 26:99–122

Libouton X, Barbier O, Plaghki L, Thonnard JL (2010) Tactile roughness discrimination threshold is unrelated to tactile spatial acuity. Behav Brain Res 208:473–478

Libouton X, Barbier O, Berger Y, Plaghki L, Thonnard JL (2012) Tactile roughness discrimination of the finger pad relies primarily on vibration sensitive afferents not necessarily located in the hand. Behav Brain Res 229:273–279

Louw S, Kappers AML, Koenderink JJ (2000) Haptic detection thresholds of Gaussian profiles over the whole range of spatial scales. Exp Brain Res 132:369–374

Louw S, Kappers AML, Koenderink JJ (2002) Haptic discrimination of stimuli varying in amplitude and width. Exp Brain Res 146:32–37

Manning H, Tremblay F (2006) Age differences in tactile pattern recognition at the fingertip. Somatosens Mot Res 23:147–155

Montague A (1978) Touching—the human significance of the skin. Harper & Row, New York

Moseley GL, Wiech K (2009) The effect of tactile discrimination training is enhanced when patients watch the reflected image of their unaffected limb during training. Pain 144:314–319

Mountcastle VB (2005) The sensory hand: neural mechanisms of somatic sensation. Harvard College, Boston

Mueller S, Habermann S, Dudda J, Grunwald M (2013) Observation of own exploration movements impairs haptic spatial perception. Exp Brain Res 231(4):415–423

Norrsell U, Eliasson B, Frizell M, Wallin BG, Wesslau C, Olausson H (2001) Tactile directional sensibility and diabetic neuropathy. Muscle Nerv 24:1496–1502

Patton JL, Kovic M, Mussa-Ivaldi FA (2006) Custom-designed haptic training for restoring reaching ability to individuals with post-stroke hemiparesis. J Rehabil Res Dev 43:643–655

Peters RM, Hackeman E, Goldreich D (2009) Diminutive digits discern delicate details: fingertip size and the sex difference in tactile spatial acuity. J Neurosci 29:15756–15761

Ragert P, Schmidt A, Altenmuller E, Dinse HR (2004) Superior tactile performance and learning in professional pianists: evidence for meta-plasticity in musicians. Eur J Neurosci 19:473–478

Ramachandran VS, Rogersramachandran D, Stewart M (1992) Perceptual correlates of massive cortical reorganization. Science 258:1159–1160

Sathian K, Zangaladze A (1997) Tactile learning is task specific but transfers between fingers. Percept Psychophys 59:119–128

Singapogu RB, DuBose S, Long LO, Smith DE, Burg TC, Pagano CC, Burg KJL (2013) Salient haptic skills trainer: initial validation of a novel simulator for training force-based laparoscopic surgical skills. Surg Endosc Other Interv Tech 27:1653–1661

Stankov L, Seizova-Cajiç T, Roberts RD (2001) Tactile and kinesthetic perceptual processes within the taxonomy of human cognitive abilities. Intelligence 29:1–29

Stevens JC, Alvarez-Reeves M, Dipietro L, Mack GW, Green BG (2003) Decline of tactile acuity in aging: a study of body site, blood flow, and lifetime habits of smoking and physical activity. Somatosens Mot Res 20:271–279

Strenze T (2007) Intelligence and socioeconomic success: a meta-analytic review of longitudinal research. Intelligence 35:401–426

Vanboven RW, Johnson KO (1994) The limit of tactile spatial-resolution in humans—grating orientation discrimination at the lip, tongue, and finger. Neurology 44:2361–2366

Vrethem M, Boivie J, Arnqvist H, Holmgren H, Lindstrom T (2002) Painful polyneuropathy in patients with and without diabetes: clinical, neurophysiologic, and quantitative sensory characteristics. Clin J Pain 18:122–127

Wong M, Peters RM, Goldreich D (2013) A physical constraint on perceptual learning: tactile spatial acuity improves with training to a limit set by finger size. J Neurosci 33:9345–9352

Yang TT, Gallen CC, Ramachandran VS, Cobb S, Schwartz BJ, Bloom FE (1994) Noninvasive detection of cerebral plasticity in adult human somatosensory cortex. NeuroReport 5:701–704