Erschien zuerst in: Biological psychology 63 (2003), S. 117-127, im Verlag Elsevier

Blind Braille readers mislocate tactile stimuli

Annette Sterr [a,b,*], Lisa Green [c], Thomas Elbert [c]

[a] *Department of Psychology, University of Liverpool, Eleanor Rathbone Building, Bedford Street South, Liverpool L69 7ZA, UK*
[b] *Center for Child and Adolescent Psychiatry, University of Zürich, Zürich, Switzerland*
[c] *Department of Psychology, University of Konstanz, Konstanz, Germany*

Received 3 October 2002; accepted 25 January 2003

Abstract

In a previous experiment, we observed that blind Braille readers produce errors when asked to identify on which finger of one hand a light tactile stimulus had occurred. With the present study, we aimed to specify the characteristics of this perceptual error in blind and sighted participants. The experiment confirmed that blind Braille readers mislocalised tactile stimuli more often than sighted controls, and that the localisation errors occurred significantly more often at the right reading hand than at the non-reading hand. Most importantly, we discovered that the reading fingers showed the smallest error frequency, but the highest rate of stimulus attribution. The dissociation of perceiving and locating tactile stimuli in the blind suggests altered tactile information processing. Neuroplasticity, changes in tactile attention mechanisms as well as the idea that blind persons may employ different strategies for tactile exploration and object localisation are discussed as possible explanations for the results obtained.

Keywords: Touch; Tactile perception; Somatosensory; Spatial discrimination

1. Introduction

Braille reading is an impressive example of a specialised perceptual capability of the tactile sense. For Braille-naive persons, distinguishing different Braille characters is very difficult and slow and it takes intensive training to achieve a modest level of

---

* Corresponding author. Tel.: +44-151-794-6708; fax: +44-151-794-2945.
E-mail address: asterr@liverpool.ac.uk (A. Sterr).

reading ability, while highly experienced Braille readers can read up to 200 words per min (Foulke, 1991). Thus, the question arises as to how the functional specialisation in the tactile modality is achieved. We addressed this issue in a previous experiment by measuring the functional organisation of the hand representations in the primary somatosensory cortex (area 3b), and the tactile perception threshold for passive touch in professional Braille readers (Sterr et al., 1998a,b). During the assessment of the tactile perception threshold, we observed that some Braille readers tended to attribute tactile stimuli to a non-stimulated finger at the same hand, a phenomenon we called ‘tactile mislocalisations’. In this setup, participants were asked to tell on which finger the tactile stimulus, which could occur on either fingertip of one hand, was felt.

With the present experiment, we aimed to further explore the characteristics of this perceptual phenomenon. In particular, we asked whether these localisation errors were equally common on all fingers (distribution of errors), and to which fingers the misperception was attributed, i.e. on which finger the participant perceived the touch when the stimulation had indeed occurred at another finger. Ten non-professional blind Braille readers and ten age-matched Braille-naïve sighted controls were tested using Semmes–Weinstein Monofilaments (SWMF). The experiment aimed to answer the following questions (1) can we replicate the finding that tactile mislocalisations occur more often in the blind than in the sighted, (2) are tactile mislocalisations related to Braille reading, i.e. do they occur more often at the reading hand, (3) how are the errors distributed, i.e. are some fingers more often subject to the localisation error than others, and (4) which fingers ‘attract’ the perception of the stimuli that are not correctly located.

2. Methods

Ten (five female, five male) blind Braille readers and ten (five female, five male) sighted non-Braille reading control subjects, matched for age and gender, participated in the study. Financial compensation was awarded for participation.

Braille readers were aged 25–56 years (group mean: 44.5 years, mean females 40.2 years, mean males 48.8 years; nine right hand dominant (Edinburgh Handedness Inventory, Oldfield, 1971). Blindness was due to peripheral damage or disease of the visual system. Nine subjects had been blind or severely visually impaired since birth. If residual vision was present during childhood, the visual capabilities had progressively decreased to full blindness by early adulthood. The tenth subject lost sight at age 30. A detailed description of blind participants is given in Table 1.

