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Perceptual Learning: Tactile Letter Recognition Transfers Across Body Surfaces

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Abstract

Visual-to-tactile sensory substitution devices are designed to assist visually impaired people by converting visual stimuli into tactile stimuli. The important claim has been made that, after training with these devices, the tactile stimuli can be moved from one body surface to another without any decrease in performance. This claim, although recurrent, has never been empirically investigated. Moreover, studies in the field of tactile perceptual learning suggest that performance improvement transfers only to body surfaces that are closely represented in the somatosensory cortex, i.e. adjacent or homologous contralateral body surfaces. These studies have however mainly used discrimination tasks of stimuli varying along only one feature (e.g., orientation of gratings) whereas, in sensory substitution, tactile information consists of more complex stimuli. The present study investigated the extent to which there is a transfer of tactile letter learning. Participants first underwent a baseline session in which the letters were presented on their belly, thigh, and shin. They were subsequently trained on only one of these body surfaces, and then re-tested on all of them, as a post-training session. The results revealed that performance improvement was the same for both the trained and the untrained surfaces. Moreover, this transfer of perceptual learning was equivalent for adjacent and non-adjacent body surfaces, suggesting that tactile learning transfer occurs independently of the distance on the body. A control study consisting of the same baseline and post-training sessions, without training in between, revealed weaker improvement between the two sessions. The obtained results support the claim that training with sensory substitution devices results in a relative independence from the stimulated body surface.

Keywords

Perceptual learning, touch, sensory substitution, generalization, tactile letter recognition

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1. Introduction

Sensory substitution devices convert stimuli that are normally accessed through one sensory modality (e.g., vision) into stimuli accessible through another sensory modality (e.g., touch or audition). Among them, visual-to-tactile and visual-to-auditory conversion systems were designed to assist blind and visually impaired people by converting visual stimuli into tactile or auditory stimuli.

The first sensory substitution device was the tactile-vision sensory substitution (TVSS) developed by Bach-y-Rita and colleagues (Bach-y-Rita *et al.*, 1969; see also Bach-y-Rita and Kercel, 2003, for a review). The TVSS comprises a camera, a translation system, and a matrix of tactile stimulators (that provides electrical or vibratory stimulation) placed on a body surface such as the back or the tongue (see Bach-y-Rita and Kercel, 2003, for a description). The principles of sensory substitution have been extended to the conversion of visual images into sounds. This led to the design of visual-to-auditory devices such as the vOICe (Meijer, 1992), the prosthesis for substitution of vision by audition (PVSA, see Capelle *et al.*, 1998), and the Vibe (Hanneton *et al.*, 2010).

Since their invention, a variety of devices have been designed and tested across a variety of tasks (see Auvray and Myin, 2009; Bubic *et al.*, 2010; Deroy and Auvray, 2012, for reviews). In particular, studies have revealed that these devices allow their users to perform localization tasks (Jansson, 1983; Levy-Tzedek *et al.*, 2012; Renier *et al.*, 2005) and simple as well as complex shape recognition (Arno *et al.*, 2001; Auvray *et al.*, 2007; Pollok *et al.*, 2005; Sampaio *et al.*, 2001). A defining feature of perception with sensory substitution devices is that extensive training is required. Most users are able, in one or two hours, to explore their environment and to approximate objects' position and shape. However, the training required to obtain more precise object localization and recognition behaviour is estimated at around eight hours with visual-to-tactile devices (Kaczmarek and Haase, 2003) and 10 to 15 with visual-to-auditory devices (Auvray *et al.*, 2007). Perceptual acuity (measured with the Snellen tumbling E test) has also been reported to increase with training, reaching for instance 20/430 after nine hours of training with the Tongue Display Unit (Sampaio *et al.*, 2001; see also Haigh *et al.*, 2013, for a similar study with the vOICe).

One important claim of Bach-y-Rita is that, once trained, TVSS-users no longer feel the stimulation on their skin, where it occurs, but they directly attribute the stimulation as resulting from an external object, i.e. located at a distance (Bach-y-Rita, 1995, p. 181; Bach-y-Rita and Kercel, 2003, p. 543). Furthermore, Bach-y-Rita asserted that, consequent to this externalization process, the tactile stimulator array can be moved from one body surface to another (e.g., from the back to the abdomen or to the forehead), without loss in spatial localization abilities or other perceptual capacities (see Note 1) (such as depth estimates). However, this claim was based solely on users' verbal reports and it has never been experimentally investigated.

One way to investigate if perceptual abilities in trained users of visual-to-tactile sensory substitution devices depend on the stimulated surface or not, is to study the extent to which there is a transfer of tactile learning across body surfaces. If indeed what is learned on a given body surface can be transferred to another one without loss in performance, this would provide reasons to believe that Bach-y-Rita's claim of independence from the stimulated body surface is correct. Perceptual learning is defined as performance improvement in perceptual tasks resulting from training (Fahle and Poggio, 2002; Gibson, 1969). In tactile perceptual learning, the question of the specificity (i.e., learning is body-surface dependent) *versus* generalization (i.e., there is a transfer of performance improvement from a trained to an untrained body surface) is still debated. Some studies reported a transfer to untrained body surfaces (Harrar *et al.*, 2014; Harris *et al.*, 2001; Kaas *et al.*, 2013; Nagarajan *et al.*, 1998; Sathian and Zangaladze, 1997; Spengler *et al.*, 1997) whereas other studies did not find evidence of such transfer (Dinse *et al.*, 2006; Godde *et al.*, 2000). In addition, when transfer has been reported, it was restricted to adjacent and homologous contralateral body surfaces only (e.g., adjacent fingers of the same hand and same fingers of the untrained hand — Harrar *et al.*, 2014; Harris *et al.*, 2001). In other words, transfer to non-adjacent and non-homologous body surfaces has never been reported. The extent to which there is a transfer of tactile learning therefore appears to be related to the topographic organization of the somatosensory cortex.

