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Adaptable Categorization of Hands and Tools in Prosthesis Users

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Some theories propose that tools become incorporated into the neural representation of the hands (a process known as *tool embodiment*; Maravita & Iriki, 2004). Others suggest that conceptual body representation is rigid and that experience with one's own body is insufficient for adapting bodily cognition, as shown in individuals born without hands (Vannuscorps & Caramazza, 2016) and in amputees with persistent phantom hand representation (Kikkert et al., 2016). How sharp is the conceptual boundary between hands and tools? This question is particularly relevant for individuals who have lost one hand and use prosthetic hands as tools to supplement their missing hand function. Although both congenital one-handers (i.e., amelia patients) and one-handed amputees are encouraged to use prostheses, the former show a greater tendency than the latter to use prosthetic hands in daily tasks (Jang et al., 2011). One-handers have a fully functional remaining hand (allowing them to use handheld tools, etc.), which makes them less likely to show semantic distortions in hand and tool representation. However, their bodies and their interactions with their environment are fundamentally altered by their disability (Makin et al., 2013; Makin, Wilf, Schwartz, & Zohary, 2010).

To determine how real-world experience shapes conceptual categorization of hands, tools, and prostheses, we recruited one-handers with congenital or acquired unilateral hand loss to take part in a study involving a priming task. We predicted that one-handers, particularly congenital one-handers, would show more conceptual blurring between hands and tools than control participants would, as a result of less experience with a hand and more reliance on prostheses (which are essentially tools) for typical hand functions. We further predicted that individual differences in prosthesis usage would be reflected in implicit categorization of hands, manual tools, and prostheses.

Method

Twenty-four one-handers (12 born without a hand and 12 who lost a hand through amputation) and 21 matched control participants performed a visual priming task in which they verbally categorized target images of hands and tools (Fig. 1a). On each trial, participants saw a prime stimulus followed by a target stimulus, each of which appeared for 32 ms (stimulus onset asynchrony = 600 ms). On baseline trials, the prime was always a scrambled image, and on experimental trials, the prime could be an image of a hand, a tool, or a prosthesis. On all trials, the target was either a hand or a tool. Participants were instructed to ignore the prime and to verbally report whether the target image was a hand or a tool. Time from the start of the target display to voice onset was recorded as the participants' reaction time (RT). Participants completed 40 baselines trials and four blocks (60 trials each) of experimental trials.

Ten different exemplars were used as prime and target items in each category (for example stimuli, see Fig. S1 in the Supplemental Material available online). Hand and prosthesis images showed the side of the participants' missing hand (one-handers) or nondominant hand (controls). When possible, images were of the participant's own prosthesis, so daily prosthesis usage (assessed both by asking how often participants wore their prosthesis and by 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 the Supplemental Material for additional methodological details).

