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Effect of peri-hand space among users of a familiar tool: More attention enhancement in space near palm than dorsal side of hand

Xiang Che[1], Yu Zhang[2], Jukka Hyönä[3], Jijun Lan[1], and Jie Li[4,5]

[1] Key Laboratory of Behavior and Cognitive Neuroscience of Shaanxi, School of Psychology, Shaanxi Normal University, Xi'an, China
[2] School of Psychology, Beijing Sport University, Beijing, China
[3] Department of Psychology and Speech-Language Pathology, University of Turku, Turku, Finland
[4] Center for Cognition and Brain Disorders, the Affiliated Hospital, Hangzhou Normal University, Hangzhou, China
[5] Institutes of Psychological Sciences, Hangzhou Normal University, Hangzhou, China

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Correspondence
Jie Li
Room 119, No. 18 Shuyuan Building, Cangqian Campus, Hangzhou Normal University, Hangzhou, 311121, China. e-mail: lijie.psy@hznu.edu.cn
or
Jijun Lan
Room 9407, No. 9 Teaching Building, 199 South Chang'an Road, Yanta Campus, Shaanxi Normal University, Xi'an, 710062, China. e-mail: xingzhilab@126.com

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Author Contributions

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Abstract

Peri-hand space (PHS) can be extended to space near tools used in everyday life, indicating that the space near the functional area of a tool acquires more spatial attention, which may be affected by tool experience. In previous studies, effects of extensive experience in tool use on the allocation of spatial attention near a tool have not been investigated. We aimed to remedy this by examining spatial attention allocation among table tennis athletes experienced in using a racket. Hands — the body parts that directly link the body and a tool — are vital for tool utilization; yet, few studies have explored whether holding a highly familiar tool in hand biases spatial attention toward it. Using an attentional cuing paradigm, we examined attention allocation in peri-hand space by comparing three hand-held conditions: table tennis racket, short brush and free hand. The performance of table tennis athletes was compared to that of badminton athletes and non-athletes. All three groups demonstrated attentional enhancement in PHS. More importantly, only table tennis athletes differentiated the space near the palm and dorsal side: attentional bias was greater for the palm side. We suggest that attentional enhancement at the palm side may be due to their frequent use of the forehand stroke. We further argue that as the functional area of the table tennis racket is very close to the hand, it is feasible that the attentional advantage related to the peri-hand space may be strengthened by extensive tool use.

Keywords: spatial attention, table tennis, peri-hand space (PHS), tool familiarity

Introduction

To interact with objects, humans use the functional area of the hand—specifically the palm side—to connect the mind to the outside environment via grasping and attentional guidance. Although the hands allow us to connect with objects, we rarely keep track of our hands and seem to deliberately ignore their location, focusing instead on objects within the near space (Reed et al. 2010). This space is defined as peri-hand space (PHS), the relevance of which has been demonstrated in numerous studies (Bamford et al. 2020; Patané et al. 2019).

In environments where tools are necessary for connecting with other objects (e.g., keyboards, chopsticks), their influence on our attention is of prime importance. We interact with objects around us using our hands, while we also utilize tools to satisfy various purposes. Notably, PHS can modify attention allocation by facilitating the processing of hand-adjacent stimuli (Reed et al. 2006, 2010), as this space is prioritized for attentional processing via recruitment of bimodal visual-tactile neurons (Di Pellegrino and Làdavas 2015; Serino Canzoneri et al. 2015). Moreover, the space near the functional area of actively used tools can extend PHS (Cardinali et al. 2016; Holmes et al. 2007; Miller et al. 2014). Therefore, the space near tools can also benefit from attention enhancement.

Tool Morphology and Experience of Tool Use

PHS, especially the palm space, can be influenced via tool use, reflected in the allocation of spatial attention (Bush and Vecera 2014). Numerous studies suggest that tools with different morphologies have diverse impacts on spatial attention allocation (Kao and Goodale 2009; Romano et al. 2019). Specifically, a series of studies revealed that tools with or without functional areas and additional function parts may induce different mechanisms of spatial attention allocation; moreover, reaction times (RTs) to targets near the end of the functional part of the tools are sped up (Park 2018; Park and Reed 2015).

Tool morphology provides only a part of the story. Experience in tool use can enhance one’s capacity for action (Weser and Proffitt 2021). When a tool is used extensively, its properties may be exploited to regard the tool as an extension of the body (Clark, 2003). For instance, table tennis athletes have extensive experience in using the table tennis racket (Poizat et al. 2004; Iino and Kojima 2009; Malagoli Lanzoni et al. 2014). The long-term racket experience of athletes thereby can induce a durable extension from the space around the hand to the space around the implement (Biggio et al. 2017).

