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The sixth finger illusion induced by palm outside stroking shows stable ownership and independence

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Recently, the sixth finger illusion has been widely studied for body representation. It remains unclear how the stroking area, visual effects and the number of trials affect the illusion. We recruited 80 participants to conduct five trials by stroking the palm outside or little finger outside in conditions with and without wearing supernumerary rubber finger. The results show the stroking area has a greater impact on the intensity and independence of the illusion. And the palm outside can induce a stronger and more independent illusion. In addition, the sixth finger illusion induced by these four conditions was significantly influenced by the number of trials, and there is a significant enhancement in the intensity of the illusion induced by the palm outside as the number of trials increases. These indicate that stroking the outer lateral side of the palm can induce a relatively stronger and more independent sixth finger illusion, and the intensity of it reaches a steady state after three trials when wearing a supernumerary rubber finger and five trials when not wearing a supernumerary rubber finger. This study adds evidence to the research on multisensory integration and sensory feedback of the supernumerary robotic fingers.

Keywords Body representation, Multi-sensory illusion, Locations, Longitudinal study, Supernumerary robotic fingers

We may have seen people with six fingers in our lives. Supernumerary fingers are usually removed at birth[1], which may be because people believe that supernumerary fingers represent a malformation and are useless. However, it has been shown that polydactyly participants produce a higher sensorimotor ability for manipulation with one hand than normal-bodied individuals[2]. Their research with two preaxial polydactyly participants from the same family reveals fully functional supernumerary fingers and demonstrates their utility and the augmented manipulation capabilities they can provide. In recent research, scholars from various countries have already begun to develop wearable supernumerary robotic fingers (SRFs) to compensate for or augment the sensorimotor capabilities of humans[3]. They carried out scientific research work from different perspectives, such as ontology structure design[4–6], control and driving[7–9], sensing and perception[10–12], and evaluated initial usability in diverse user groups[13], so as to further improve the safety, adaptability and collaboration of operations[14]. Given the integrated functioning of the brain, it is improbable that augmentation plasticity will exclusively affect the motor system without altering our sensory representation of the body[3]. If the SRF is worn without sensory representation, it is like having only hardware without software, and the SRF cannot assist actions with little cognitive load. Further research on SRLs should also focus on establishing cognitive foundations and developing sensorimotor interfaces to receive feedback from them[3], thereby modifying body schema to embody the SRFs.

In recent years, many cognitive scientists and neuroscientists have been studying the human brain's illusions of external limbs, such as a third arm[15–17], an extra sixth finger[18,19], and even a tail[20,21], in order to explore how the perception of body ownership arises from multisensory integration[14,22]. The experience of the sixth finger illusion was created by Newport[18] and Hoyet[19] et al. Newport et al. used the mirror box illusion to create the illusion of a sixth finger, what they called the Anne Boleyn illusion[18]. This illusion is induced by conflicting multisensory signals. That is, stroking the little finger outside behind the mirror at the same time as stroking the empty space next to the mirror-reflected hand's little finger creates conflicting visual and tactile signals. Cadete et al. maintained the illusion of a sixth finger for an extended period of time by altering the paradigm to a double back and forth stroking along the participant's fingers, followed by twenty double strokes on the sixth finger location simultaneously to the hidden hand's little finger[23]. These show that the illusion of a sixth finger

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is not a transient confusion caused by conflicting multisensory signals, but rather a lasting representation of a supernumerary finger. Research on polydactyly subjects demonstrates that the human nervous system is able to develop, embody and control a supernumerary finger[2]. The sixth finger illusion proves that the brain can add supernumerary fingers into our body schema, which can provide references for exploring the establishment of bodily sensations and cognition of the SRFs. In order to investigate the independence of the sixth finger, i.e., whether the sixth finger is a copy of the other fingers or has its own independent characteristics, Cadete et al. tested whether the length[24] and curvature[25] of the illusory sixth finger could be altered independently of the actual fingers. Specifically, the sixth finger illusion was induced with different lengths and curves while the physical features of the little finger remained the same, proving the sixth finger can have its own independent features and is not a copy of the actual fingers. This illusion of having a sixth finger with independent features can provide a perceptual foundation for the establishment and positional reference for sensory feedback of the SRFs.

While some studies have focused on the neuroplasticity effects induced by the sixth finger illusion, there are few studies on the impact of inducing the illusion through multiple trials. By increasing the number of inductions, participants can gradually learn to apply their own experiences and knowledge to the perception of the sixth finger illusion. For example, they may employ different cognitive strategies and shifts in attention focus in order to modulate the performance of the illusion. Therefore, it is essential to further investigate the impact of multiple induced trials on the sixth finger illusion, to gain a deeper understanding of its potential and limitations in neuroplasticity, and to explore the possibility of utilizing neuroplasticity in clinical trials and everyday applications to facilitate learning and rehabilitation. In addition, the sixth finger illusion is usually induced on a physiological matching location, which may help to induce the sixth finger illusion to some extent. However, further research needs to explore the possibility of inducing similar illusions on different body locations through stimulation experiments. Additionally, to further enhance the intensity of the sixth finger illusion, we introduced an enhanced visual stimulation to promote the induction of the sixth finger illusion by wearing a supernumerary rubber finger on the outer lateral side of the little finger. Our research will contribute to a better understanding of the neural basis and mechanisms underlying the sixth finger illusion and may contribute to the development of better and more independent induction methods.