Seven subjects had learned to read Braille in childhood, and three as adults (at ages 30, 26, and 20). All were fluent Braille readers for at least 4 years prior to testing. The right index finger was identified as the main reading finger, and most subjects (8/10) simultaneously engaged the middle finger in the reading process as a “guide”. Braille was employed for everyday purposes and used for 0.5–3.5 h/day (participants’ retrospective estimation of average reading time).

Table 1
Personal details of blind participants

Ss	Age at test	Visual impairment and cause
#B1	26	Congenitally blind; no light perception; optical neuropathy (morbus leber)
#B2	34	Fully blind since age 30; no light perception; transection of optical and olfactory nerve during accident (no further neurological problems)
#B3	37	Fully blind since age 1, no light perception; bilateral retina ablation at age 1(to treat retinal cancer)
#B4	48	Fully blind since age 19; minimal light perception (can discriminate bright light from darkness); primary congenial glaucoma with progressive deterioration; ability to read enlarged print until age 10
#B5	56	Fully blind since age 25, no light perception; primary congenial glaucoma with progressive deterioration; ability to read enlarged print until age 18
#B6	41	Fully blind since age 19, no light perception; primary congenial glaucoma with progressive deterioration; ability to read enlarged print until age 12
#B7	43	Congenitally blind; no light perception; retinapathy of prematurity
#B8	50	Fully blind since age 8; no light perception; progressive retinapathy
#B9	54	Fully blind since age 10; no light perception; progressive retinapathy
#B10	56	Fully blind since age 10; no light perception; sports accident

Summary of visual impairment and its cause for each individual.

The control group consisted of ten sighted Braille-naïve matched participants (mean age 44.0 years, range 25–53 years; mean females 40.4 years, mean males 47.6 years; nine right-handed). Exclusion criteria comprised (1) playing an instrument and (2) any report of sensitivity disturbance or neurological disorder. We refrained from using sighted Braille readers as a control group, since these persons tend to visually discriminate the dot-pattern instead of tactually reading the language.

Blind subjects were recruited via several institutions for the Blind in the vicinity of San Diego, California, CA and contacted by phone. Suitability for the study was based on the following inclusion criteria: (1) using Braille for everyday purposes, (2) blindness due to peripheral cause, and (3) no neurological damage or illness. A semi-structured interview was used to assess the individual reading habit. Control subjects were recruited via advertisements on University notice boards. For blind participants, the informed consent agreement as well as the patient information sheet were read out. The study was approved by the Ethic Committee of the University of California at San Diego.

The sensory testing employed SWMF (Model #16010, Lafayette Instruments Co., Indiana, USA) and comprised (1) the determination of the tactile perception threshold for each finger tip and (2) the localisation task. Participants could not see their hands when tested.

Testing was carried out with the subject's hand resting palm upward on the testing table. Stimulation was applied to the mid-volar surface of the distal phalanges (exact point of stimulation was marked by a little dot) and followed a pseudo-randomised sequence involving all five fingers. The order of left and right hand testing was counterbalanced across subjects. Test instructions were given verbally (to avoid Braille reading in the Blind prior to testing).

The tactile perception thresholds consisted of two experimental blocks, each assigned to determine the thresholds for the fingers of one hand. The tactile perception threshold was determined for ascending and descending presentation with six stimulus intensities ($\log^{10}$ force/g required to bow the monofilament: 0.008, 0.015, 0.036, 0.8, 0.172, 0.217) using the methods of limits. The threshold was defined as the cross-over value for the lowest monofilament strength that could be felt for a particular finger (correctness of named finger was not taken into account). In no instance did the finger-specific thresholds differ more than one monofilament strength.