The issue regarding effects of tool familiarity on spatial attention has received considerable research interest. For example, Bassolino et al. (2010) recruited right-handed staff members who were daily mouse-users as a group highly familiar with the mouse tool. They responded via the mouse to tactile stimuli cued by presenting a sound from a loudspeaker placed either next to the mouse or next to the monitor. Reaction times were equally fast in these conditions, implying that familiar tool use can extend spatial attention near the functional area of the tool. An analogous effect was demonstrated among blind people who passively held their regularly used cane during a similar task (Serino et al. 2007).

Tool familiarity is a result of the experience gained over years of practice (Biggio et al. 2017, 2020). While learning to use a tool, learners need feedback for motor and semantic information regarding the tool use in order to familiarize the motor pathways relevant for this particular tool (Matheson et al. 2019). As a result, familiar tools induce activation in sensorimotor areas of the brain related to previously learned experience (Valyear et al. 2012). Recent studies indicate that the long-term experience of tool use may result in a permanently extended PHS that is selectively activated while holding the tool (Longo and Serino 2012; Serino 2019). Furthermore, long-term tool users often demonstrate distinct effects of tool use that can be elicited even in the absence of active tool using (Weser and Proffitt 2021).

A common method adopted to investigate this question in previous studies (i.e., comparing participants' attention performance before and after a brief training) has produced results highlighting the importance of the degree of familiarity with a tool. Yet, studies on tool use have adopted different definitions of tool familiarity, so that the training period has varied from one to several minutes to ensure that the tool can be properly used (Galigani et al. 2020; McManus and Thomas 2020; Park and Reed 2015). In the present study, we significantly departed from the commonly used training intervention. Instead, we selected a group who had had extensive practice with the tool use prior to the study. The group of our primary interest was table tennis athletes possessing long-time experience in using the table tennis racket.

Hands and Tools

The hands, especially the palm, are critical and intimate parts of the body used to interact with objects in the environment. Their grabbing mechanism, which induces behavioral guidance, incurs more attention to be allocated near the palm space than near the dorsal side (Reed et al. 2010; Vyas et al. 2019). To investigate whether the hand's grab function induces a peri-hand attention bias, McManus and Thomas (2018) adopted an attention cueing paradigm with a mitten-shaped, rigid orthosis to fix hand postures and restrain grabbing. Interestingly, an attentional bias in the palm space was nevertheless observed, signifying that the palm space exerts a stable effect in attentional allocation. Further supporting evidence has come from studies examining effects of actively using hand-held tools with only one functional area (e.g., a rake has a functional area only at one of its two ends; Kao and Goodale 2009; Reed et al. 2006; Vyas et al. 2019). This evidence suggests that the palm-side attentional bias extends to the functional area of tools.

The hand's grabbing mechanism results in the ability to utilize tools. At the same time, improved tool use may positively correlate with attentional allocation advantages near the space of the tool (Bamford et al. 2020; Biggio et al. 2017). Attentional enhancement may not only be observed at PHS but also near the tool's functional area (Reed et al. 2010). In other words, the tool's end attracts more spatial attention and brings with it visual cognitive facilitation after training (Park et al. 2013; Park and Reed 2015). However, in order to observe a peri-hand attention allocation bias, the hand has to hold the tool. McManus and Thomas (2020) observed that only tools in the hand-held conditions (e.g., rake) produced attentional enhancement near the tool's functional area; no effect was found in the remote-control condition (e.g., drone).

It is also noteworthy that handedness and hand posture are significant factors to be taken into consideration. For handedness, Lloyd et al. (2010) found that only the dominant hand can induce obvious attention attraction bias in PHS. For hand posture, a study found that the recognition of action affordances may depend on an object's grasp-appropriate posture (Handy et al. 2003). Thomas (2013) asked participants to adopt two different hand postures in a study utilizing the attentional cueing paradigm, an effective paradigm to investigate the peri-hand effect (Colman et al. 2017; McManus and Thomas 2018, 2020; Reed et al. 2010). Interestingly, peri-hand vision facilitation occurred only in the power grab posture condition, not in the precision grasp condition.

As reviewed above, after a short training period of tool use, trained tools attract more attention near their space similar to the hand itself. Yet, it is still unclear whether high familiarity with tool use brings with it increased attention allocation in PHS, especially when handedness and hand posture are taken into consideration. This is what we set out to investigate in the present study.

The Present Study

As reviewed above, PHS can modify attention allocation by enhancing attention to hand-adjacent stimuli (Reed et al. 2006, 2010). Moreover, attention enhancement has been observed for the space near tools when participants have experience in tool use and the tool is held in hand (Reed et al., 2010; McManus and Thomas 2020). Enhancement in attention allocation for the space near a tool may be considered an extension of the PHS effect. Existing research recognizes the critical role played by tool familiarity for attention enhancement observed for the space near a tool. It seems reasonable to argue that the training time needed to master a tool depends on the tool’s complexity and function. However, prior research has not fully exploited individual variability in tool experience and familiarity. Therefore, we adopted a tool their users are highly familiar with and have ample experience in its use.