There is thus an apparent contradiction between this reported limit to the transfer of tactile learning (i.e., restricted to adjacent and homologous body surfaces) and the post-training independence from the stimulated body surface (i.e., occurring even in non-adjacent surfaces such as the back and the abdomen), as claimed by Bach-y-Rita. One hypothesis to account for such a discrepancy is that the discrimination tasks used in tactile learning studies involved low-level stimuli that mainly vary along only one feature (e.g., gratings with different orientations), whereas reports in the field of sensory substitution were based on more complex objects consisting of combinations of different features. Discrimination of low-level stimuli may involve somatosensory areas with a topographic representation of body surfaces. In these areas, receptive fields are narrow and overlap only with receptive fields of adjacent or contralateral homologous body surfaces (for instance, see Iwamura *et al.*, 1994, for the topographic organization of the hands). On the other hand, sensory substitution devices are mainly used to convey tactile information resulting from higher-level stimuli such as objects, faces, and scenes. These high-level stimuli involve less topographically organized areas in which receptive fields are large and not restricted to a specific body surface. Moreover, according to the reverse hierarchy theory (Ahissar and Hochstein, 2004), perceptual learning begins at higher cortical levels and continues at lower levels of processing dependent on the feature learnt. As a result, tactile learning of high-level stimuli should transfer more easily to different body surfaces than low-level stimulus features.

The study reported here aims at investigating the extent to which there is a transfer of tactile learning in the recognition of high-level symbols (i.e., made of the combinations of several features rather than consisting of single features). To do so, a tactile letter recognition task was used. Letters were drawn on the participants' body by means of sequential vibrotactile stimulations (see Yanagida *et al.*, 2004, for a similar method). In order to evaluate learning effects rather than mere repeated exposure effects, we measured recognition performance before and after training, as in Harrar *et al.*'s (2014) study. The participants first completed a baseline session in which they had to recognize tactile letters drawn on three different body surfaces: the belly, the front of the right thigh, and the right shin (see Fig. 1 below). They then underwent a training session in which the letters had to be recognized on only one of the three above-mentioned body surfaces. Finally, the participants performed a post-training session on all three body surfaces. The amount of tactile learning was evaluated by computing performance improvement (both accuracy and response times) between the baseline and the post-training sessions. If there is a transfer of tactile learning from a trained to an untrained body surface, then the amount of performance improvement should be similar for trained and untrained surfaces. On the other hand, if tactile learning is specific to a given body surface, then performance improvement should be greater for trained than for untrained body surfaces. In addition, a control group of participants performed the baseline and post-training sessions, but without the training session in between. For these participants, performance is expected to be either similar between the two sessions, or to improve in the second one but less than for the participants in the trained group.

It should be mentioned that the belly, the thigh and the shin are represented in adjacent areas of the somatosensory cortex (Merzenich *et al.*, 1978; Nakamura *et al.*, 1998). Thus, performance improvement, computed as a function of the trained body surface, allows behaviourally evaluating the topographic organization of areas in which tactile learning of high-level symbols occurs. If tactile learning occurs in non-topographic areas, the amount of improvement should not depend on the trained body surface. On the other hand, if tactile learning occurs in topographic areas, the amount of improvement should be greater for two adjacent body surfaces (e.g., the belly and the thigh) than for two non-adjacent ones (e.g., the belly and the shin).

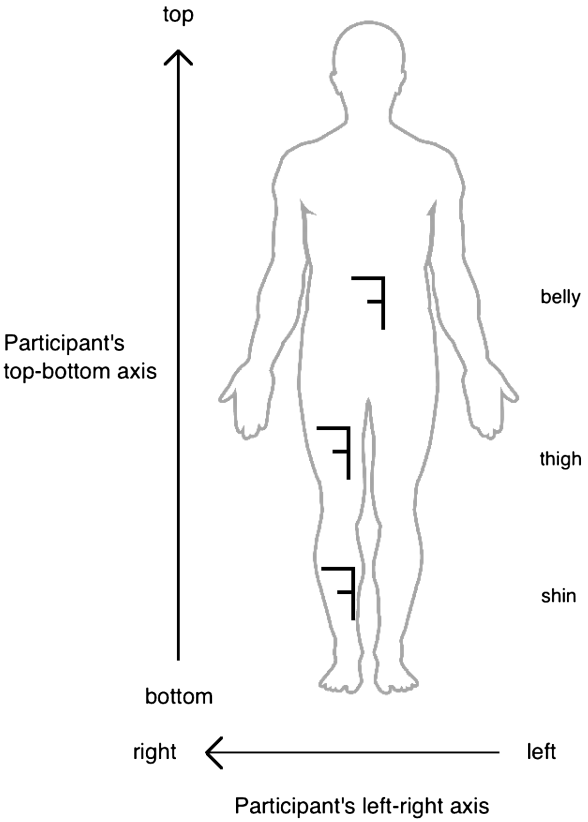

Figure 1. Example of the letter F drawn on the three body surfaces (belly, thigh, and shin). The letters' left-right and top-bottom axes were always congruent to the participants' left-right and top-bottom axes.

2. Methods

2.1. Participants

Forty-five participants completed the experiment (26 females and 19 males; mean age = 25.7 years, range = 18–47 years). Thirty participants were included in the trained group and 15 in the control group. All the participants were naïve to the purpose of the experiment. They provided their informed consent and received payment for their participation. The experiment took approximately one hour and a half to complete (one hour for the control group) and was performed in accordance with the ethical standards laid down in the Declaration of Helsinki (1991).

It should be mentioned that there was a selection process used to determine if participants were included in the study. Given that tactile letters drawn on the skin can be interpreted within different reference frames (see Parsons and

Shimojo, 1987; Sekiyama, 1991), each participant's preferred reference frame was identified prior to the start of the experiment. This was done by means of a task requiring the participants to recognize the tactile letters b, d, p, and q. Recognizing these ambiguous asymmetrical letters requires assigning the top-bottom and left-right axes to the letters, and the reference frame that was adopted can be determined from how the stimulus is interpreted. Only the participants that freely assigned the top-bottom and left-right axes congruently to their body's axes were selected for participation in the study. The letters were then drawn consistently to these body-congruent assignments during the rest of the experiment (see Fig. 1). The reason for this choice is that — as the aim of the study was not to investigate the influence of reference frame on tactile learning — we wanted to avoid any interference due to differences in the reference frames that are freely adopted. We consequently chose the most frequently adopted one among the four possible reference frames. This reference frame with body-congruent assignments of axes was adopted by 52% of participants across all the experiments that were conducted in our laboratory ($N = 244$). Note that 28% of participants reversed the top-bottom axis, while the left-right axis was consistent with the body. A further 20% of participants reversed the left-right axis, while the top-bottom axis was consistent with the body. No participants reversed both the vertical and horizontal axes.