The localisation task consisted of four trials using consecutive monofilaments, "−1" (one stimulus strength below threshold), "0" (threshold strength) and "+1" and "+2" (one and two steps above threshold stimulus strength, respectively). If the cross-over threshold value was between to SWMF intensities, the higher hair was used as threshold strength for the localisation task. Subjects chose the method of specifying the finger that felt most comfortable and natural for them: either naming the finger or referring to them by number 'first" (thumb)–'fifth' (little finger). The monofilaments were applied in decreasing order beginning with monofilament strength +2 to give subjects practice naming their fingers with a stimulus that was clearly perceivable. This ensured that any errors in identifying the stimulated finger that occurred at or around threshold monofilament strengths were not due to difficulties in naming fingers. For each stimulus strength, a sequence of 25 stimuli was presented to the fingertips following a fixed irregular order. On a response sheet we recorded (1) whether the stimulus was reported (+, −), and if reported (2) the finger physically stimulated, and (3) the finger named. For statistical analysis, the raw data obtained with each stimulus strength were collated.

A three way repeated measurement ANOVA model (group factor (blind/control) and repeated measurements factors HAND (right/left) and FINGER (thumb, index, middle-, fourth-, fifth-finger)) was used to determine group differences. The Greenhouse–Geisser algorithm was used to correct for sphericity. P-values displayed refer to corrected values and the epsilon correction factor is provided where appropriate. Further analysis was conducted in those participants who exhibited mislocalisations with respect to the distribution of errors and the attribution of misperceived stimuli.

3. Results

No significant differences for the tactile perception threshold measure were found between blind Braille readers and sighted controls ($F_{(1,18)} < 1$). In both groups, the tactile perception thresholds of the left hand fingers were lower than those for the right hand (main effect hand $F_{(1,18)} = 12.1$; $P < 0.05$). Furthermore, in both groups and for both hands, the thumb was found to be less sensitive than the other fingers (main effect finger $F_{(4,72)} = 4.2$; $P = 0.02$ (GG; $\varepsilon = 0.059$).

In the localisation task, all but one sighted subject localised the tactile stimuli correctly, i.e. if subjects were able to perceive the stimulus, they correctly identified the finger stimulated. This observation applied for right as well as left hand stimulation. In one sighted participant, localisation errors occurred when fingers of the left hand were stimulated while all stimuli presented at the right hand were localised correctly. In contrast to all blind mislocalisers, the sighted subject produced localisation errors at all four consecutive stimulus intensities employed in the task.

In the blind group, three participants were able to correctly localise the tactile stimuli. Seven participants (mislocalisers) made localising errors when fingers of the right hand were stimulated. In no instances were left hand stimuli mislocalised at right-hand locations or vice versa. We further found that 71.4% of the incorrect responses occurred at threshold stimulus intensity only (strength “0”), and in 28.6% at two consecutive stimulus intensities (strengths “0” and strength “+1”). In all cases, all fingers were named correctly when the “2” stimulus intensity was used.

Statistical analysis of the correct responses revealed that the average proportion of correctly localised stimuli was significantly lower for the right hand in the blind than the sighted (main effect group: $F_{(1,18)} = 6.9$; $P < 0.05$; hand × group interaction: $F_{(1,18)} = 5.6$; $P < 0.05$). This effect is depicted in Fig. 1. Post-hoc tests further indicated significant differences for the between-group comparison of right-hand responses (blind vs. sighted: $t = -4.0$; $P < 0.05$), as well as for the within-group comparison in the blind (right vs. left: $t = -3.2$; $P < 0.05$). No significant effects were found for the different fingers.

Further analysis of the data obtained in the blind ‘mislocalisers’ revealed that the relative error frequency (depicted in Fig. 2) was not equally distributed across fingers ($\chi^2_{(4)} = 15.04$; $P < 0.05$), and that localisation errors were less pronounced at the reading fingers (index and middle finger) than the non-reading fingers (Fisher’s r to z: $r = -0.78$; $P < 0.05$).