Previous studies suggest that attention enhancement of PHS extends to the functional area of a tool. The hand as the body part that directly links the body and tool is vital for tool utilization. Therefore, the present study investigated attention allocation near the hand and near the space of a tool's functional area while manipulating tool familiarity between participant groups. We adopted the attentional cueing paradigm developed by Posner et al. (1987). Studies using this paradigm have reliably demonstrated biased attention allocation in the PHS and space near the functional area of a tool (Carrasco and Barbot 2019; McManus and Thomas 2020; Reed et al. 2010). Thus, it is highly suitable for the present study.

Table tennis athletes (TTAs) comprise a group that is likely to demonstrate an extension of PHS to the functional area of their tool, table tennis racket. TTAs use the racket similarly to their hand, as the functional area of the racket is near the palm. To tease apart the effect of tool familiarity, we also recruited badminton athletes (BAs), who utilize a racket proficiently at the same interceptive sport level as TTAs (Mann et al. 2007). However, the functional area of the badminton racket is much further away from the hand than that of the table tennis racket. Yet, TTAs and BAs are similar in that they both are better using the forehand (palm side) than backhand (dorsal side) stroke. Non-athletes (NAs) provided a control for the possible influence of sport experience on attentional guidance (You et al. 2018; Zhao et al. 2018).

To minimize the influence of hand posture, we used the same grip for the two hand-held tool conditions, table tennis racket and short brush. We selected the shake-hand grip, one of the most common table tennis grip styles (Suzuki and Yamamoto 2015). It differs somewhat from the grip BAs use for holding the badminton racket. Moreover, to examine possible effects of tool morphology, in addition to using the table tennis racket, we created a custom short brush with two dimensions of functional orientation similar to the table tennis racket and with approximately the same length, weight, and attachment. The free-hand condition was included to test whether attentional enhancement is similar in size with and without a tool in hand.

In the attentional cuing paradigm, we presented visual targets either to the left or right side of the monitor. During a subset of trials, a visual cue was presented prior to the target presentation. Three hand-held conditions were tested: table tennis racket, short brush and free hand. In all these conditions, the hand was held near the monitor. Moreover, two hand locations were created: right and middle. In the right-hand condition, the target presented to the right appeared in the palm side of the hand, whereas in the middle location it appeared in the dorsal side. In addition, no-hand condition was also tested as a baseline block: the hand was resting on the participant’s lap. Reaction times to the targets were used as the dependent measure.

The following predictions were entertained. If PHS is extended to the functional area of a highly familiar tool, TTAs should demonstrate a stronger rightward bias than NAs and BAs. The bias should be particularly noticeable for the trials where the target appears to the right at the same time as TTAs hold a table tennis racket in the right-hand location.

Method

Participants

Power analysis (G-Power) was calculated using the effect size of 0.25. It indicated that a sample of 17 participants would yield 0.80 power at $\alpha = .05$. Yet, to ensure sufficient power, we recruited 21 TTAs, 21 BAs, and 27 NAs for the study. The participants earned course credit and a monetary reward for their participation. All athletes qualified at least for the national level II according to the General Administration of Sport of China from Beijing Sport University. We excluded from the final sample all participants whose performance accuracy was under 70% in the catch trials. The final sample included 18 TTAs (age = 21.4 ± 1.8 years, 9 males), 18 BAs (age = 20.9 ± 1.3 years, 12 males), and 24 NAs (age = 24.6 ± 1.9 years, 11 males). All participants were right-handed and had a normal or corrected-to-normal vision. The study was approved by the Ethics Committee of Beijing Sport University (No. 20200826). All participants provided demographic information and signed a consent form.

Procedure

The experiment was conducted in a closed, empty, quiet room with a 22-inch monitor set in the corner with a resolution of 1920 × 1080 and a refresh rate of 60 Hz. A mouse wired through a USB 2.0 port, a standard table tennis racket, and a short brush similar in weight and size to the racket were utilized. A cushion covered with a thick soft braided fabric was placed on a clean, flat desktop area in front of the monitor. The participants placed their right arm on the cushion and adjusted their position depending on their height or any other physical needs. The experimental task was run with E-prime 2.0.

Participants' sitting position was adjusted so they could sit up straight against the back of the chair. The cushion was fixed on the desktop to better control participants' body posture and maintain the distance of 54 cm between their eyes and the monitor. Participants were required to hold in their right hand either a table tennis racket, a short brush or be free-handed. Both tools had a shaft and two symmetrical functional areas. Participants held a racket or short brush using a shake-hand grip (see Fig. 1). NAs and BAs lacked experience with the shake-hand grip, so the experimenters provided instructions and checked the hand posture during every block.

Hand location was also manipulated with two conditions, middle and right. For the right condition, the cushion was located on the table so that the right hand was located near the right corner of the monitor (see Fig 3). For the middle condition, the cushion was placed so that the right hand was located a little bit to the right of the center fixation point not to occlude the fixation point. This way the palm (right hand condition) and the dorsal (middle hand condition) of the hand was kept at an identical distance to the right target.