2.2. Apparatus

The tactile stimuli were presented by means of nine rectangular vibrators (Haptuator Mark II, Tactile Labs, Montreal, Canada) arranged in a three-by-three array with a centre-to-centre spacing of 5 cm (see Fig. 2A). The surface area of each vibrator was 0.9 cm vertically by 3.2 cm horizontally. The vibrator array was placed on the participants' body surface, above their clothes, by means of an elastic belt. When the participants were tested on the belly, the vibrator array was placed symmetrically to their body mid-sagittal line

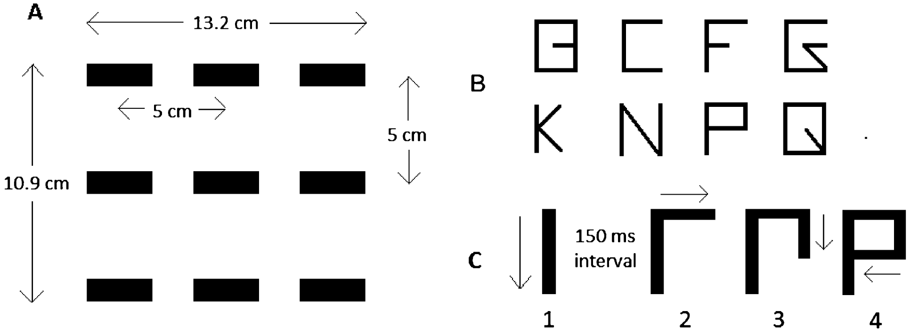

Figure 2. (A) Schematic figure illustrating the 3 × 3 array of rectangular vibrators. (B) The 8 letters used as tactile stimuli. (C) The sequence of vibrations chosen for drawing the letter P.

(see Fig. 1). In this case, the three lower tactors were located above the waist. When they were tested on the front of the thigh and on the shin, the vibrator array was both horizontally and vertically centred. The position of the vibrator array on each body surface was exactly the same between the baseline and the post-training sessions; this was achieved by means of stickers indicating the positions of the vibrators.

A nine-channel amplifier drove each vibrator independently at a 250 Hz frequency. The intensity of each vibrator was individually selected with an adjustment method at the beginning of each session. Specifically, the participants were instructed to adjust the vibration intensity until each vibrotactile stimulus could be perceived clearly and with the same felt intensity. The activation of the vibrators was controlled through a PC running custom software written in MATLAB R2008a. Instructions and feedback were presented on a 23-inch screen with a 1920 × 1080 resolution. Participants wore noise-reducing headphones with a noise reduction rating of 30 dB, in order to mask any sounds made by the vibrators.

2.3. *Stimuli*

The eight upper-case letters B, C, F, G, K, N, P, and Q were drawn on the participants' body surfaces (see Fig. 2B). These letters were selected on the basis of previous experiments we conducted, in which they were sufficiently well recognized (above 87% accuracy) and induced little confusion. The order in which the vibrators were successively activated was chosen to approximate the gesture of manual letter drawing (see Fig. 2C). This sequential mode of presentation was chosen over a simultaneous mode because it allows better performance in letter recognition (Yanagida *et al.*, 2004; see also Loomis, 1974). In order to choose the sequence of each letter, 14 persons, who did not participate in the main experiment, were asked to draw the letters on a paper sheet. From this we calculated the most frequent way of writing each of the letters. For instance, the letter P is the most frequently drawn by an initial vertically descending stroke followed by a loop beginning from the top of the vertical stroke. Each vibrator composing the sequence was activated for 250 ms. There was no interval between two consecutive vibrations composing one stroke of the letter (e.g., the three vibrators composing the vertical stroke of the letter P); nor between two consecutive strokes that were spatiotemporally continuous (e.g., the three strokes of the loop of the letter P). However there was a 150-ms interval between two consecutive strokes that were spatiotemporally discontinuous (e.g., the end of the vertical descending stroke and the beginning of the loop of the letter P). This interval avoided possible errors of interpretation caused by an irrelevant grouping of vibrations. Participants were instructed that these temporal intervals corresponded to a spatial discontinuity in manual letter drawing. The mean duration of letters was 2338 ms.

2.4. Procedure

2.4.1. Baseline and Post-Training Sessions

The participants were required to stand in front of the computer screen. On each trial, one of the eight letters was drawn on the participant's body surface. The participants were instructed to report which letter was drawn by pressing the corresponding key on the computer keyboard with the index finger of their dominant hand. Stickers were used to represent the eight letters on two lines of four adjacent keys. Participants were required to respond as accurately and as rapidly as possible. Accuracy was emphasized over speed of response. Given that posture has an influence on how tactile symbols are perceived (see Parsons and Shimojo, 1987; Sekiyama, 1991), we made sure that the participant's posture was consistent across sessions. As they had to look at the screen when visual feedback was provided to them, the participants were instructed to look at the empty screen during the conditions in which there was no feedback. However, note that, in all the conditions, the participants were allowed to look at the keyboard when giving their answers. The participants were able to give their responses at any time from the onset of the first vibration and up to 3000 ms after the end of the last vibration (at which point the trial was terminated). At the end of each trial, there was an interval of 3000 ms before the beginning of the next trial. No feedback was given regarding the correctness of the participants' responses.

The baseline and the post-training sessions were composed of three blocks each: one block for each body surface. The six possible orders of these three blocks were counterbalanced across participants. However, the order remained the same for each participant during the baseline and the post-training sessions. The three body surfaces were thus each separated by the same amount of letter expositions (i.e., five blocks of trials) between the baseline and the post-training sessions. Each block was composed of 48 randomized trials corresponding to six presentations of each letter.

In the baseline session, before each of the experimental blocks, the participants were given eight practice trials, corresponding to one presentation of each letter. In this practice block, feedback was given after each response: the correct answer was visually displayed on the computer screen once participants responded.