In this study, one of our aims was to investigate how the ownership of the sixth finger illusion increased or decreased as the number of trials increased. To do this, we referenced the experimental paradigms and questionnaires of Newport and Cadete et al. to test how the participants' own experiences changed as each of the five sixth finger illusion trials. We also divided the experiment into four conditions to induce the sixth finger illusion on the palm outside or the little finger outside, both with and without wearing a supernumerary rubber finger. This design allowed us to investigate the influence of the enhanced visual stimulation on inducing the sixth finger illusion, as well as the matching relationship between the location of illusion induction and physiology, and to explore a better and more independent induced location. Each participant was required to complete five identical trials under one of the conditions, with an interval of two hours between each trial. The reason we chose the palm outside for research is that this location contains many tactile receptors[26], and it does not interfere with the functions of the existing fingers. If we can induce the sixth finger illusion on the palm outside while wearing the supernumerary rubber finger as well, and if the questionnaire scores of the sixth finger illusion tend to increase as the number of trials increases, then our results will be beneficial for promoting the establishment of sensory perception in the SRFs and providing better positional references for their sensory feedback.

Methods

Participants

We recruited 80 healthy naive right-handed participants (40 females) between 19 and 29 years of age (M = 24.45 years, SD = 4.7) in this study. All participants had corrected-to-normal or normal vision, and no participants had reported any psychological problems. They were randomly divided into four age- and gender-matched groups. The study was approved by the Regional Ethical Review Board of Tianjin University and all participants provided written informed consent at the start of the experiments. All methods were performed in accordance with the relevant guidelines and regulations. We used GLIMMPSE (General Linear Mixed Model Power and Sample Size, Version 3.1.3, available at https://v3.glimmpse.samplesizeshop.org)[27] to calculate the required sample size for the three-way interaction of interest (Tactile × Vision × Time). Statistical significance was set at $p < 0.05$. The required sample size to achieve a power of 0.80 and an effect size of 0.2 is a minimum of 60 participants, that is a minimum of 15 participants for each between-participants condition. As a result, a sample size of 80 should be able to replicate the illusion well and explore the impact of different factors on the illusion.

Design and procedure

We referred to the experimental setup of Cadete et al. and other studies that used similar illusions to manipulate bodily experience. The experiments were taken place in a quiet laboratory. The participants sat in a comfortable chair with their arms resting on the table in front of them (Fig. 1A). There was a mirror on the Table (42 cm high and 50 cm wide) aligned with the midline of their bodies. They placed their left hand behind the mirror and their right hand in front of the mirror. The index fingertips of both hands were placed 24 cm from the edge of the table and 20 cm from the mirror[23]. During the experiment, the participant was asked to keep looking at the image of his/her right hand mapped in the mirror and try not to have his own hands in the visual field so that the hand in the mirror was visually perceived as his left hand. The experimenter sat opposite the participant.

This study employed a between-subject design, whereby participants were randomly assigned to one of the following four conditions to induce the sixth finger illusion: (1) SvLPs: represents the presence and vision of the supernumerary rubber finger on the right hand (Sv) (Fig. 1B) and the stroke applied to the outer lateral palm of the left hand (LPs); (2) SvLFs: represents the presence and vision of the supernumerary rubber finger on the right