At the beginning of each block, the screen displayed the instructions and two dashed lines aligned vertically at an equal distance (1.2 cm, subtending 1.27° visual angle) to the target on the right, which helped the experimenter adjust the participants' hand location (i.e., if the left line turned red, the participants placed their hands aligned to the left line; see Fig. 2). The experimenter helped participants adjust their arms comfortably on the cushion (see Fig. 3).

The attentional cueing paradigm was used to examine the allocation of spatial attention in the peri-hand area or near the functional area of the tool. At the beginning of each trial (Fig. 2), a blank screen with a central fixation cross appeared for 1000ms; the participants were told to focus their gaze on the cross throughout the experimental task. Then, a 1500–3000-ms random delay appeared during which the fixation cross and the two boxes (one 5°of visual angle to the left and another 5° to the right of the fixation cross) were presented. After that, one of the boxes was cued for 200ms by bolding it. Finally, the target (a star) appeared in the valid trials in the cued box and in the invalid trials in the uncued box. In the catch trials no target was presented. The cue remained visible until response or up to 2000ms. The valid trials accounted for 70% of the total number of trials, the invalid trials for 20% of the trials, and the catch trials for 10% of the trials. Participants were instructed to click the right mouse button with their left hand to respond to the target as quickly as possible. In the catch trials, the participants were instructed not to click the mouse button. The catch trials served the purpose of distinguishing participants who did not follow the instructions.

In total, four blocks were conducted: a baseline block (no hand) and the three hand-held condition blocks (free hand, table tennis racket, short brush). A Latin square design was adopted for ordering the presentation of the hand-held conditions and the baseline condition. Within each hand-held condition block, there were two sub-blocks of the hand location condition (middle, right), the order of which was randomized. In the baseline block (no hand) there was just one sub-block, in which the participant placed his/her right hand on his/her lap under the table (not to appear in their visual field).

Thus, the random ordering of hand location did not apply to the baseline condition.

The first practice block contained 20 trials, aiming to familiarize the participants with the task requirements and the required hand locations. The next seven blocks comprised the experiment proper; each block comprised 80 trials (McManus and Thomas 2020). The number and probability of the target stimuli appearing in the left and right box was identical with 36 randomly presented trials for each box. The duration of the experiment was approximately 35 minutes.

Results

To eliminate anticipation and inattention errors, trials with RT < 150ms (3.11%) or > 1000ms (0.11%) for TTAs, RT < 150ms (3.19%) or > 1000ms (0.16%) for NAs and RT < 150ms (6.98%) or > 1000ms (0.19%) for BAs were excluded from the analyses (Colman et al. 2017). Additionally, catch trials were excluded from the analyses. SPSS 26.0 was used for all statistical analyses. First, a separate within-subjects repeated-measures analysis of variance (ANOVA) was conducted for TTAs, NAs, and BAs. Then, a between-subjects ANOVA was carried out to investigate whether the peri-hand effect varied between groups.

TTAs

RT data (ms) were submitted to a 3 × 2 × 2 × 2 within-subjects repeated-measures ANOVA. Within-subjects factors included hand-held condition (free hand, table tennis racket, short brush), cue validity (invalid vs. valid), hand location (middle vs. right), and target location (left vs. right).

The main effect of target location was significant, $F(1, 17) = 12.467$, $p = .003$, $\eta_p^2 = .423$; right targets were responded to significantly faster than left targets ($RT_{\text{right target}} = 330\text{ms}$, $SE = 12\text{ms}$, $RT_{\text{left target}} = 354\text{ms}$, $SE = 15\text{ms}$). Further, the main effect of cue validity was significant, $F(1, 17) = 69.032$, p

$< .001$, $\eta_p^2 = .802$; valid cues resulted in significantly faster RTs than invalid cues (RT $_{valid}$ = 316ms, *SE* = 11ms, RT $_{invalid}$ = 367ms, *SE* = 16ms). There was also a significant interaction between cue validity and target location, $F(1, 17) = 8.133$, $p = .011$, $\eta_p^2 = .324$. To follow up this interaction, we compared the mean difference of two target locations (RT $_{left\ target}$ – RT $_{right\ target}$) between the two cue validity conditions. The paired sample *t*-test, $t(17) = -2.947$, $p = .009$, revealed a stronger attentional bias toward right for the invalid condition ($M_{invalid\ difference}$ = 31ms, *SE* = 9ms) than for the valid condition ($M_{valid\ difference}$ = 11ms, *SE* = 5ms). On the other hand, the rightward attentional bias was not modulated by the hand-held condition. In other words, the observed bias was similar in size for the space near hand or a tool.