Further consideration was given to the attribution of errors, i.e. which finger the participants falsely identified as the stimulated one. We found that index and middle finger most often ‘attracted’ the mislocalised stimuli, while the attribution to the thumb as well as the forth and fifth finger occurred less often. This observation was mirrored in a significant main effect for the named fingers (one-way ANOVA:

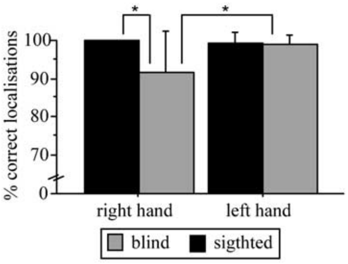

Fig. 1. Illustrates the group × hand interaction for correct responses. Significantly more localisation errors are observed at the right hand of blind participants than in the sighted as well as in the left hand of the blind.

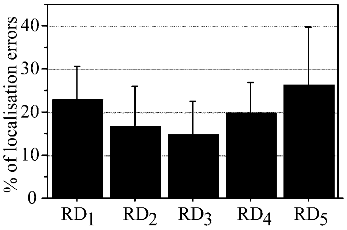

Fig. 2. Depicts distribution of localisation errors across the finger of the right hand in the blind (group mean derived from the seven blind participants in which localisation errors have occurred).

$F_{(6,24)} = 3.1$; $P < 0.05$). Bonferroni/Dunn post-hoc analysis revealed significant contrasts for thumb–index, thumb–middle finger, index–fifth finger, and middle–fifth finger. These effects are illustrated in Fig. 3. Interestingly, the distribution of named fingers is almost the inverse of the distribution of errors.

No systematic variation in the occurrence of mislocalisations was found for age at onset of blindness, age at learning Braille, or average daily reading.

4. Discussion

Previously, we have observed a dissociation between stimulus perception and stimulus location in blind Braille readers, i.e. blind participants do not always identify the location of tactile stimuli correctly. This is a surprising observation, not only because it contradicts the intuitive expectation of enhanced tactile perception in the blind, but in particular, because the task involved a rather coarse identification of stimulus location, i.e. one of five fingertips of the hand. Apparently, mislocalisations in the blind have not been reported in the literature. Furthermore, our previous experiment only tested whether persons produced mislocalisations or not, but no data was collected on either the frequency of mislocalisations, their distribution across the different fingers, or the attribution of mislocalised stimuli towards other fingers. Therefore, the present experiment aimed to characterise the fundamental features of this perceptual phenomenon. Overall, the results confirm that blind subjects have more difficulty in identifying the finger to which a light tactile stimulus

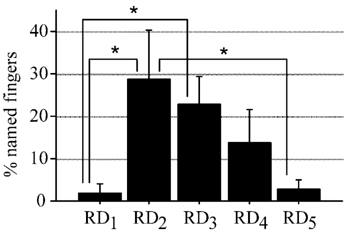

Fig. 3. Depicts the relative frequency of attributed stimuli for each finger, i.e. at which finger the incorrectly localised stimulus is perceived.

is administered than sighted subjects. We found that in 70% of the blind participants, the touch was clearly felt but not attributed to the actually stimulated finger. To this end, the study confirms our previous finding that the ability to perceive and locate a weak tactile stimulus is often dissociated in the blind. With respect to the sensory threshold, however, we could not confirm our previous finding that sensory thresholds are significantly lower in the blind (Sterr et al., 1998b). This is despite the fact that identical methods for threshold determination were used in both experiments. The existing literature on tactile thresholds is equally contradictive (Weinstein, 1968; Heinrich and Moorhouse, 1969; Liddle, 1969; Lindblom and Lindström, 1976; Warren, 1978; Bernard, 1979; Niemeyer and Starling, 1981; Bross and Borenstein, 1982; Hollins, 1989; Muchnik et al., 1991; Stevens et al., 1996), and we, therefore, conclude that neither visual deprivation nor Braille reading or the combination of both conditions is coupled with a substantial decrease of tactile perception thresholds.

Further investigation of the localisation errors in the blind revealed that the great majority occurred at the right (reading) hand, and that mislocalisations affected all fingers. However, the reading fingers were found to be less prone to mislocalisations than the non-reading fingers, while, at the same time, the reading fingers attracted most of the misperceived stimuli. Blindness and Braille reading were confounded variables and in principle, both factors could equally account for the group differences. However, the fact that mislocalisations are significantly more common on the reading hand suggests that mislocalisations are related to Braille reading rather than the loss of the visual sense.