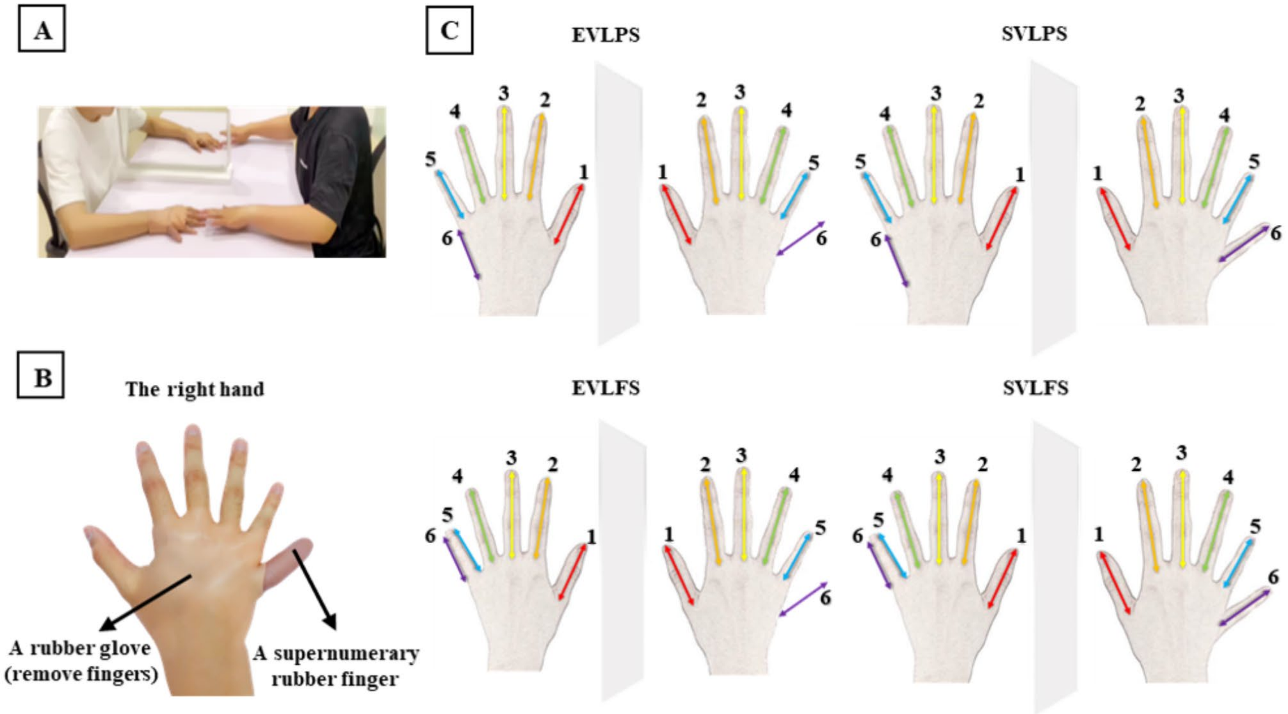

Fig. 1. The experimental setup and procedures. (**A**) Experimental scene; (**B**) Image of the right hand wearing a supernumerary rubber finger and a rubber glove (remove fingers); (**C**) Schematic of stroking location. In the EVLPS and SVLPS conditions, the number 6 on the left hand represents the location of the palm outside, while in the EVLFS and SVLFS conditions, it represents the location of the little finger outside.

hand (Sv) and the stroke applied to the outer little finger of the left hand (LFs); (3) EvLPs: represents the absence of the supernumerary rubber finger, i.e., the empty space in view being stroked (Ev), and the stroke applied to the outer lateral palm of the left hand (LPs); (4) EvLFs: represents the absence of the supernumerary rubber finger, i.e., the empty space in view being stroked (Ev), and the stroke applied to the outer little finger of the left hand (LFs). During each trial, the experimenter stroked the top of each finger back and forth from the knuckle to the fingertip, except for the little finger and the sixth finger (Fig. 1C). In the SvLPs condition, the stroke of the little finger applied to the top of the little finger of the left hand and the right hand, while the stroke of the sixth finger applied to the outer lateral side of the palm of the left hand and the top of the supernumerary rubber finger of the right hand. In the SvLFs condition, the stroke of the little finger applied to the inside lateral side of the little finger of the left hand and the top of the little finger of the right hand, while the stroke of the sixth finger applied to the outer lateral side of the little finger of the left hand and the top of the supernumerary rubber finger of the right hand. In the EvLPs condition, the stroke of the little finger applied to the top of the little finger of the left hand and the right hand, while the stroke of the sixth finger applied to the outer lateral side of the palm of the left hand and the blank desktop next to little finger of the right hand. In the EvLFs condition, the stroke of the little finger applied to the inside lateral side of the little finger of the left hand and the top of the little finger of the right hand, while the stroke of the sixth finger applied to the outer lateral side of the little finger of the left hand and the blank desktop next to little finger of the right hand. The stroking proceeded sequentially from the thumb to the sixth finger, with each finger being stroked four times before moving on to the next, except for the sixth finger which was stroked twenty times[23]. During each stroke process, make sure that the stroke speed and strength of the left and right hands were synchronized. The stroking in each finger lasted between 7 s and 9 s, except for the sixth finger which lasted between 75 s and 85 s, with a frequency of approximately 1 Hz. The interval between the stroking of each finger was between 3 s and 5 s, and the entire stroking procedure lasted for about 3 min[28,29].

Each participant was required to complete five trials under the same condition, with an interval of two hours between each trial. During the two-hour interval after each trial, participants engage in their normal learning and work activities. We applied the same reporting method for agreement with the questionnaire items used in Newport's and Cadete's studies[18]. Participants were asked to choose a value from −3 (strongly disagree) to 3 (strongly agree) after each trial to rate the following five questions in order to reflect the specificity of the sixth finger illusion and its characteristics:

1. It felt like I had six fingers on my left hand.
2. It felt like I had two little fingers on my left hand.
3. I felt a touch where I do not normally feel a touch.
4. I felt a touch that was not on my body.
5. It felt like I had an extra hand.

We changed the order of the five questions after each trial based on a Latin Square design to achieve a balance and reduce the impact of questionnaire order on the experimental results. Each trial lasted approximately 6 min.

Analysis

The questionnaire data of each condition, trial and questionnaire item were tested for normal distribution with histograms, residual plots and Shapiro–Wilk tests. As some of the data were non-normally distributed, non-parametric statistical tests were used to subsequent analysis. We used permutational multivariate analysis of variance (PERMANOVA) to analyze the independent effects of tactile factors (stroking the outer lateral side of the palm or the little finger), visual factors (whether wearing a supernumerary rubber finger), and time factors (number of experimental trials) on inducing the sixth finger illusion, as well as their interactive effects. Due to the significant interaction between various factors, we used the Mann Whitney U-test and Benjamini–Hochberg correction to compare the consistency of each questionnaire item between each condition in the first and fifth trials, respectively. To examine the overall change from the first trial to the fifth trial, we performed the nonparametric Friedman tests for each questionnaire of the four conditions. We used Dunn's test to compare the five trials with each other. In addition, the participants in this experiment had a balanced gender ratio under all four conditions, so we also compared the gender differences in each questionnaire score under each condition using the Mann Whitney U-test.