Importantly, ANOVA also revealed a significant interaction between hand location and target location, $F(1, 17) = 4.657$, $p = .046$, $\eta_p^2 = .215$. A simple effects analysis (Bonferroni corrected) revealed that the RTs to the right targets were significantly shorter when the hand was positioned in the right location (palm near the right target; RT $_{right}$ = 325ms, *SE* = 12ms) than when the hand was positioned in the middle location (dorsal near the right target; RT $_{middle}$ = 335ms, *SE* = 12ms) ($p = .032$). On the other hand, for RTs to the left targets, there was no significant difference between the right and middle hand location (RT $_{right}$ = 352ms, *SE* = 16ms, RT $_{middle}$ = 355ms, *SE* = 15ms, $p = .649$) (see Fig. 4a). This finding indicates that TTAs allocate more attention to their palm space than the dorsal side in all hand-held conditions also including the racket.

NAs

For the NAs, the 3 × 2 × 2 × 2 within-subjects repeated-measures ANOVA revealed a significant main effect of target location, $F(1, 23) = 9.759$, $p < .001$, $\eta_p^2 = .298$; responses to right targets were significantly faster than those to left targets (RT $_{right\ target}$ = 336ms, *SE* = 6ms, RT $_{left\ target}$ = 346ms, *SE* =

8ms). Moreover, the main effect of cue validity, $F(1, 23) = 170.584$, $p < .001$, $\eta_p^2 = .881$, indicates that cued trials were responded to significantly faster than uncued trials (RT $_{\text{valid}} = 321$ms, $SE = 7$ms, RT $_{\text{invalid}} = 363$ms, $SE = 7$ms). None of the other main effects or interactions were significant.

BAs

The results of BAs were similar to those of NAs. The within-subjects 3 × 2 × 2 × 2 ANOVA revealed a significant main effect of target location, $F(1, 17) = 14.267$, $p = .002$, $\eta_p^2 = .456$, indicating that BAs reacted to right targets significantly faster than to left targets (RT $_{\text{right target}} = 314$ms, $SE = 12$ms, RT $_{\text{left target}} = 324$ms, $SE = 13$ms). A main effect of cue validity, $F(1, 17) = 66.363$, $p < .001$, $\eta_p^2 = .796$, indicates that cued trials resulted in significantly faster responses than uncued trials (RT $_{\text{valid}} = 297$ms, $SE = 12$ms, RT $_{\text{invalid}} = 341$ms, $SE = 14$ms). There were no significant interactions, including hand location and target location (see Fig. 4c), implying that for BAs no significant attentional enhancement was observed for the palm compared to the dorsal of the hand.

Group differences for PHS

To investigate whether TTAs had a greater attention allocation bias near tools or hands (i.e., PHS) than BAs or NAs, we calculated the mean difference of target location (RT $_{\text{target left}}$ – RT $_{\text{target right}}$) for the three groups. We then computed a between-subjects ANOVA on the difference score. A significant main effect of group emerged, $F(2, 57) = 3.178$, $p = .049$, $\eta_p^2 = .100$. Post-hoc analyses indicated that the TTAs had a significantly larger PHS bias (see Fig. 5a; $M_{\text{TTAs difference}} = 23$ms, $SE = 7$ms) compared to the NAs ($M_{\text{NAs difference}} = 9$ms, $SE = 3$ms, $p = .022$) and BAs ($M_{\text{BAs difference}} = 10$ms, $SE = 3$ms, $p = .047$). The stronger attentional bias for TTAs suggests that they pay more visual attention to the space of near the tool than the other groups.

Further, we also calculated the mean difference of target location (RT $_{\text{target left}}$ – RT $_{\text{target right}}$) in the no-hand condition (See Fig 5b) of TTAs ($M_{\text{TTAs difference}} = 4$ms, $SE = 5$ms), NAs ($M_{\text{NAs difference}} = 4$ms, $SE = 5$ms) and BAs ($M_{\text{BAs difference}} = 3$ms, $SE = 5$ms). These effects were not different significantly from zero (TTAs, $t(23) = .746$, $p = .463$; NAs, $t(17) = .607$, $p = .552$; BAs group, $t\ (17) = 1.036$, $p = 0.315$) or from each other ($F_{(2,57)} = 0.003$, $p = 0.997$, $\eta_p^2 < 0.000$). The results corroborated that the biased attention allocation towards the right target in the free-hand and tool-holding conditions were due to the PHS effect rather than a general bias towards target at right.

Discussion

The present study set out to examine whether ample experience in tool use can extend PHS to the functional area of a familiar tool. In order to study this, we tested in an attentional cuing paradigm a group of table tennis athletes (TTAs), whose tool, table tennis racket, is a close extension of their hand. Their performance was compared to another group of athletes, badminton athletes (BAs), who are also highly experienced in racket use. Yet, the functional area of the badminton racket is not a natural extension of the hand but rather that of the arm. A group of non-athletes (NAs) was tested as another control group to table tennis athletes.

