Adaptable Categorisation of Hands and Tools in Prosthesis Users

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Abstract

Hands and tools are distinct categories, though in daily life both are used to interact with our environment. Prosthetic limbs are tools designed to substitute lost hand function. Does the conceptual distinction between hands and tools prevail after hand loss and subsequent use of prosthetic limbs? Using a categorical priming paradigm with images of hands, manual tools, and prostheses, we show that one-handed participants with acquired or congenital limb-loss had blurred categorical boundaries between hands and tools, compared to controls. This blurring reflected individuals' experience using natural and artificial limbs. Furthermore, we assessed how one-handed participants categorise their own prosthetic limb. The categorical similarity between prostheses and hands was predicted by natural limb experience, whereas prosthesis-tool association related to use of the prosthesis in individuals' daily lives. Our results show that experience of limb-loss and prosthesis use changes the categorical conceptual relationship between hands and tools.

Keywords: Disabilities, Human Body, Motor Processes, Priming, Vision

Main text

Some theories propose that tools become incorporated into the neural representation of the hands (tool embodiment; Maravita & Iriki, 2004). Others suggest that conceptual body representation is rigid, such that experience with our own body is insufficient for adapting bodily cognition (as shown with individuals born without hands, Vannuscorps & Caramazza, 2016). How sharp is the conceptual boundary between hands and tools? This question is particularly relevant in individuals who lost one hand and use prosthetic limbs as tools to supplement their missing hand function. Although one-handers are encouraged to use prostheses, individuals greatly vary in the extent to which they use them in daily tasks (Jang et al., 2011), with congenital one-handers showing a greater tendency to use prosthetics than amputees. One-handers have a fully functional remaining hand (allowing them to use hand-held tools, etc), making them less likely to show semantic distortions in hand and tool representation. However, their own bodies and their interactions with their environment are fundamentally altered (Makin et al., 2013; Makin, Wilf, Schwartz, & Zohary, 2010).

To determine how real-world experience shapes conceptual categorisation of hands, tools, and prostheses, we used a priming task in one-handers with congenital or acquired unilateral hand-loss We predicted that one-handers, particularly congenital one-handers, would show more conceptual blurring between hands and tools than controls, based on less experience with a hand and more reliance on prosthetics (tools) for typical hand functions. We further predicted that individual differences in prosthesis usage would be reflected in implicit categorisation of hands, manual tools and prostheses.

One-handers with congenital (n=12) or acquired (n=12) limb-loss and matched controls (n=21) performed a visual priming task in which they verbally categorised target images of hands and tools (Fig. 1a). Voice onsets were registered as reaction times (RTs). Target images were primed with images of hands, tools, or prostheses (Fig. S1), which participants were instructed to ignore. Participants also performed a block of baseline-trials with a scrambled-prime. Ten different exemplars were used as prime and target items per category. Hand- and prosthesis-images showed the side of the missing (one-handers) or nondominant hand (controls). Where possible, images were of the participant's own prosthesis. As such, prosthesis daily usage (assessed using an adapted version of the Motor Activity Log, Makin et al., 2013) generally reflected individuals' experience with the prime prosthesis image presented to them; see Supplementary Materials for additional methodological details.