Results

The results of PERMANOVA analysis on tactile factors, visual factors, and time factors are shown in Table 1. The results indicated that for Q1, which is the feeling of having six fingers on left hand, all factors and their interactions were significant, except for vision and time which had no significant interaction. Specifically, for each factor, $p_{Tactile} = 0.001$, $p_{Vision} = 0.001$, $p_{Time} = 0.001$, and for their interactions, $p_{Tactile \times Vision} = 0.001$, $p_{Tactile \times Time} = 0.001$, $p_{Tactile \times Vision \times Time} = 0.001$. For Q2, which is the feeling of having two little fingers, there was a significant effect of tactile and visual and their interaction. Specifically, for the tactile and visual factors, $p_{Tactile} = 0.001$, $p_{Vision} = 0.001$, $p_{Tactile \times Vision} = 0.001$. Overall, these three factors and their interactions affected the induction of the sixth finger illusion from different perspectives.

The results of the Mann Whitney U test analysis are shown in Table 2.

Figure 2 shows the consistency of the questionnaire items between the four conditions in the first and fifth trials. The identification of significant differences was based on the results in Table 2. Overall, there were significant differences between the four conditions in the first trial in terms of scoring on the Q2 (the feeling of having two little fingers) and Q5 (the feeling of having an extra hand). The results of the Mann Whitney U test analysis indicated that for Q2 (the feeling of having two little fingers), $Z_{EVLPS-EVLFS} = -2.434$, $p_{EVLPS-EVLFS} = 0.015$, $Z_{SVLPS-SVLFS} = -2.041$, $p_{SVLPS-SVLFS} = 0.041$, $Z_{EVLPS-SVLFS} = -3.037$, $p_{EVLPS-SVLFS} = 0.002$, for Q5 (the feeling of having an extra hand), $Z_{EVLFS-SVLPS} = -2.564$, $p_{EVLFS-SVLPS} = 0.010$. These results show that all four conditions can induce the sixth finger illusion, and stroking the little finger outside is more likely to induce the feeling of having two little fingers compared to stroking the palm outside. Although there was no significant difference in terms of scoring on other questionnaires, further analysis revealed that for Q1 (the feeling of having six fingers on left hand), the average scores of SvLPs and SvLFs were slightly higher than those of EvLPs and EvLFs ($\mu_{SvLPs} = 1.25 > \mu_{EvLPs} = 1.05$, $\mu_{SvLFs} = 0.95 > \mu_{EvLFs} = 0.5$), respectively. Additionally, the average scores of SvLPs and EvLPs were higher than those of SvLFs and EvLFs ($\mu_{SvLPs} = 1.25 > \mu_{SvLFs} = 0.95$, $\mu_{EvLPs} = 1.05 > \mu_{EvLFs} = 0.5$), respectively. Although these differences did not reach a level of statistical significance, their trends are still worth paying attention to. This suggests that both wearing a supernumerary rubber finger and stroking the palm outside have some positive effects on inducing the feeling of having six fingers.

In the fifth trial, there were significant differences between the four conditions regarding the Q1 (the feeling of having six fingers on left hand), $Z_{EVLPS-EVLFS} = -2.421$, $p_{EVLPS-EVLFS} = 0.015$, $Z_{SVLPS-SVLFS} = -2.074$, $p_{SVLPS-SVLFS} = 0.038$, $Z_{EVLFS-SVLPS} = -3.344$, $p_{EVLPS-EVLFS} < 0.001$, the Q2 (the feeling of having two little fingers), $Z_{EVLPS-EVLFS} = -4.268$, $p_{EVLPS-EVLFS} < 0.001$, $Z_{SVLPS-SVLFS} = -3.968$, $p_{SVLPS-SVLFS} < 0.001$, $Z_{EVLPS-SVLFS} = -4.653$, $p_{EVLPS-SVLFS} <$

		Q1		Q2		Q3		Q4		Q5	
	df	R^2	Pr (> F)	R^2	Pr (> F)	R^2	Pr (> F)	R^2	Pr (> F)	R^2	Pr (> F)
Tactile	1	0.276	**0.001**	0.462	**0.001**	0.212	**0.001**	0.226	**0.001**	0.063	**0.007**
Vision	1	0.166	**0.001**	0.180	**0.001**	0.181	**0.001**	0.153	**0.001**	0.281	**0.001**
Time	1	0.100	**0.001**	0.008	0.461	0.035	**0.033**	0.074	**0.005**	0.047	**0.024**
Tactile × vision	1	0.243	**0.001**	0.183	**0.001**	0.317	**0.001**	0.118	**0.001**	0.265	**0.001**
Tactile × time	1	0.039	**0.001**	0.022	0.073	0.040	**0.028**	0.049	**0.033**	0.057	**0.011**
Vision × time	1	0.014	0.094	0.016	0.174	0.029	0.066	0.047	0.055	0.056	**0.018**
Tactile × vision × time	1	0.072	**0.001**	0.019	0.104	0.026	0.088	0.042	0.078	0.042	**0.039**
Residual	12	0.090	-	0.110	-	0.160	-	0.292	-	0.189	-
Total	19	1.000	-	1.000	-	1.000	-	1.000	-	1.000	-

Table 1. Main effects of tactile, vision and time in inducing the six-finger illusion (PERMANOVA). Q1 = It felt like I had six fingers on my left hand; Q2 = It felt like I had two little fingers on my left hand; Q3 = I felt a touch where I do not normally feel a touch; Q4 = I felt a touch that was not on my body; Q5 = It felt like I had an extra hand. The values in bold are significant at a minimum value of $p < 0.05$.