Attentional advantage in PHS

All groups replicated the PHS effect (Garza et al. 2013; Gozli et al. 2012; Reed et al. 2013; Tseng and Bridgeman 2011): participants' reaction times to targets appearing close their hand were faster than to targets appearing farther away from their hand. In both tested hand locations (middle vs. right), participants' right hand was much closer to the target on the right (both middle and right: 1.2 cm, 1.27°) than on the left (middle: 7.2 cm, 7.59°; right: 9.6 cm, 10.08°). These results are interpreted to reflect the difference in processing objects near an action-relevant effector, such as a hand, compared to objects farther in space (Thomas and Sunny 2017a, 2017b). More importantly, we found that TTAs' performance was modulated by their hand location; reaction times to targets appearing on the right were faster when the targets appeared in space near the palm side than the dorsal side of their right hand. The effect reflects an attentional bias in processing objects present close to the palm (see also Coleman et al. 2017; Reed et al. 2006).

Attentional advantage in near palm space among TTAs

Attentional enhancement at the palm side observed for TTAs was not present for BAs or NAs. On the other hand, unlike what was predicted, the palm-side advantage was not particularly robust for the condition where TTAs held a table tennis racket in their hand. In other words, the effect was not modulated by the hand-held condition. Instead, TTAs demonstrated a more general palm advantage. Why is that?

We speculate that this may be because in table tennis games TTAs use more the forehand (palm) than the backhand (dorsal) stroke. Forehand shots involve whole-body movements, thus generating a greater force compared to a smaller force generated by backhand shots that rely on a range of arm movements concerning the trunk (Bańkosz et al. 2020; Bańkosz and Winiarski 2017; Caliari 2008). Thus, forehand (palm) strokes are frequently performed in table tennis games. Moreover, forehand topspin shots enacted with the palm side of the racket are associated with much higher maximal acceleration in table tennis than backhand topspin shots (Bańkosz et al. 2020). In sum, TTAs' attentional enhancement at the palm side may be due to their frequent use of the forehand stroke.

Why was the palm advantage not observed primarily in the racket condition but also apparent in the brush and free-hand condition? It is unlikely due to the shake-hand grip familiar to TTAs. This is because the results for the free-hand condition were similar to those of the two shake-hand grip conditions (racket and brush). Instead, it may be due to the table tennis racket being a natural extension of the hand. Its functional area is very close to the hand, so it is feasible that the attentional advantage related to the peri-hand space may be strengthened by extensive use of the table tennis racket. This may explain why it is also observed in the free-hand condition.

Attentional cuing among TTAs

We also obtained an attentional cuing effect for TTAs not observed for the two other groups. The main effect of cue validity, observed for all three groups, was qualified by target location for TTAs. TTAs responded to 11ms faster to right than left targets. In other words, with valid target location cues, the PHS advantage was rather small. On the other hand, with invalid target location cues, TTAs showed a stronger PHS effect. When the target was invalidly cued to appear in the right but was instead presented in the left, their target responses were much longer (381ms) than when the target was invalidly cued to appear in the left but was instead presented in the right (350ms). A visual cue presented to the right probably strengthened their attentional bias to PHS. Therefore, their responses to left targets that were invalidly cued to appear in the right were particularly slow. Although the effect was not predicted, it may be considered as further evidence for the view that extensive tool use near PHS is capable of strengthening the attentional bias toward PHS.

Tool familiarity and PHS

As mentioned above, ample experience in tool use did not modify the PHS effect among TTAs, nor was there a main effect of the hand-held condition. Thus, the present study did not lend support for the effect of tool familiarity observed in previous studies. In some studies, rarely used tools showed significantly slower RTs than often-used tools (Bassolino et al., 2010; Biggio et al., 2017). Moreover, an fMRI analysis demonstrated that the left precuneus that provides a visuo-spatial representation of the functionally appropriate hand-tool interaction was active more for participants seeing familiar tools than they saw unfamiliar tools (Vingerhoets 2008). On the other hand, the present study demonstrated for TTAs a greater spatial attention bias in PHS than for BAs and NAs regardless of the tool held in hand. Thus, this result suggests that a long-term use of the table tennis racket can generally enhance attention in PHS. Broadly in line with this suggestion, Hung et al. (2004) showed elite table tennis players to exhibit greater motor preparation than non-athletes and thus get a greater reaction time benefit for processing stimuli on the side of their hand. In sum, we argue that due to TTAs long-term use of the racket as an extension of their hand and particularly their palm has strengthened attentional processing in PHS.

Limitations

This study has some limitations that should be addressed in future research. First, in real life TTAs' use of the racket is very dynamic during intense and fast-paced games. However, in the present study, its use was static, as we instructed them to passively hold the racket in the same place. Second, in table tennis games TTAs must decide fast the actions to be performed. Thus, they may have acquired an ability to detect the ball located in relatively distant spaces. Therefore, whether also stimuli far from the racket gain increased attention seems worth investigating. Third, the tools adopted in this study were short tools, which offer a limited extension of the limb. Thus, the issue of attention allocation of familiar users of long tools while holding it in extra-personal space remains unclear.