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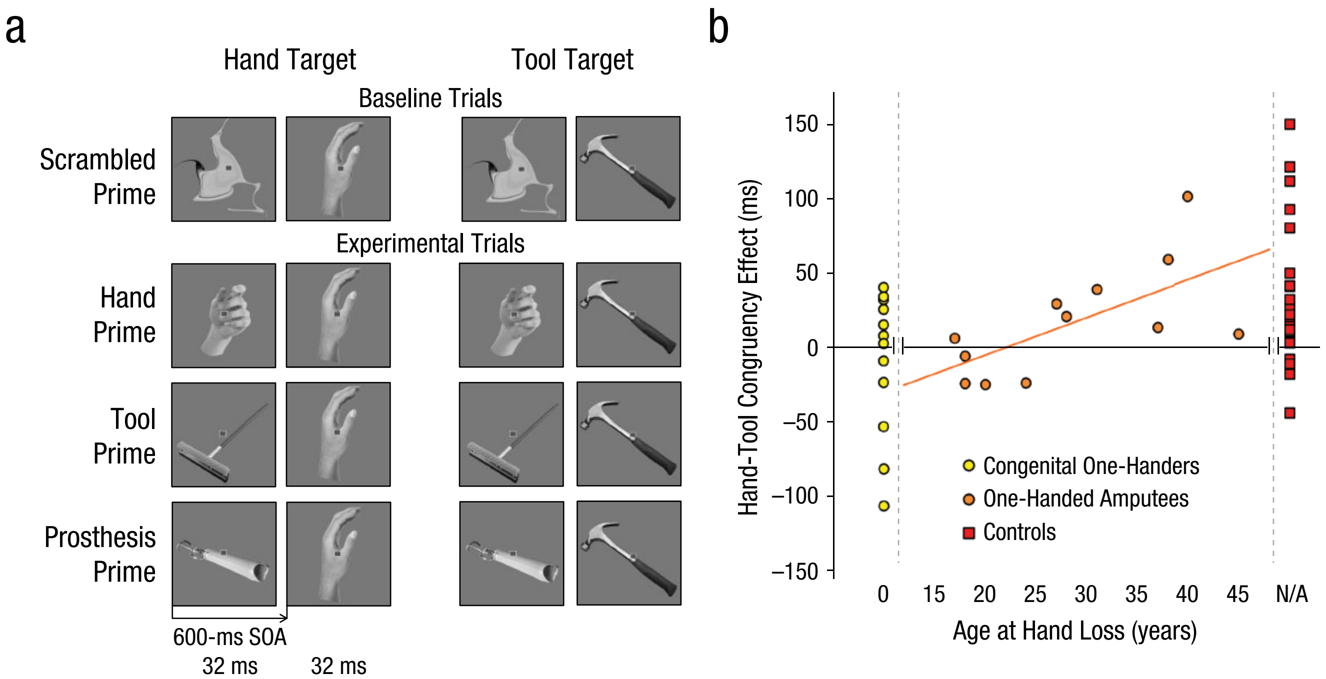

Fig. 1. Experimental procedure and results. On each trial (a), participants saw a 32-ms prime stimulus followed by a 32-ms target stimulus, with a 600-ms stimulus onset asynchrony (SOA). Participants were asked to make a speeded, forced-choice verbal response as to whether the target was a hand or a tool. Baseline trials differed from experimental trials only in that the prime was a scrambled image rather than an image of a hand, tool, or prosthesis. Reaction times on incongruent trials (in which prime and target stimuli were from different categories) were subtracted from reaction times on congruent trials (in which prime and target stimuli were from the same category) to calculate the hand-tool congruency effect. The scatter plot (b; with best-fitting regression line) shows the mean hand-tool congruency effect as a function of age at hand loss for congenital one-handers and one-handed amputees, along with the mean congruency effect for control participants.

Results

We first examined the prime-target congruency effect on trials with hand and tool primes in one-handers and control participants. RTs for controls were slower when the prime and target were congruent (i.e., from the same category; e.g., hand prime and hand target) than when they were incongruent (i.e., from different categories; e.g., hand prime and tool target), which indicates same-category prime interference in target processing (Boy & Sumner, 2010; see also Vainio, 2011, for negative stimulus-response compatibility for hand images). Next, a 2 (prime) × 2 (target) × 2 (group) repeated measures analysis of variance revealed a significant three-way interaction, $F(1, 43) = 5.37$, $p = .025$; this indicates that, unlike the results for control participants, the priming effect was absent in one-handers (for further analysis, see Results and Fig. S2 in the Supplemental Material). In control participants, we found a significant Prime × Target interaction, $F(1, 20) = 11.24$, $p = .003$. Further, planned comparisons using paired-samples t tests revealed a significant RT difference between congruent and incongruent trials for both hand targets, $t(20) = 2.19$, $p = .041$, $d = 0.175$, and tool targets, $t(20) = 3.31$, $p = .003$, $d = 0.261$. However, in one-handers, there was no significant Prime × Target interaction ($F < 1$), which suggests that the conceptual hand-tool category boundary is blurred in one-handers, compared with control participants.