		Q1		Q2		Q3		Q4		Q5	
		Z	*p value*	*Z*	*p value*	*Z*	*p value*	*Z*	*p value*	*Z*	*p value*
First trial	EVLPS vs. EVLFS	-0.584	0.56	-2.434	**0.015**	-0.236	0.814	-0.623	0.534	-1.884	0.060
	SVLPS Vs SVLFS	-1.18	0.238	-2.041	**0.041**	-0.778	0.437	-0.085	0.933	-1.014	0.310
	EVLPS vs. SVLPS	-0.515	0.607	-0.07	0.945	0.000	1	-0.434	0.664	-0.237	0.813
	EVLFS vs. SVLFS	-0.028	0.978	-0.431	0.667	-0.954	0.340	-1.171	0.242	-2.564	**0.010**
	EVLPS vs. SVLFS	-0.493	0.622	-3.073	**0.002**	-0.778	0.437	-0.673	0.501	-0.749	0.454
	EVLFS vs. SVLPS	-1.087	0.277	-1.9	0.057	-0.236	0.814	-0.947	0.344	-1.648	0.099
Fifth trial	EVLPS vs. EVLFS	-2.421	**0.015**	-4.268	**< 0.001**	-0.112	0.911	-1.740	0.082	-0.448	0.655
	SVLPS vs. SVLFS	-2.074	**0.038**	-3.968	**< 0.001**	-1.638	0.101	-1.388	0.165	-0.653	0.514
	EVLPS vs. SVLPS	-1.027	0.304	-1.882	0.060	-0.717	0.473	-0.384	0.701	-0.949	0.342
	EVLFS vs. SVLFS	-1.110	0.267	-0.291	0.771	-0.990	0.322	-0.014	0.989	-2.091	0.052
	EVLPS vs. SVLFS	-1.149	0.251	-4.653	**< 0.001**	-1.158	0.247	-1.895	0.058	-1.713	0.087
	EVLFS vs. SVLPS	-3.344	**< 0.001**	-3.378	**< 0.001**	-0.858	0.391	-1.311	0.190	-1.328	0.184

Table 2. The consistency of each questionnaire item between each condition in the first and fifth trials (Mann Whitney U-test). The values in bold are significant at a minimum value of $p < 0\,0.05$.