Conclusion

The current study demonstrated that the space near a hand-held short tool can attract increased attention similar to the peri-hand space (PHS). Moreover, it provided further insight into the PHS effect by reporting effects of tool familiarity and sports experience. The results indicate that table tennis athletes show an attention-allocation bias particularly for the space near the palm. We speculate that the palm-side bias in attentional allocation may be a result of the frequent use of the forehand (palm) strokes in table tennis games.

Figure captions

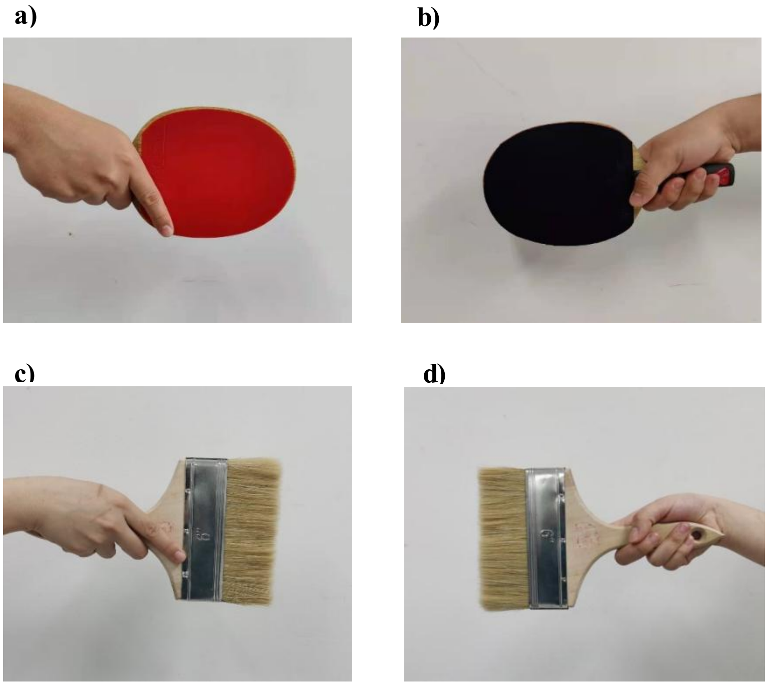

Fig. 1 In the shake-hand grip posture, one holds the racket shaft in the palm of the hand with the thumb-index web on the root of the shaft while gripping the middle, ring, and little finger bent over the shaft and the index finger naturally straight against the racket dorsal side. The figure illustrates the dorsal side (a) and palm side (b) of holding a table tennis racket and the dorsal side (c) and palm side (d) of holding a short brush with this posture.

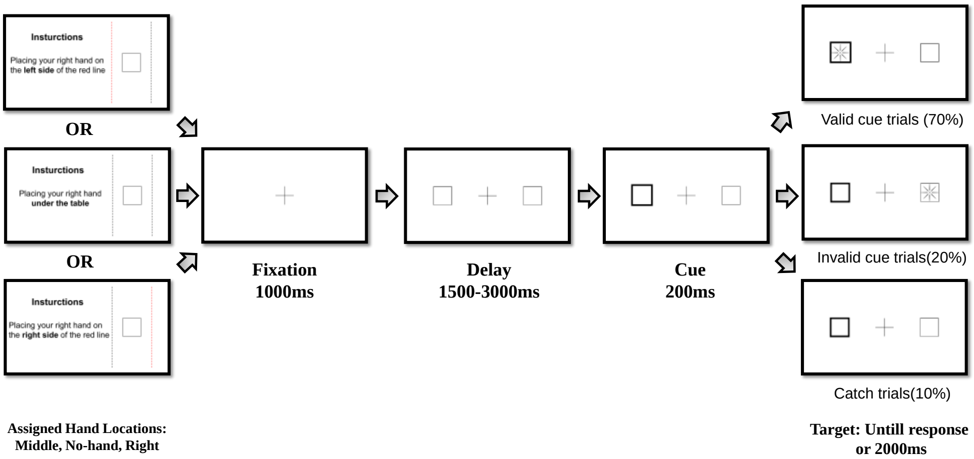

Fig. 2 A graphic depiction of the attentional cueing paradigm used in the present study with three alternative

instructions for placing the right hand either in the middle or right side, with the no-hand serving as the baseline. In the present study, 70% of cases were valid-cue trials where the visual cue (the box appearing in bold) correctly indicated the location of the target (a star), while 20% were invalid-cue trials where the cue appeared in the opposite box to the target. Ten percent of the trials were catch trials in which the target was not present in either box.