2.4.2. Training Session

The participants in the control group completed the post-training session just after the baseline session. Only the participants of the trained group were trained in between the two sessions. During this training session, the participants were trained on only one of the three body surfaces. This trained surface was always the surface that was tested in the second position during the baseline and the post-training sessions. Thus, one third of the participants from the trained group were trained on each of the possible body surfaces. The training session consisted of three consecutive blocks of 48 trials. Given that a trial-by-trial feedback has been shown to reinforce learning (Herzog and Fahle, 1998), in this session, the participants were given visual feedback on the correctness of their answers after each trial.

3. Results

Trials in which participants failed to make a response before the trial was terminated (less than 0.9% of trials overall) were not included in the data analyses. The accuracy of letter recognition was measured by the percentage of correct responses in each condition. The mean response times (RTs) were also computed. However, RTs corresponding to errors were excluded from the RT analysis. The first analysis presented here evaluated training effects by measuring performance improvement across sessions for the trained and control groups. The second analysis evaluated the transfer of learning by comparing training effects in trained and untrained body surfaces for the trained group only. The third one evaluated the possible topographic organization of perceptual transfer by measuring performance improvement as a function of the different body surfaces in the trained group. For all analyses, an alpha level of 0.05 was used.

In order to evaluate the effect of training on performance, ANOVAs were conducted both on accuracy and on RTs with Group (trained, control) as a between-participant factor and Session (baseline, post-training) as a within-participant factor. Because the sample sizes were unequal, type III sum of squares were used (Shaw and Mitchell-Olds, 1993). With respect to accuracy, there was a significant effect of Session ($F(1, 43) = 45.42$; $p < 0.001$). Accuracy was greater in the post-training (86.51%, SD = 11.72) than in the baseline (77.49%, SD = 12.67) sessions, thus showing performance improvement. Importantly, there was a significant interaction between Group and Session ($F(1, 43) = 6.35$; $p < 0.05$), showing that performance improvement was greater in the trained (increase of 11.02 points of percentage, SD = 8.34) than in the control group (5.02 points of percentage, SD = 5.47). As a consequence, global accuracy (i.e., across the two sessions) was also significantly greater ($F(1, 43) = 7.27$; $p < 0.01$) for the trained (85.07%, SD = 12.69) than for the control group (75.87%, SD = 11.35). Specific comparisons showed that the group difference was significant only for the post-training session ($F(1, 43) = 14.06$; $p < 0.001$); not for the baseline session ($F(1, 43) = 2.48$; $p = 0.12$). In other words, prior to training, accuracy in letter recognition was similar for the two groups. However, after training, recognition improved

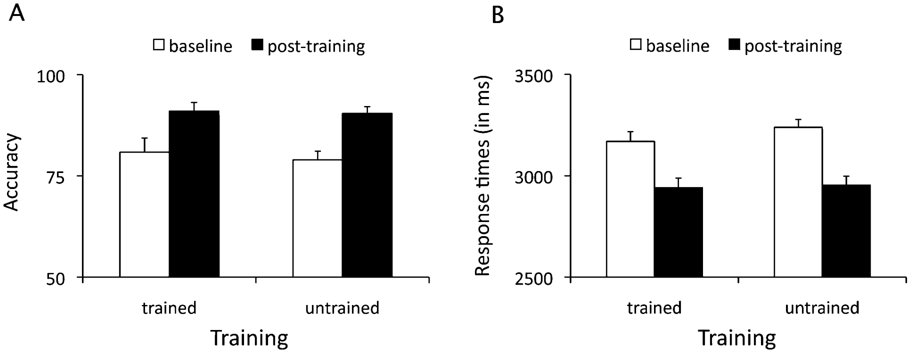

Figure 3. Participants' (A) accuracy and (B) response times of the trained group for the trained and untrained body surfaces obtained during the baseline session (in white) and the post-training session (in black). Error bars represent the standard errors of the means.

differentially as the percentage of correct responses was significantly higher for the trained group than those obtained for the control group. With respect to RTs, there was a significant effect of Session ($F(1, 43) = 102.24$; $p < 0.001$). RTs were shorter in the post-training (3067 ms, SD = 282) than in the baseline (3319 ms, SD = 259) sessions. RTs were also significantly shorter ($F(1, 43) = 21.62$; $p < 0.001$) for the trained (3088 ms, SD = 268) than for the control group (3403 ms, SD = 238). The interaction between Group and Session was not significant ($F(1, 43) = 1.88$; $p = 0.18$).

In order to determine if there was a transfer of tactile learning, ANOVAs were conducted with Session (baseline, post-training) and Training (trained, untrained) as within-participant factors for the trained group only (see Fig. 3A and 3B). As with the previously reported ANOVA, accuracy was significantly greater in the post-training than in the baseline sessions ($F(1, 29) = 42.70$; $p < 0.001$). There was no effect of Training ($F(1, 29) < 1$). More importantly, there was no significant interaction between Session and Training ($F(1, 29) < 1$); which shows that performance improved between the baseline and post-training sessions for both trained (increase of 10.13 points of percentage, SD = 12.32) and untrained (11.47 points of percentage, SD = 7.79) body surfaces. The analysis conducted on RTs yielded the same pattern of results, with a significant decrease in RTs from the baseline to the post-training sessions ($F(1, 29) = 85.10$; $p < 0.001$). There was a significant effect of Training ($F(1, 29) = 4.32$; $p < 0.05$) but no significant interaction between Session and Training ($F(1, 29) = 3.37$; $p = 0.08$). Note that although the interaction approached significance, the RT analysis did not show a greater training effect for trained than untrained body surfaces. The decrease in RTs was 228 ms (SD = 173) for trained and 285 ms (SD = 176) for untrained body surfaces. Thus, for both accuracy and RTs, the performance improvement obtained with training was similar for trained and untrained body surfaces, showing that perceptual learning transfers to untrained surfaces.