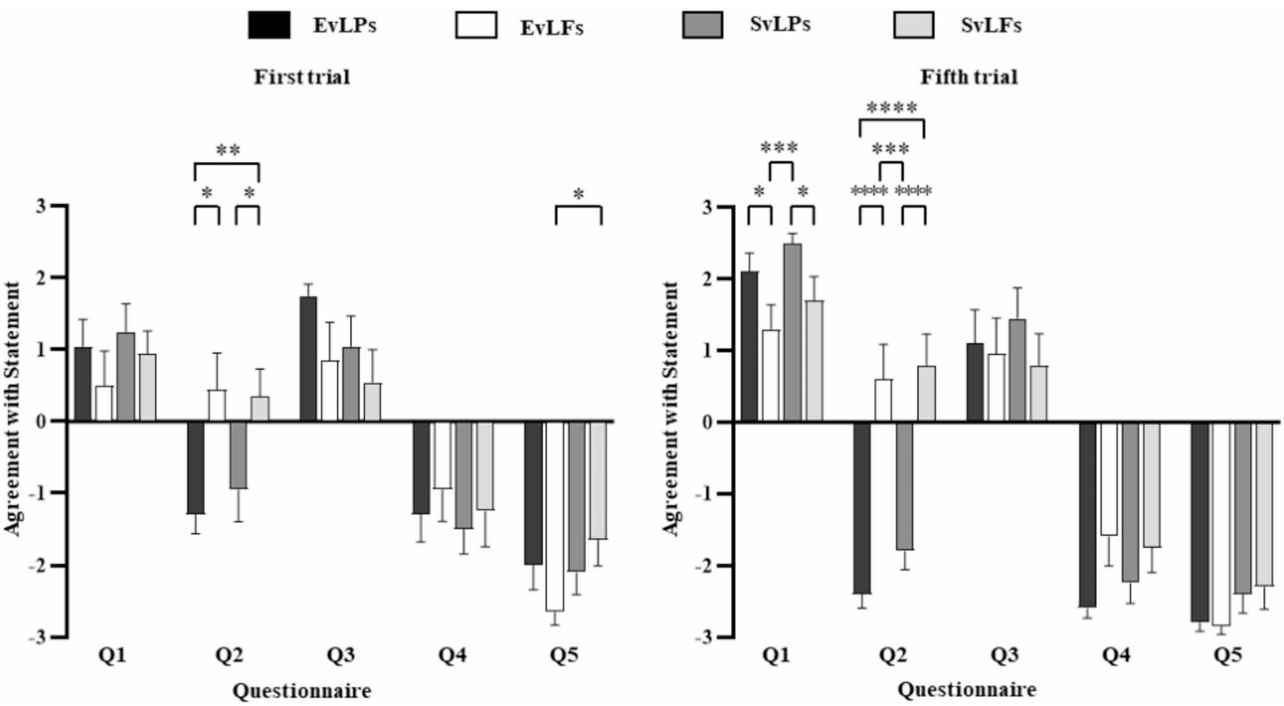

Fig. 2. Mean scores for each questionnaire item under the four conditions in the first and fifth trials. The error bars represent the standard error of measurement ("SEM"). The asterisk indicates statistically significant differences (Mann Whitney U tests, $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$, $^{****}P < 0.0001$). Note: Q1 = It felt like I had six fingers on my left hand; Q2 = It felt like I had two little fingers on my left hand; Q3 = I felt a touch where I do not normally feel a touch; Q4 = I felt a touch that was not on my body; Q5 = It felt like I had an extra hand.

0.001, $Z_{EVLFS-SVLPS}$ = -3.378, $p_{EVLFS-SVLPS}$ < 0.001. These results show that after 5 trials, the palm outside induced a more pronounced illusion of having six fingers compared to the little finger outside, and the little finger outside induced a more pronounced illusion of having two little fingers compared to the palm outside. Although there was no significant difference in other scores, further analysis revealed that for Q1 (the feeling of having six fingers on left hand), the average scores of SvLPs and SvLFs were slightly higher than those of EvLPs and EvLFs ($\mu_{SvLPs} = 2.5 > \mu_{EvLPs} = 2.1$, $\mu_{SvLFs} = 1.7 > \mu_{EvLFs} = 1.3$), respectively. Although these differences did not reach a level of statistical significance, their trends are still worth paying attention to. This again suggests that wearing a supernumerary rubber finger has some positive effects on inducing the feeling of having six fingers.

The impact of the number of trials on the scores of each questionnaire under four conditions is shown in Fig. 3. Friedman tests showed under EVLPS condition, there were significant main effects of the number of trials for Q1 (the feeling of having six fingers on left hand), Q2 (the feeling of having two little fingers), Q4 (the

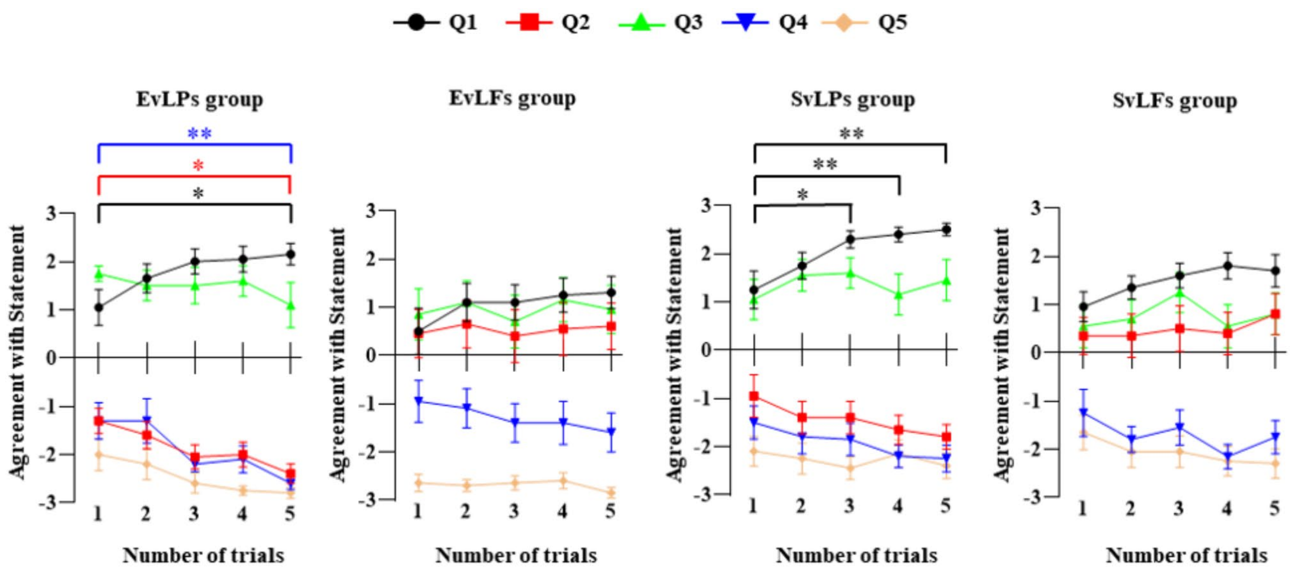

Fig. 3. The variation of mean scores for each questionnaire item in each trial as the number of experimental trials in four conditions. The error bars represent the standard error of measurement ("SEM"). The asterisk indicates statistically significant differences (Dunn's tests, $^{*}P<0.05$, $^{**}P<0.01$). Note: Q1 = It felt like I had six fingers on my left hand; Q2 = It felt like I had two little fingers on my left hand; Q3 = I felt a touch where I do not normally feel a touch; Q4 = I felt a touch that was not on my body; Q5 = It felt like I had an extra hand.