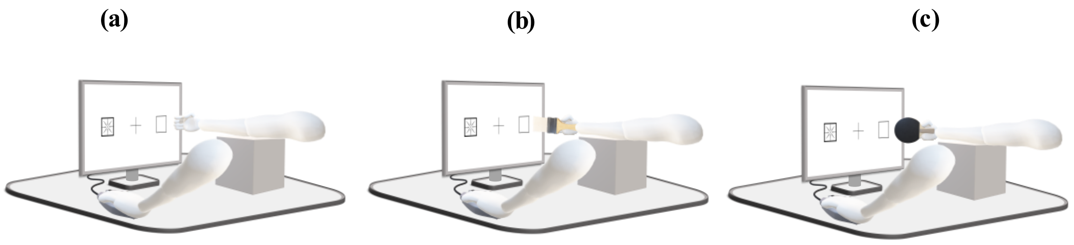

Fig. 3 The schematic diagram illustrates the three hand-held conditions for the right-hand location: (a) free hand, (b) holding a short brush and (c) holding a table tennis racket.

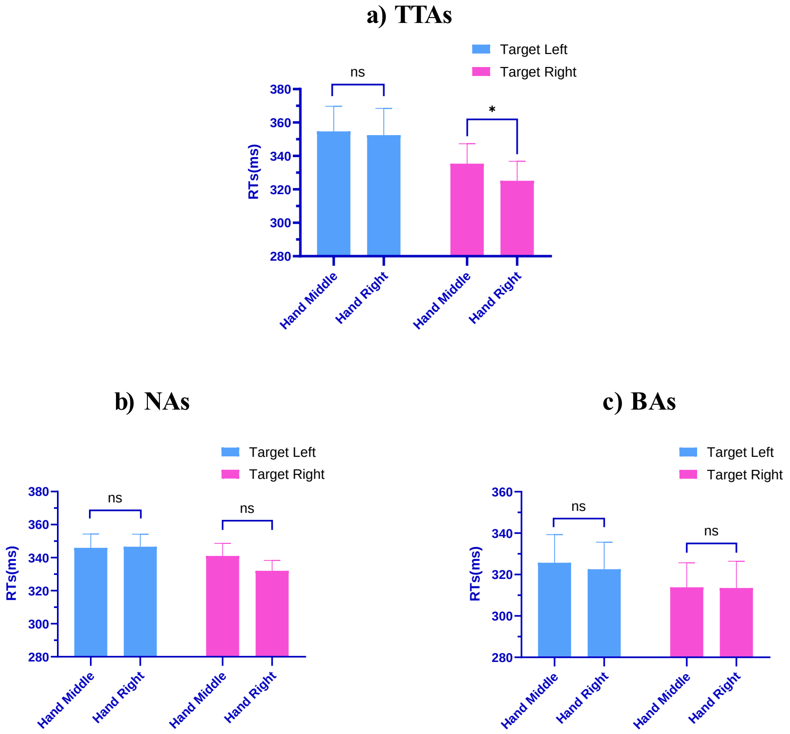

Fig. 4 Reaction times (ms) for the three groups (TTAs = table tennis athletes; NAs = non-athletes; BAs = badminton athletes) as a function of target location (left vs. right) separately for the palm side (hand located on the right adjacent to the target) and the dorsal side (hand located in the middle adjacent to the right target) of the hand. The graphs

show the interaction of the hand and target location for (a) TTAs, (b) NAs, and (c) BAs. Error bars denote the standard error of the mean (SEM); * = p < .05; ** = p < .01, ns = p > .05.

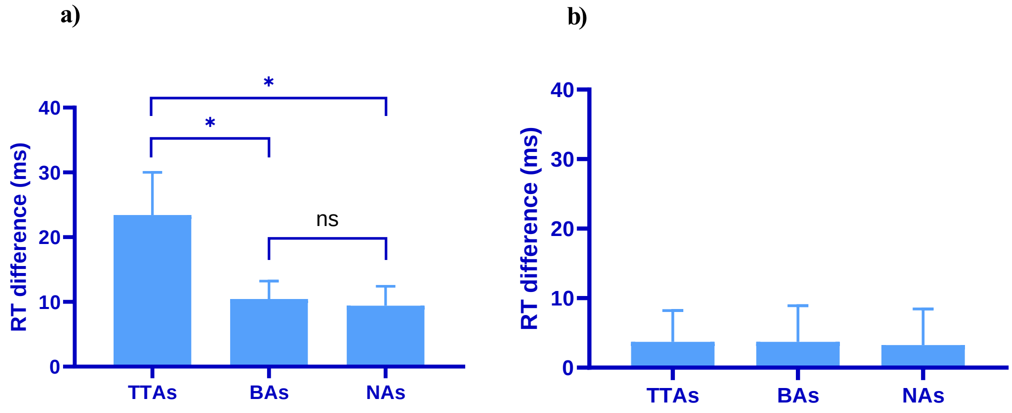

Fig. 5 The mean RT (ms) difference (left target minus right target) for the three groups (TTAs = table tennis athletes; BAs = badminton athletes; NAs = non-athletes) (a) across the three hand-held conditions and (b) for the no-hand condition.

Statements and Declarations

Competing Interests

The authors declare they have no financial or nonfinancial interests to disclose.

Ethics Approval

The study was approved by the Ethics Committee of Beijing Sport University (No. 20200826).

Consent to Participate

Informed consent was obtained from all participants.

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