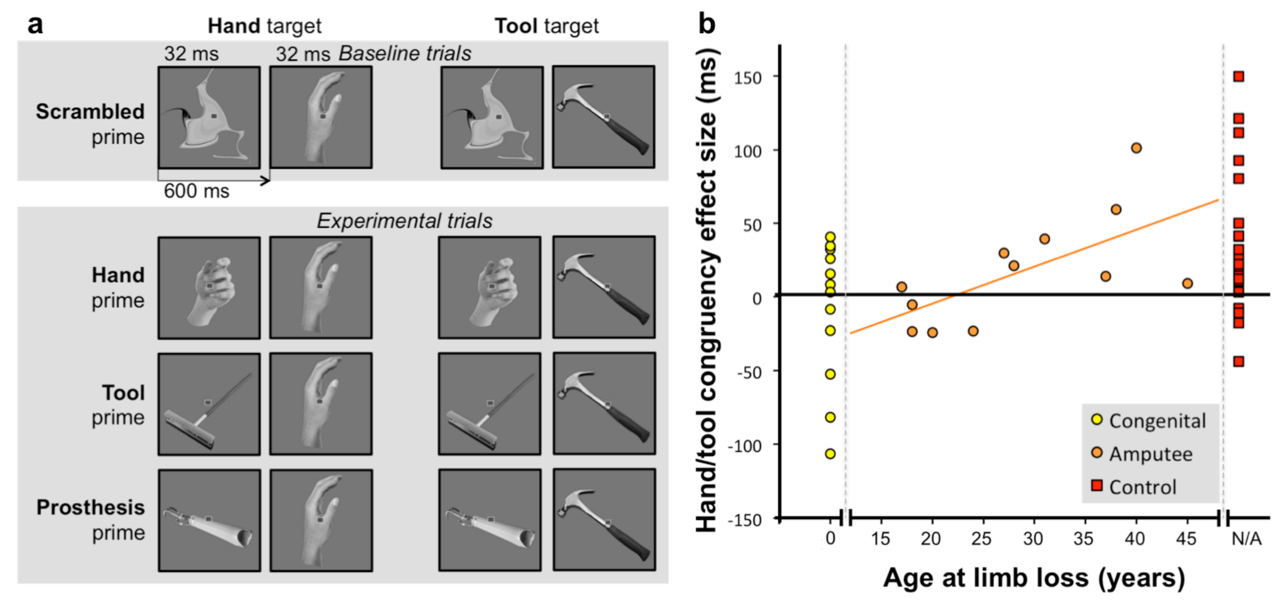

Fig 1. The hand/tool perceptual distinction depends on natural limb experience. Experimental conditions are shown in (a). Prime (top to bottom: neutral, hand, tool, prosthesis) and target (hand – left panel; tool – right panel) were presented for 32 ms, with a 600-ms prime-target stimulus onset asynchrony. Different exemplars were used as prime- and target-images. Neutral scrambled (diffeomorphed) images were used in baseline-trials. The hand/tool congruency effect size (b) (calculated as the summed difference between congruent and incongruent reaction times; (hand-hand&tool-tool) minus (hand-tool&tool-hand)) is plotted against age at limb-loss. As a group, control participants showed a significant slowing of responses in congruent vs. incongruent trials, whereas one-handers did not. Within the acquired amputee group the age at which participants lost their limb correlated with the congruency effect.

We first examined the prime–target congruency effect for hand- and tool-primes in one-handers and controls. Control participants were slower when the prime and target were congruent (hand-hand or tool-tool) than when incongruent (hand-tool or tool-hand), indicating same-category prime interference of target processing (Boy & Sumner, 2010). Conversely, the priming effect was absent in one-handers (Fig. S2), as supported by a significant prime(2)*target(2)*group(2) interaction in a repeated measures ANOVA ($F(1,43)=5{,}37$, $p=0.025$). In controls, we found a significant prime*target interaction ($F(1,20)=11.24$, $p=0.003$), and significant RT differences between congruent and incongruent trials for both hand- and tool-targets (planned comparisons, paired t-tests: $t(20)=2.19$, $p=0.041$, $d=0.175$, and $t(20)=3.31$, $p=0.003$, $d=0.261$, respectively). However, in one-handers there was no significant prime*target interaction ($F<1$), suggesting that the conceptual hand/tool boundary is blurred in one-handers compared to controls.

We calculated each individual's congruency effect as the summed difference in RTs between congruent and incongruent trials for both hand- and tool-targets [(hand-hand&tool-tool) – (hand-tool&tool-hand)]. Based on our finding in controls showing slower responses to same-category versus different-category trials, a greater congruency effect reflects greater dissociation between hands and tools. Although one-handers did not show a significant congruency effect, there was evidence that their categorisation-behaviour was modulated by their case histories, specifically the age at which amputees lost their hand and their habitual prosthesis usage. We found a significant correlation between age at limb-loss and congruency effect ($r(10)=0.65$, $p=0.022$; Fig. 1b): limb-loss early in life related to weaker congruency effects whereas amputees who lost a hand later in life (and therefore had more experience with the now-missing hand) showed greater congruency effects. These findings suggest that conceptual distinction between hands and tools develops through experience with natural limbs. We also found that one-handers who used their prostheses more tended to show weaker congruency effects than those who used prostheses less frequently (correlation between congruency effect and prosthesis usage, $r(22)=-0.38$, $p=0.068$), such that the hand-tool boundary (reflected in the congruency effect) tended to blur with the regularity of prosthesis usage.

Theories of tool-embodiment state that prosthesis usage should result in categorisation of the prosthesis as a hand (Murray, 2008). In the final set of analyses, we assessed the degree to which prosthesis-primes affect responses to hands and tools as a function of experience. Given that categorical similarity resulted in slower responses for congruent prime-target pairs, slowing of RTs for prosthesis-primes can be taken to reflect the conceptual similarity between prostheses and hands or tools. We found that people who lost their hand earlier in life showed greater conceptual similarity between the prosthesis and hands. This was exemplified by backwards regression on prosthesis-hand RT using the following predictors: age at limb-loss, years since limb-loss, prosthesis usage, congruency effect size, and baseline-RT. The final model for hand-target trials ($F(2,21)=35.08$, $p<0.001$, $R=0.88$, $R^2_{\mathrm{adj}}=0.75$) included age at limb-loss ($\beta=-0.29$, $t(23)=-2.72$, $p=0.013$) and baseline-RT ($\beta=0.78$, $t(23)=7.28$, $p<0.001$), Fig. S3. Conversely, the conceptual relationship between prostheses and tools was best predicted by prosthesis usage, with those using their prosthesis more showing greater conceptual similarity between prostheses and tools. This finding was supported by backwards regression on prosthesis-tool RT using the same parameters as above. The final model ($F(2,21)=42.48$, $p<0.001$, $R=0.90$, $R^2_{\mathrm{adj}}=0.78$) included prosthesis usage ($\beta=0.24$, $t(23)=2.39$, $p=0.026$) and baseline-RT ($\beta=0.83$, $t(23)=8.36$, $p<0.001$), Fig. S4.

Together, our findings demonstrate that categorisation of hands and tools in one-handers depends on both prior experience with a natural hand before amputation and later artificial limb usage. Specifically, dissociation between hands and tools (exemplified by the congruency effect) depends on the degree of experience with that hand. Moreover, the representation of prostheses as hands and tools depends on daily life experience. Given the relatively limited semantic categorical deficit but profoundly changed body experience due to limb-loss, we suggest the adaptable conceptual relationship between hands, tools and prostheses is embodied. Nevertheless, as high-level lexico-semantic processing may implicitly depend on body representation (Rueschemeyer, Pfeiffer & Bekkering, 2010), further studies are necessary to elucidate on the underlying process.

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