feeling of touch that is not on the body) and Q5 (the feeling of having an extra hand), $Q_{Q1}(4)=23.73$, $p_{Q1}<0.001$, $Q_{Q2}(4)=22.02$, $p_{Q2}<0.001$, $Q_{Q4}(4)=24.72$, $p_{Q4}<0.001$, $Q_{Q5}(4)=24.47$, $p_{Q5}<0.001$. Under SVLPS condition, there were significant main effects of the number of trials for Q1 (the feeling of having six fingers on left hand) and Q2, $Q_{Q1}(4)=39.72$, $p_{Q1}<0.001$, $Q_{Q2}(4)=14.36$, $p_{Q2}=0.006$. Under EVLFS condition, there was a significant main effect of the number of trials for Q1 (the feeling of having six fingers on left hand), $Q_{Q1}(4)=9.783$, $p_{Q1}=0.044$. Under SVLFS condition, there were significant main effects of the number of trials for Q1 (the feeling of having six fingers on left hand) and Q5 (the feeling of having an extra hand), $Q_{Q1}(4)=11.89$, $p_{Q1}=0.018$, $Q_{Q5}(4)=10.09$, $p_{Q5}=0.039$. Further Dunn's tests showed that under EVLPS condition, there were significant differences between the scores of the first trial and the scores of the fifth trial for Q1 (the feeling of having six fingers on left hand), Q2 (the feeling of having two little fingers), and Q4(the feeling of touch that is not on the body), $p=0.037$, 0.012, 0.005. Under SVLPS condition, there were significant differences between the scores of the first trial and the scores of the third, fourth, and fifth trials for Q1 (the feeling of having six fingers on left hand), $p=0.016$, 0.008, 0.001. This clearly indicates that the feeling of having six fingers on left hand is significantly influenced by the number of trials, with the feeling induced on the palm outside showing a significant enhancement as the number of trials increases.

The analysis revealed no significant differences between men and women in each questionnaire in the first and fifth trials in these four conditions.

Discussion

The purpose of this study was to explore the effects of tactile and visual factors in inducing the sixth finger illusion and to investigate the changes in the ownership of the illusion as the number of trials increased. The research results indicate that all three factors have a significant influence on the representation of the sixth finger illusion, and there is an interaction among these factors. Further analysis reveals that, compared to visual effects, the stroking area has a greater impact on the intensity and independence of the illusion. In particular, the palm outside can induce a stronger and more independent sixth finger illusion than the little finger outside. Additionally, the sixth finger illusion induced by these four conditions was significantly influenced by the number of trials, with a significant enhancement in the intensity of the illusion induced by the palm outside as the number of trials increases. Overall, stroking the outer lateral side of the palm can induce a relatively stronger sense of ownership and independence of the sixth finger, and this advantage becomes more prominent as the number of trials increase and reaches a steady state after three trials when wearing a supernumerary rubber finger, while it reaches a steady state after five trials when not wearing a supernumerary rubber finger. Our results provide more evidence for the experience of multisensory integration and the sensory perception establishment of the wearable SRFs.

A prominent feature of the present study is the simultaneous exploration of the effects of the stroking area and visual effects on the sixth finger illusion. The results show that different stroking areas and visual effects have a significant impact on the representation of the sixth finger illusion, and there are complex and interactive effects. This not only emphasizes the contribution of a single sensory channel to the sixth finger illusion, but also highlights the importance of visuo-tactile integration in inducing the illusion. This provides useful clues for further exploring the mechanism of multisensory integration. In order to explore the inducing effects of different combinations of tactile and visual stimuli, we further analyzed the differences in inducing the sixth finger illusion among these four conditions. We observed that the stroking area played a significant role in inducing the sixth finger illusion, while the visual effects had a relatively small effect. Specifically, by analyzing the questionnaire results of the first and fifth trials, we found that tactile factors caused significant differences in the representation of the illusion, whereas visual factors did not. This finding emphasizes the crucial role of tactile input in the formation of bodily illusions.

We further analyzed the effect of stroking area on the representation of sixth finger illusion and found that the palm outside could induce a stronger and more independent sixth finger illusion than the little finger outside. Specifically, we observed that the feeling of having six fingers on left hand induced on the palm outside was more significant than that induced by the little finger outside on the fifth trial. Conversely, the feeling of having two little fingers induced by the little finger outside was more significant than that induced by the palm outside on both the first and fifth trials. However, the illusion of having two little fingers is a proprioceptive illusion and not the illusion of SRFs that we were trying to establish. Therefore, the result indicates that stroking the palm outside can induce a new finger feeling that is more different from the little finger. Cadete et al. have previously verified the independence of the sixth finger illusion induced by the little finger outside without wearing a supernumerary rubber finger in terms of length[24] and curvature[25], so our results can prove that the sixth finger illusion induced by the palm outside will have stronger independence. At the same time, this result also indicates that after multiple induced trials, the advantage of the palm outside in inducing the sixth finger illusion will be more significant, especially in terms of sensory intensity and independence. Currently in the induction of illusions[30,31], especially the sixth finger illusion[18,23], most of the induction locations are physiologically matched, and there are a few studies involving other biased locations. Our study fills this gap. Future research on sensory induction and feedback in the wearable SRFS can establish the palm outside as an independent sixth finger area without sharing existing finger resources to avoid confusion with other fingers.