Finally, in order to evaluate the possible influence of topographic organization on tactile perceptual learning, ANOVAs were conducted with the Trained surface (belly, thigh, shin) as a between-participant factor, and with Session (baseline, post-training) and Stimulated surface (belly, thigh, shin) as within-participant factors for the trained group only (see Tables 1 and 2). As with previous analyses, the performance improvement from the baseline to the post-training sessions was significant for both accuracy ($F(1, 29) = 49.77$; $p < 0.001$) and RTs ($F(1, 29) = 87.26$; $p < 0.001$). There was also a significant effect of the Stimulated surface for both accuracy ($F(2, 58) = 11.92$; $p < 0.001$) and RTs ($F(2, 58) = 5.13$; $p < 0.01$). Tukey's HSD tests showed that performance was significantly better ($p < 0.01$, for accuracy; $p < 0.05$, for RTs) for the belly (89.72%, SD = 10.85; 3028 ms, SD = 279) than for the thigh (83.71%, SD = 14.28; 3114 ms, SD = 302) and significantly better ($p < 0.001$, for accuracy; $p < 0.05$, for RTs) for the belly than for the shin (81.78%, SD = 16.91; 3121 ms, SD = 310), but there was no significant difference between the thigh and the shin. More importantly, there was neither a significant interaction between Trained surface and Session ($F(2, 27) < 1$, for both accuracy and RTs) nor any significant interaction between Trained surface, Stimulated surface and Session ($F(4, 54) < 1$, for both accuracy and RTs), indicating that performance improvement did not vary with the distance between the trained and stimulated surfaces. Performance was significantly better ($p < 0.05$ for all comparisons) in the post-training than in the baseline sessions for all the combinations of trained and stimulated surfaces, i.e., including adjacent and non-adjacent body surfaces (for both accuracy and RTs). There was no other significant effect or interaction.

The confusion matrices of the trained participants' responses (see Table 3) indicate that before training, the participants made the same types of confusions for the three stimulated surfaces. In particular, the letters K and F were reciprocally confused and the letter G was frequently mistaken for the letter Q. In addition, the letter N was frequently mistaken for the letter P when it was displayed on the shin but not when it was displayed on the belly and the thigh. Overall, the same types of letter confusion were observed after training, with however less errors than before training.

4. Discussion

The study reported here aimed at investigating the extent to which a performance improvement in tactile letter recognition transfers across body surfaces. Three main results emerged from this study. First, training improved both participants' accuracy and response latency. In addition, participants performing

Table 1.
Mean accuracy (in percentages) during the baseline and post-training sessions and the corresponding training effects, as a function of stimulated surface (belly, thigh, shin), and trained surface (belly, thigh, shin, untrained). Note that the participants were tested on all three surfaces but trained on only one of them. Standard deviations of the mean are in brackets

Surface trained	Baseline			Post-training			Training effect		
	Belly	Thigh	Shin	Belly	Thigh	Shin	Belly	Thigh	Shin
Belly	87.9 (8.8)	77.5 (11.9)	71.7 (14.0)	95.2 (7.8)	89.6 (6.7)	87.3 (13.4)	7.3 (9.9)	12.1 (10.7)	15.6 (8.9)
Thigh	81.5 (14.7)	74.8 (22.6)	74.6 (16.9)	92.3 (8.6)	87.5 (11.7)	87.1 (13.2)	10.8 (11.0)	12.7 (13.1)	12.5 (12.9)
Shin	87.1 (10.7)	81.3 (13.4)	79.8 (22.3)	94.4 (8.7)	91.7 (7.7)	90.2 (14.9)	7.3 (8.0)	10.4 (11.2)	10.4 (14.2)
Untrained (control)	84.6 (9.5)	69.4 (16.0)	66.0 (16.3)	86.2 (11.6)	73.8 (15.7)	75.2 (13.6)	1.6 (6.1)	4.4 (12.1)	9.2 (12.1)

Table 2.
Mean response times (in ms) during the baseline and post-training sessions and the corresponding training effects, as a function stimulated surface (belly, thigh, shin), and trained surface (belly, thigh, shin, untrained). Standard deviations of the mean are in brackets

Surface trained	Baseline			Post-training			Training effect		
	Belly	Thigh	Shin	Belly	Thigh	Shin	Belly	Thigh	Shin
Belly	3106 (230)	3247 (320)	3286 (293)	2843 (197)	2931 (202)	2964 (199)	263 (136)	316 (221)	322 (232)
Thigh	3216 (259)	3182 (240)	3311 (266)	2966 (236)	3008 (205)	2971 (201)	250 (250)	174 (175)	340 (277)
Shin	3174 (244)	3279 (349)	3218 (336)	2863 (307)	3038 (349)	2973 (351)	311 (237)	241 (250)	245 (205)
Untrained (control)	3422 (290)	3551 (260)	3548 (293)	3225 (279)	3335 (207)	3336 (211)	197 (251)	216 (197)	212 (198)

Table 3.
Confusion matrices of trained participants' responses for each stimulated surface in the baseline and post-training sessions. The scores are expressed in percentages. Digits in bold indicate correct recognition percentages. Values may not add to 100% due to rounding