Recent research on use-related changes of primary representations provides one possible explanation for the occurrence of mislocalisations. Tactile reading places a much greater demand on the somatosensory and motor areas involved in hand control than under average use conditions. This is reflected in altered representational arrangements in sensory and motor areas of blind Braille readers. For instance, transcranial magnetic stimulation (TMS) studies revealed expanded motor output maps of the first dorsal interosseous and the abductor digiti minimi at the reading hand of blind Braille readers (Pascual-Leone and Torres, 1993a; Pascual-Leone et al., 1993b). In our own studies, we found evidence for enlarged hand representations in area 3b of the primary somatosensory cortex in professional blind Braille readers (Sterr et al., 1998a,b). Such expansion in response to Braille reading seems not to be restricted to the blind but can also be observed in sighted subjects who have practised tactile reading (Rockstroh et al., 2000). In sum, neuroplasticity studies suggest that the increased sensory input provided by Braille reading changes the neural networks underlying the representations in primary sensorimotor areas. Furthermore, there is initial evidence that tactile mislocalisations may be related to functional reorganisation of primary representations. In our previous experiments we found that three-finger Braille readers who displayed tactile mislocalisations also featured a topographical disarrangement of finger representations in area 3b. These results led to the hypothesis that Braille reading leads to enlarged finger representations with greater overlap of the respective neural networks. Therefore, the ability to locate stimuli correctly is diminished when signal-to-noise is low, and thus errors occur. This idea is further supported by a recent study (Braun et al., 2000) involving high-density EEG recordings. Sighted subjects were trained on a tactile discrimination task, which involved simultaneous stimulation of thumb and little finger, for several weeks. Following the training, digit representations had expanded, and there was evidence for increased overlap of the neural networks forming the digit representations. At the same time, localisation errors were observed in this group. Transient differentiation studies (e.g. Buchner et al., 1995; Biermann et al., 1998) further indicate a much greater connectivity within the hand area than mapping experiments in the awake monkey suggest (Clark et al., 1988; Wang et al., 1995). In the light of these findings, we propose that Braille reading not only leads to an enlargement of reading finger representations, but, at the same time, strengthens the connections to more distant regions in the hand area by means of Hebbian mechanisms. As a consequence, the neural network activated by a weak tactile stimulus is less circumscribed in the blind than in the sighted, which, under low signal-to-noise conditions, leads to localisation errors. At higher stimulus intensities signal-to-noise ratio increases, and thus the output of the activated network is more precise and no errors are observed. Since the reading-finger representations dominate the hand area in the blind, localisation errors at these fingers occur least often while, at the same time, incorrectly localised stimuli are most often attributed to these fingers.

An alternative explanation involves the idea that stimuli presented at the reading finger automatically attract attention, which in turn leads to an anchorage effect. Anchorage effects describe a characteristic feature of tactile perception in normal controls. For example, stimuli presented to the middle of the volar forearm tend to be localised considerably towards the wrist; and points near the elbow tend to be perceived at the elbow (Pillsbury, 1895; Parrish, 1897). These displacements, or migrations, have been explained by the idea that the skin is organised into regions of anchorage, which provide frames of reference; attention is always focused on the region in which the stimuli occur, and thus the anchor points. Consequently, stimuli to remoter regions in the frame of reference tend to ‘migrate’ towards the anchor (Lewy, 1895). Following this line of argumentation, one could propose that the reading finger in the blind ‘automatically’ attracts attention when stimuli are presented to the hand, and thus forms the Center of the reference frame. This could explain why, in the present study the least number of localisation, but the highest number of false attributions were observed at the right index and middle finger. The idea that the attentional focus influences tactile perception is further supported by a more recent study in upper-limb amputees (Moore et al., 1999), which suggests that the increase in sensory acuity in the region close to the stump is to do with greater attentional focusing within this region (‘cortical focusing’). Event-related potential data from our own laboratory further indicates that tactile attention mechanisms are greatly enhanced in the blind. Thus, the anchorage model provides a plausible alternative explanation for the distribution of tactile mislocalisations across the hand. But it can not easily explain why mislocalisations occur in the first place.