This study is the first to track the changes in the sixth finger illusion over time and as the number of trials increased. The study found that during the changes of five trials, the feeling of having six fingers on the left hand induced by the four conditions was significantly affected by the number of trials, with the feeling induced by the palm outside showing a significant enhancement as the number of trials increases. This indicates that this illusion is not merely an instantaneous multisensory integration but rather a stable and sustained experience of the sense of ownership and agency. This finding is similar to the results reported by Pazzaglia et al., who restored abnormal pain in an SCI patient who had initially lost somatosensation in all his fingers through several months of stimulation of rubber hand illusion[32]. Bottom-up multisensory input can change the body schema[33], allowing participants to develop a sense of ownership of the sixth finger. And after several trial stimuli, top-down cognition did not allow participants to reject the existence of this illusion, but instead increased the sense of ownership of the sixth finger with the help of the body's image. The participants generally felt a touch that they would not normally feel, yet perceived the touch as being on their own body, which reflects their sense of ownership of this illusion. Further analysis of the result indicated that the sixth finger illusion induced under SVLPS conditions can reach a significant enhancement after three trials, and then reach a relatively stable state. However, under EVLPS conditions it took five trials before a significant enhancement occurred. This suggests that stroking the palm outside while wearing a supernumerary rubber finger can more quickly induce the strong sixth finger illusion.

It should be noted that although the analysis of the questionnaire results from the first and fifth trials did not show significant differences in visual factors, the comparison found that wearing a supernumerary rubber finger has some positive effects on inducing the feeling of having six fingers compared to not wearing a supernumerary rubber finger. This indicates that visual factors may not directly have a good promoting effect on the induction of the sixth finger illusion. Instead, they might exert a positive influence on participants' performance through other factors, such as enhancing their confidence via psychological suggestion, altering the allocation of attention, improving body perception, and so on. This result is consistent with previous research on the rubber hand illusion. Specifically, the RHI is significantly stronger when the artificial object is congruent with the human body than when it is not. For example, when using a rubber prosthetic hand as an artificial object, the intensity of RHI was stronger than when using a tabletop[34], a wooden stick[35], or a two-dimensional projection of the fake hand[36]. These findings provide better insights into the study of body illusions and the design of SRFs.

Taken together, we found that stroking the outer lateral side of the palm could induce a relatively stronger sense of ownership and independence of the sixth finger, and this advantage could be maximized after a shorter number of trials when wearing a supernumerary rubber finger. The establishment of the sixth finger illusion can provide a good perceptual foundation for the use of the SRF and construct connections in the sixth finger region in neural networks. Further study can refer to these findings to advance the development of embodiment and perceptual feedback for long-term wear of wearable SRFs. We also excluded the effect of gender differences on the illusion.

Although this study found that visual factors can also affect the representation of the sixth finger illusion and that wearing a supernumerary rubber finger has some positive effects on inducing the feeling of having six fingers compared to not wearing a supernumerary rubber finger, the current evidence is not sufficient to demonstrate that the visual factor of wearing a supernumerary rubber finger has a significant advantage in inducing the sixth finger illusion. Further in-depth research is needed to explore the specific effect of visual factors in inducing the sixth finger illusion. In addition, the evaluation method used in this study is relatively single, and further research could employ a broader range of methods, such as behavioral measures, neuroimaging, and neurophysiology, to explore the underlying neurophysiological mechanisms. Future research should also include a control condition that does not induce the sixth finger illusion to ensure the comprehensiveness and rigor of the entire experiment. This would provide a more robust foundation for other diverse research endeavors.

Conclusion

In this paper, we explored the effects of tactile, visual, and the number of trials in inducing the sixth finger illusion. We conducted five sixth finger illusion induction trials by stroking the palm outside or the little finger outside in conditions with and without wearing a supernumerary rubber finger, respectively. The results show that the stroking area has a greater impact on the intensity and independence of the illusion compared to visual effects. In particular, the palm outside can induce a stronger and more independent sixth finger illusion compared to the little finger outside. In addition, the sixth finger illusion induced by these four conditions was significantly influenced by the number of trials, and there is a significant enhancement in the intensity of the illusion induced by the palm outside as the number of trials increases. These results indicate that stroking the outer lateral side of the palm can induce a relatively stronger and more independent sixth finger illusion, and the intensity of the illusion reaches a steady state after three trials when stroking the outer lateral side of the palm while wearing a supernumerary rubber finger, while it reaches a steady state after five trials when stroking the outer lateral side of the palm while not wearing a supernumerary rubber finger. This study adds evidence to the research on multisensory integration and sensory feedback of the supernumerary robotic fingers. However, the evaluation method used in this study is relatively single, and further research could employ a broader range of methods, such as behavioral measures, neuroimaging, and neurophysiology, to explore the underlying neurophysiological mechanisms.

Data availability

The data that support the findings of this study are available from the corresponding author, Yuan Liu (ryanliu@tju.edu.cn), upon reasonable request.

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Author contributions
Design of the study: G.W., Y.L., W.W., and D.M.; Experiment and data acquisition: G.W. and Z.W.; Analysis and interpretation of data: G.W., S.H., Y.L., and D.M.; Writing manuscript: G.W., W.W., and Y.L.; Funding: Y.L. and D.M. All authors reviewed the manuscript.

Declarations

Competing interests
The authors declare no competing interests.

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