Baseline										Post-training									
Stimulus	Response									Stimulus	Response								
	B	C	F	G	K	N	P	Q	Missing		B	C	F	G	K	N	P	Q	Missing
Belly										Belly									
B	**97**	0	0	1	0	1	0	1	1	B	**99**	0	0	0	0	0	1	0	0
C	0	**91**	1	5	0	0	2	1	1	C	0	**97**	1	1	0	0	0	1	1
F	0	0	**80**	0	11	0	8	0	1	F	1	0	**89**	1	8	0	1	0	0
G	0	2	0	**90**	2	0	2	2	2	G	0	1	1	**91**	1	1	1	6	0
K	0	0	13	1	**75**	8	1	2	1	K	1	0	4	1	**89**	5	0	1	0
N	0	0	2	3	3	**82**	7	0	3	N	0	0	0	1	1	**94**	1	1	3
P	2	0	1	0	3	2	**91**	1	2	P	0	0	1	1	1	1	**97**	1	0
Q	1	0	1	18	1	0	1	**79**	0	Q	0	0	0	4	1	0	0	**93**	1
Thigh										Thigh									
B	**92**	0	0	1	4	1	0	2	0	B	**99**	0	0	1	0	0	0	0	0
C	0	**89**	1	5	1	0	1	1	3	C	1	**92**	0	7	0	0	1	0	0
F	2	0	**67**	1	19	4	6	2	1	F	0	0	**80**	0	13	2	3	1	0
G	1	6	1	**79**	2	0	2	9	1	G	1	3	0	**92**	1	0	1	3	0
K	1	0	16	4	**58**	14	3	2	2	K	0	0	6	0	**86**	7	2	0	0
N	0	1	1	1	7	**79**	9	0	3	N	0	0	1	1	1	**90**	7	0	0
P	3	1	2	3	2	3	**82**	2	2	P	1	0	1	0	2	4	**89**	2	1
Q	3	2	1	18	1	1	1	**75**	1	Q	0	0	1	10	1	0	0	**88**	0
Shin										Shin									
B	**86**	0	0	1	1	5	2	3	3	B	**96**	0	0	1	0	1	0	1	1
C	0	**92**	0	4	0	0	1	1	1	C	0	**95**	1	1	1	1	2	0	0
F	1	0	**77**	2	15	1	2	0	2	F	1	0	**86**	0	11	1	2	0	0
G	1	10	0	**79**	1	1	2	6	2	G	1	2	1	**92**	2	0	1	1	1
K	2	0	28	2	**57**	8	1	1	2	K	0	0	13	0	**80**	6	0	1	0
N	1	1	2	3	5	**61**	21	1	6	N	0	0	2	1	1	**76**	19	1	1
P	3	0	3	1	4	4	**78**	1	6	P	2	0	1	1	1	3	**92**	0	1
Q	1	0	1	23	3	0	0	**72**	1	Q	0	0	1	8	2	1	0	**89**	0

intensive training with trial-by-trial feedback (trained group) improved performance to a greater extent than the participants merely repeating the task twice on each body surface (control group). Second, performance improvement was not restricted to the trained body surface but it transferred to the untrained ones. Third, the obtained transfer of tactile learning was similar for surfaces represented in adjacent (e.g., belly and thigh) and in non-adjacent (e.g., belly and shin) areas of the somatosensory cortex (see Merzenich *et al.*, 1978; Nakamura *et al.*, 1998, for descriptions of the somatosensory cortex's topographic organization). Taken together, these results reveal that there is a transfer of learning in tactile letter recognition, which occurs independently of the distance between body surfaces. These three results provide support for Bach-y-Rita's claim that, after training with visual-to-tactile sensory substitution devices, perceptual abilities reached on a given body surface transfer to another one (Bach-y-Rita and Kercel, 2003). However, as will be further highlighted below, the extent to which there is no loss in perceptual performance needs to be further qualified.

The degree of learning transfer is considered to reflect the level of involved perceptual processing (Recanzone *et al.*, 1992). Transfer has therefore been reported to depend both on the task and on the stimuli. For example, transfer was not found when using a passive two-point discrimination task (Dinse *et al.*, 2006; Godde *et al.*, 2000) whereas transfer was found in gratings tasks, which involve more active discrimination, i.e. actively scanning the shapes with the fingertip (Harrar *et al.*, 2014; Sathian and Zangladze, 1997). Transfer also depends on the type of tactile stimuli (vibration, pressure, or roughness; see Harris *et al.*, 2001). Moreover, using low-level stimuli only, the above-mentioned studies reported a transfer limited to adjacent and homologous contralateral body surfaces only. The results reported here reveal that, contrary to the discrimination of low-level stimuli, the recognition of high-level symbols transfers across body surfaces without restrictions of their closeness in location. As compared with discrimination tasks of low-level stimuli varying along one feature (e.g., gratings with different orientations), the recognition of letters, which are made of several features in combination, may require the involvement of a holistic process allowing the integration of the different features into a global and unique percept. This holistic process involves higher-level areas than those perceptual processes that operate on simple features (Lerner *et al.*, 2001; Tanaka, 2003). Moreover, in our study, the sequential mode of drawing the letters may have involved a spatiotemporal integration process rather than a purely spatial one that would be involved with a simultaneous mode of presentation. This spatiotemporal integration process also depends on high-level areas (Battelli *et al.*, 2007). High-level perceptual areas are less topographically organized than low-level ones. Consequently, their receptive fields are larger and not restricted to a specific area, facilitating the transfer of perceptual learning across body surfaces that are further apart. The transfer of learning we found regarding high-level symbol recognition is thus compatible with the reverse hierarchy theory, which describe a perceptual learning guided by a top-down process, from high-level to low-level areas (Ahissar and Hochstein, 2004).

In the letter recognition task used in our study, training effects occurred at different levels. During the training session, the repetition of letters improved the recognition of the sequence of tactile stimuli corresponding to each letter. The trial-by-trial feedback provided in this training session also helped participants to associate the sequence of tactile stimuli with the correct letter. In addition, the performance improvement that was observed for the control group indicates that participants are learning the task before the training session. This result is probably influenced both by the use of three different blocks during the baseline session and by the repeated exposure of letters within each block. Harrar *et al.* (2014), using a similar procedure but with a grating discrimination task, did not find such a performance improvement for their control group. This difference between Harrar *et al.*'s and our study suggests that perceptual learning is faster for high-level than for low-level stimuli; which is consistent with the reverse hierarch theory (Ahissar and Hochstein, 2004). However, the greater performance improvement that was obtained for the trained group than for the control group suggests that explicit training improved performance beyond a mere repeated exposure effect and thereby it supports the claim that a perceptual learning transfer occurred in our study.

It should be mentioned that the perception of the global configuration (e.g., the letter B which is made of one vertical stroke and two loops) was probably sufficient to correctly recognize tactile letters. However, the participants in our study reported more difficulties in correctly discriminating between two letters with similar global configurations (e.g., the letters F and K which are both made of a vertical stroke and two other strokes; see the confusion matrices in Table 3) that require finer discrimination processes (e.g., to discriminate between the horizontal strokes of the letter F and the diagonal strokes of the letter K). The discrimination of feature differences required for recognition of high-level symbols with high similarity may thus involve lower-level processes and reduce the amount of perceptual learning transfer. However, according to the reverse hierarchy theory, expert perceivers (in touch as well as in other sensory modalities), who have had substantial amounts of training, are able to base their perception on high-level processes even in difficult conditions (e.g., discrimination of stimuli with high similarity such as two exemplars of the same bird species); they then show transfer of perceptual learning (Ahissar and Hochstein, 2004). Intensive training should thus allow transfer of tactile learning even in the cases of discrimination of highly similar tactile symbols.