At first glance, the tactile mislocalisations in the blind may appear as a large-scale error-of-localisation, which again is a typical feature of tactile perception in controls

(Boring, 1942, for review). However, this appears unlikely when one considers the main characteristics of the error-of-localisation phenomenon: (1) it is proportional to the two-point limen, i.e. it varies for different body regions, (2) it is always smaller than the radius of the two-point limen for the given body region, and (3) it decreases when visual imagery is allowed and is smallest for full visual input. For the fingertips the error-of-localisation is 1.1 mm for sighted persons, furthermore the error typically does not spread across a knuckle or to a neighbouring finger (Weber, 1852). The tactile mislocalisations observed in the present study circumscribed a minimal error distance of at least one centimetre (i.e. when the neighbouring finger was falsely named), and thus are ten times larger than the error-of-localisation known for the fingertips in the sighted. Furthermore, it remains to be explained why the typical proportional relationship with the two-point limen is resolved, and, taking the unilaterality of the mislocalisation phenomenon into account, this only happens for the right hand. Therefore, we would argue that the mislocalisations observed in the present study do not simply represent an enhanced error-of-localisation.

A further issue of consideration relates to the idea that blind persons might employ different strategies, including different detection criteria for tactile exploration and object localisation, than the sighted. For example, one could argue that sighted individuals can afford a more conservative criterion for discriminating tactile stimuli, because vision can be used in case of ambiguous tactile input. Blind individuals on the other hand, have to rely more on somatosensory input (but not exclusively because audition provides an additional source of information) for object location, which may lead to a less strict decision criteria. It appears plausible to assume that strategies, such as the detection criteria, represent higher cognitive operations that are equally relevant for both extremities. Consequently, the strategy-model would predict that mislocalisations are equally likely on both hands. However, the present study revealed a highly significant lateralisation effect, which contradicts the principle assumption of the strategy model. Even though we can not rule out the relevance of changed strategies in the blind as a possible explanation for the occurrence of mislocalisations, it is not exhaustive by itself and further assumptions have to be made in order to fully explain the observations made in the present experiment.

We, therefore, conclude that the neuroplasticity hypothesis discussed above provides the most plausible explanation of the data obtained in the present study. Furthermore, attention mechanisms appear to influence tactile perception, possibly by means of top–down processes, which modulate information processing in primary sensory regions. Future experiments will need to combine psychophysical and imaging techniques, in order to specify the relationship between primary cortical representations and attention, and their role in tactile localisation perception.

Acknowledgements

The study was supported by the German Research Foundation and the Royal Society, UK. We are grateful to the staff members of the San Diego Center for the

Blind, CA, the Braille Institute La Jolla, CA and the American Association for the Blind for assistance in participant recruitment and valuable advice. We further wish to thank Chantal Hayward for editorial assistance.

References

Bernard, J., 1979. Simple auditory reaction time in blind and sighted controls. Perceptual and Motor Skills 48, 465–466.

Biermann, K., Schmitz, F., et al., 1998. Interaction of finger representation in the human first somatosensory cortex: a neuromagnetic study. Neuroscience Letters 251, 13–16.

Boring, E.G., 1942. Tactual sensibility. In: Boring, E.G. (Ed.), Sensation and Perception in the History of Experimental Psychology. D. Appleton-Century Company, New York, pp. 463–513.

Braun, C., Schweizer, R., et al., 2000. Differential activation in somatosensory cortex for different discrimination tasks. Journal of Neuroscience 20, 446–450.

Bross, M., Borenstein, M., 1982. Temporal auditory acuity in blind and sighted subjects. Perceptual and Motor Skills 55, 963–966.

Buchner, H., Kauert, C., et al., 1995. Short-term changes of finger representation at the somatosensory cortex in humans. Neuroscience Letters 198, 57–59.