We calculated each participant's congruency effect by subtracting mean RTs on incongruent trials from mean RTs on congruent trials. Given our finding that control participants' RTs were slower on congruent than on incongruent 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 categorization behavior was modulated by their case histories, specifically the age at which one-handed amputees lost their hand and their habitual prosthesis usage. We found a significant correlation between age at hand loss and congruency effect, $r(10) = .65$, $p = .022$ (Fig. 1b): Hand loss earlier 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 the conceptual distinction between hands and tools develops through experience with natural hands. We also found that one-handers who used their prosthesis more tended to show weaker congruency effects than those who used prostheses less frequently—correlation between congruency effect and prosthesis usage: $r(22) = -.38$, $p = .068$—such that the hand-tool category 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 categorization of the prosthesis as a hand (Murray, 2008). In the final set of analyses, we assessed the degree to which prosthesis primes affected responses to hands and tools as a function of prosthesis experience. Given that categorical similarity resulted in slower responses for congruent prime-target pairs than for incongruent prime-target pairs, slowing of RTs for prosthesis primes can be taken to reflect the conceptual similarity between prostheses and hands or tools. To investigate this, we ran a backwards regression analysis on RTs for prosthesis-hand trials using age at hand loss, years since hand loss, prosthesis usage, congruency effect size, and mean RT on baseline trials as predictors. The final model for hand-target trials, $F(2, 21) = 35.08$, $p < .001$, $R = .88$, adjusted $R^2 = .75$, included age at hand loss, $\beta = -0.29$, $t(23) = -2.72$, $p = .013$, and baseline RT, $\beta = 0.78$, $t(23) = 7.28$, $p < .001$ (see Fig. S3 in the Supplemental Material). This analysis revealed that people who lost their hand earlier in life showed greater conceptual similarity between the prosthesis and hands. We also ran a backwards regression analysis on RTs for prosthesis-tool trials using the same parameters as for the previous set of backwards regressions. The final model, $F(2, 21) = 42.48$, $p < .001$, $R = .90$, adjusted $R^2 = .78$, included prosthesis usage, $\beta = 0.24$, $t(23) = 2.39$, $p = .026$, and baseline RT, $\beta = 0.83$, $t(23) = 8.36$, $p < .001$ (Fig. S4 in the Supplemental Material). This analysis showed that, in opposition to the previous regression, the conceptual relationship between prostheses and tools was best predicted by prosthesis usage, with participants who used their prostheses more showing greater conceptual similarity between prostheses and tools.

Conclusion

Together, our findings demonstrate that categorization of hands and tools in one-handers depends on both prior experience with a natural hand before amputation and later artificial-hand 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-category deficit but profoundly changed body experience resulting from hand loss, we suggest that the adaptable conceptual relationship between hands, tools, and prostheses is embodied. Nevertheless, because high-level lexico-semantic processing may implicitly depend on body representation (Rueschemeyer, Pfeiffer, & Bekkering, 2010), further studies are necessary to elucidate the underlying process.

Action Editor

Jamin Halberstadt served as action editor for this article.

Author Contributions

All authors contributed to the development of the study concept. F. M. Z. van den Heiligenberg, N. Yeung, and T. R. Makin designed the study. Testing and data collection were performed by F. M. Z. van den Heiligenberg. F. M. Z. van den Heiligenberg and T. R. Makin analyzed and interpreted the data. All authors contributed to drafting the manuscript and provided critical revisions. All authors approved the final version of the manuscript for submission.

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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Supplemental Material

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Open Practices

All data and materials have been made publicly available via the Open Science Framework and can be accessed at https://osf.io/ck22q/. The complete Open Practices Disclosure for this article can be found at http://journals.sagepub.com/doi/suppl/10.1177/0956797616685869. This article has received badges for Open Data and Open Materials. More information about the Open Practices badges can be found at http://www.psychologicalscience.org/publications/badges.

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