Although the results obtained in the present study support the transfer of tactile learning across body surfaces, they cannot fully support the independence of perceptual abilities from the stimulated body surface that has been claimed to occur after training. The most important counter-argument to this claim is that there would remain differences in tactile recognition and discrimination abilities as a function of the location in which the stimuli are displayed on the body surface. For instance, tactile discrimination abilities have been reported to be higher on the belly than on the legs (Haggard *et al.*, 2003). Similarly, in our study, training improved letter recognition on all body surfaces but letter recognition remained less accurate on the legs than on the belly. However, even if the claim must be watered-down in order to include differences in acuity across body surfaces (i.e., as a function of the differences in resolution of their respective tactile receptive fields) further investigations would still be required to demonstrate an independence from the stimulated body surface. First of all, the participants in our study were given purely sensory learning whereas sensory substitution devices involve a sensorimotor learning. This however has been shown to reinforce learning transfer across different sensory modalities (see Levy-Tzedek *et al.*, 2012). Second, the body surfaces used in our study remain relatively closely represented in the somatosensory cortex; thus the use of more distant body surfaces is necessary to more fully assess the possibility of complete transfer. If perceptual learning can completely transfer to all body surfaces, this should include distant body surfaces such as head and legs. Third, the tactile letters we used are more complex than low-level stimuli varying along only one feature but most sensory substitution devices convey even higher-level stimuli such as faces, objects and scenes. Moreover, the sequential mode of presentation may be more appropriate for letters than for other objects (such as everyday 3-D objects) for which it would be difficult to sequentially order their different parts in an intuitive way. Further studies should then extend the actual results to a broader range of stimuli of varying complexity and to alternative modes of presentation.

Finally, it has been suggested that the body surface independence in visual-to-tactile sensory substitution is probably due to the fact that, after training, users no longer feel the stimulation on their skin, but they directly attribute the stimulation as resulting from an external object (see Bach-y-Rita and Kercel, 2003). This externalization process would reinforce the independence of tactile learning from the stimulated surface (see Hartcher-O’Brien and Auvray, submitted, for a review on externalization). This claim would need further investigation as well to be corroborated. However, what can be said for now is that our study provides the first empirical data to support Bach-y-Rita’s claim that training in sensory substitution improves perceptual abilities, and that these perceptual abilities transfer from one body surface to another, resulting in a relative independence from the stimulated body surface. These results have implications for the use of sensory substitution devices and vibrotactile systems by visually impaired people. First, they suggest that training on one body surface is beneficial to the entire body. As a consequence, users do not need to undergo an extensive training on all body surfaces. This study also provides better understanding of the learning process, which is a crucial feature for efficient use of tactile devices. It reveals that transfer of learning for tactile letters occurs within a relatively short time frame, i.e., the 90 min of our experiment. The longer learning reported for recognition of more complex objects with sensory substitution devices (Kaczmarek and Haase, 2003) indicates that the amount of training required to reach accurate object recognition with tactile devices depends on the complexity of the information that is provided. It would be interesting in future research to investigate the extent to which learning transfers between different subsets of stimuli with similar level of complexity, and between stimuli of varying complexity; for instance between moderately complex stimuli such as tactile letters and highly complex stimuli such as everyday 3-D objects.

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Note

1 Note that Bach-y-Rita also concurrently asserted that the camera could then be moved, for instance from a hand-held to a head-mounted display, without any loss in performance. However, the present study only focused on the effect of training on a change in the stimulated body surface and not on a change in the camera's position.

References

Ahissar, M. and Hochstein, S. (2004). The reverse hierarchy theory of visual perceptual learning, *Trends Cogn. Sci.* **8**, 457–464.

Arno, P., Vanlierde, A., Streel, E., Wanet Defalque, M. C., Sanabria-Bohorquez, S. and Veraart, C. (2001). Auditory substitution of vision: pattern recognition by the blind, *Appl. Cogn. Psychol.* **15**, 509–519.

Auvray, M., Hanneton, S. and O'Regan, J. K. (2007). Learning to perceive with a visuo-auditory substitution system: localization and object recognition with The Voice, *Perception* **36**, 416–430.

Auvray, M. and Myin, E. (2009). Perception with compensatory devices: from sensory substitution to sensorimotor extension, *Cogn. Sci.* **33**, 1036–1058.

Bach-y-Rita, P. (1995). *Nonsynaptic Diffusion Neurotransmission and Late Brain Reorganization*. Demos, New York, NY, USA.

Bach-y-Rita, P., Collins, C. C., Saunders, F., White, B. and Scadden, L. (1969). Vision substitution by tactile image projection, *Nature* **221**, 963–964.

Bach-y-Rita, P. and Kercel, S. W. (2003). Sensory substitution and the human–machine interface, *Trends Cogn. Sci.* **17**, 541–546.

Battelli, L., Pascual-Leone, A. and Cavanagh, P. (2007). The "when" pathway of the right parietal lobe, *Trends Cogn. Sci.* **11**, 204–210.

Bubic, A., Striem-Amit, E. and Amedi, A. (2010). Large-scale brain plasticity following blindness and the use of sensory substitution devices, in: *Multisensory Object Perception in the Primate Brain*, J. Kaiser and M. J. Naumer (Eds), pp. 351–380. Springer, New York, NY, USA.

Capelle, C., Trullemans, C., Arno, P. and Veraart, C. (1998). A real-time experimental prototype for enhancement of vision rehabilitation using auditory substitution, *IEEE Trans. Biomed. Eng.* **45**, 1279–1293.

Deroy, O. and Auvray, M. (2012). Reading the world through sensory substitution devices, *Front. Theor. Philos. Psychol.* **3**, 457.

Dinse, H. R., Kleibel, N., Kalisch, T., Ragert, P., Wilimzig, C. and Tegenthoff, M. (2006). Tactile coactivation resets age-related decline of human tactile discrimination, *Ann. Neurol.* **60**, 88–94.