Clark, S.A., Allard, T., et al., 1988. Receptive fields in the body-surface map in adult cortex defined by temporally correlated inputs. Nature 332, 444–445.

Foulke, E., 1991. Braille. In: Heller, M.A., Schiff, W. (Eds.), The Psychology of Touch. Lawrence Erlbaum Associated Publishers, Hillsdale, NS, USA, pp. 219–233.

Heinrich, R.W., Moorhouse, J.A., 1969. Touch perception thresholds in blind diabetic subjects in relation to the reading of Braille type. New England Journal of Medicine 280, 72–75.

Hollins, M., 1989. Understanding Blindness. Lawrence Erlbaum Associated Publishers, Hillsdale, NI, USA.

Lewy, W., 1895. Experimentelle Untersuchungen ueber das Gedaechtnis. Zeitschrift fuer Experimentelle Psychologie 8, 231–292.

Liddle, D., 1969. The effects of signal strength on reaction times to auditory signals in noise. American Foundation for the Blind, Research Bulletin 19, 129–190.

Lindblom, U., Lindström, B., 1976. Tactile thresholds of normal and blind subjects on stimulation of finger pads with short mechanical pulses. In: Zotterman, Y. (Ed.), Sensory functions of the skin in primates, with special reference to man. Pergamon, Oxford, pp. 105–112.

Moore, C.E.G., Partner, A., et al., 1999. Cortical focusing is an alternative explanation for improved sensory acuity on an amputation stump. Neuroscience Letters 270, 185–187.

Muchnik, C., Efrati, M., et al., 1991. Central auditory skills in blind and sighted subjects. Scandinavian Audiology 20 (1), 19–23.

Niemeyer, W., Starling, I., 1981. Do blind hear better? Investigations on auditory processing in congenital or early acquired blindness. Audiology 20, 510–515.

Oldfield, R.C., 1971. The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia 9 (1), 97–113.

Parrish, C.S., 1897. Localization of cutaneous impressions by arm movement without pressure upon the skin. Neuropsychologia 8, 250–267.

Pascual-Leone, A., Torres, F., 1993a. Plasticity of the sensorimotor cortex representation of the reading finger in Braille readers. Brain 1160, 39–52.

Pascual-Leone, A., Cammarota, A., et al., 1993b. Modulation of motor cortical outputs to the reading hand of braille readers. Annals of Neurology 34, 33–37.

Pillsbury, W.B., 1895. Some questions of cutaneous sensibility. American Journal of Psychology 7, 42–57.

Extensive somatosensory stimulation alters somatosensory evoked fields.Rockstroh, B., Vanni, S., et al. (Eds.), Advances in Biomagnetism Research: Biomag 96 International Conference on Biomagnetism. Springer, New York 2000.

Sterr, A., Müller, M., et al., 1998a. Changed perception in Braille-Readers. Nature 381, 134–135.

Sterr, A., Müller, M., et al., 1998b. Perceptual correlates of changes in cortical representations of fingers in blind multi-finger readers. The Journal of Neuroscience 18, 4417–4423.

Stevens, J.C., Foulke, E., et al., 1996. Tactile acuity, aging, and Braille reading in long-term blindness. Journal of Experimental Psychology: Applied 2 (2), 91–106.

Wang, X., Merzenich, M.M., et al., 1995. Remodelling of hand representation in adult cortex determined by timing of tactile stimulation. Nature 378, 71–75.

Warren, D.H., 1978. Perception in the Blind. In: Carterette, E.C., Friedman, M.P. (Eds.), Handbook of Perception, vol. 10. Academic Press, New York, pp. 65–90.

Weber, E.H., 1852. Ueber den Raumsinn und die Empfindungskreise in der Haut und im Auge. Beerichte der saechsischen Gesellschaft der Wissenschaften, mathematisch-physicalische Clausur, Vol. 78, 85–164.

Weinstein, S., 1968. Intensive and extensive aspects of tactile sensitivity as a function of body part, sex, and laterality. In: Kenshalo, D.R. (Ed.), The Skin Senses. Charles C. Thomas, Springfield, IL, pp. 195–222.