Fahle, M. E. and Poggio, T. E. (2002). *Perceptual Learning*. MIT Press, Cambridge, MA, USA.

Gibson, E. J. (1969). *Principles of Perceptual Learning and Development*. Appleton Century Crofts, New York, NY, USA.

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

Haggard, P., Taylor-Clarke, M. and Kennett, S. (2003). Tactile perception, cortical representation and the bodily self, *Curr. Biol.* **13**, 170–173.

Haigh, A., Brown, D. J., Meijer, P. and Proulx, M. J. (2013). How well do you see what you hear? The acuity of visual-to-auditory sensory substitution, *Front. Psychol.* **4**, 330.

Hanneton, S., Auvray, M. and Durette, B. (2010). The Vibe: a versatile vision-to-audition sensory substitution device, *Appl. Bionics Biomech.* **7**, 269–276.

Harrar, V., Spence, C. and Makin, T. R. (2014). Topographic generalization of tactile perceptual learning, *J. Exp. Psychol. Hum. Percept. Perform.* **40**, 15–23.

Harris, J. A., Harris, I. M. and Diamond, M. E. (2001). The topography of tactile learning in humans, *J. Neurosci.* **21**, 1056–1061.

Hartcher O'Brien, J. and Auvray, M. (submitted). The process of distal attribution illuminated through studies of sensory substitution, *Multisens. Res.*

Herzog, M. H. and Fahle, M. (1998). Modeling perceptual learning: difficulties and how they can be overcome, *Biol. Cybern.* **78**, 107–117.

Iwamura, Y., Iriki, A. and Tanaka, M. (1994). Bilateral hand representation in the postcentral somatosensory cortex, *Nature* **369**, 554–556.

Jansson, G. (1983). Tactile guidance of movement, *Int. J. Neurosci.* **19**, 37–46.

Kaas, A. L., van de Ven, V., Reithler, J. and Goebel, R. (2013). Tactile perceptual learning: learning curves and transfer to the contralateral finger, *Exp. Brain Res.* **224**, 477–488.

Kaczmarek, K. A. and Haase, S. J. (2003). Pattern identification and perceived stimulus quality as a function of stimulation current on a fingertip-scanned electrotactile display, *IEEE Trans. Neural Syst. Rehabil. Eng.* **11**, 9–16.

Lerner, Y., Hendler, T., Ben-Bashat, D., Harel, M. and Malach, R. (2001). A hierarchical axis of object processing stages in the human visual cortex, *Cereb. Cortex* **11**, 287–297.

Levy-Tzedek, S., Hanassy, S., Abboud, S., Maidenbaum, S. and Amedi, A. (2012). Fast, accurate reaching movements with a visual-to-auditory sensory substitution device, *Restor. Neurol. Neurosci.* **30**, 313–323.

Loomis, J. M. (1974). Tactile letter recognition under different modes of stimulus presentation, *Percept. Psychophys.* **16**, 401–408.

Meijer, P. B. L. (1992). An experimental system for auditory image representations, *IEEE Trans. Biomed. Eng.* **39**, 112–121.

Merzenich, M. M., Kaas, J. H., Sur, M. and Lin, C.-S. (1978). Double representation of the body surface within cytoarchitectonic area 3b and 1 in “SI” in the owl monkey (*Aotus trivirgatus*), *J. Comp. Neurol.* **181**, 41–74.

Nagarajan, S. S., Blake, D. T., Wright, B. A., Byl, N. and Merzenich, M. M. (1998). Practice-related improvements in somatosensory interval discrimination are temporally specific but generalize across skin location, hemisphere, and modality, *J. Neurosci.* **18**, 1559–1570.

Nakamura, A., Yamada, T., Goto, A., Kato, T., Ito, K., Abe, Y., Kachib, T. and Kakigic, R. (1998). Somatosensory homunculus as drawn by MEG, *NeuroImage* **74**, 377–386.

Parsons, L. M. and Shimojo, S. (1987). Perceived spatial organization of cutaneous patterns on surfaces of the human body in various positions, *J. Exp. Psychol. Hum. Percept. Perform.* **13**, 488–504.

Pollok, B., Schnitzler, I., Mierdorf, T., Stoerig, P. and Schnitzler, A. (2005). Image-to-sound conversion: experience-induced plasticity in auditory cortex of blindfolded adults, *Exp. Brain Res.* **167**, 287–291.

Recanzone, G. H., Merzenich, M. M. and Schreiner, C. E. (1992). Changes in the distributed temporal response properties of SI cortical neurons reflect improvements in performance on a temporally based tactile discrimination task, *J. Neurophysiol.* **67**, 1071–1091.

Renier, L., Collignon, O., Poirier, C., Tranduy, D., Vanlierde, A., Bol, A., Veraart, C. and De Volder, A. G. (2005). Cross-modal activation of visual cortex during depth perception using auditory substitution of vision, *NeuroImage* **26**, 573–580.

Sampaio, E., Maris, S. and Bach-y-Rita, P. (2001). Brain plasticity: ‘Visual’ acuity of blind persons via the tongue, *Brain Res.* **908**, 204–207.

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

Sekiyama, K. (1991). Importance of head axes in perception of cutaneous patterns drawn on vertical body surfaces, *Percept. Psychophys.* **49**, 481–492.

Shaw, R. G. and Mitchell-Olds, T. (1993). ANOVA for unbalanced data: an overview, *Ecology* **74**, 1638–1645.

Spengler, F., Roberts, T. P. L., Poeppel, D., Byl, N., Wang, X., Rowley, H. A. and Merzenich, M. M. (1997). Learning transfer and neuronal plasticity in humans trained in tactile discrimination, *Neurosci. Lett.* **232**, 151–154.

Tanaka, K. (2003). Columns for complex visual object features in the inferotemporal cortex: clustering of cells with similar but slightly different stimulus selectivities, *Cereb. Cortex* **13**, 90–99.

Yanagida, Y., Kakita, M., Lindeman, R. W., Kume, Y. and Tetsutani, N. (2004). Vibrotactile letter reading using a low-resolution tactor array, in: *Proc. 12th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pp. 400–406. IEEE Computer Society.