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Rapid Assimilation of External Objects Into the Body Schema

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Abstract

When a warrior picks up a sword for battle, do sword and soldier become one? The notion of an extended sense of the body has been the topic of philosophical discussion for more than a century and more recently has been subjected to empirical tests by psychologists and neuroscientists. We used a unique afterimage paradigm to test if, and under what conditions, objects are integrated into an extended body sense. Our experiments provide empirical support for the notion that objects can be integrated into an extended sense of the body. Our findings further indicate that this extended body sense is highly plastic, quickly assimilating objects that are in physical contact with the observer. Finally, we show that this extended body sense is limited to first-order extensions, thus constraining how far one can extend oneself into the environment.

Keywords

body schema, proprioception, vision, tool use

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Fifty years ago, in a brief report, Gregory, Wallace, and Campbell (1959) described qualitative changes to visual afterimages in response to bodily movements. In a bulleted point in the text, the authors noted:

> If the flash tube is directed on to the subject's hand, so that an after-image of the hand is produced, some curious phenomena may be observed . . . . The visual and proprioceptive loci of the hand may separate in a disconcerting manner. Further complex effects occur if the subject attempts to pick up an object. . . . (p. 297)

Gregory and his colleagues offered little speculation on these intriguing findings, and, to date, few studies have followed up on their remarkable observations. One notable study by Davies (1973) more thoroughly documented that afterimages change in appearance in response to observers' movements. In his experiments, observers were dark adapted and exposed to a bright flash of light. This procedure generates a positive afterimage that has the appearance of a dim still photograph of the observer's field of view at the time of flash. When observers moved one of their appendages (e.g., an arm), the appendage would appear to fade, or take on a "crumbled" or "ghostly" appearance in the afterimage—an effect that we have since replicated and found to be mediated by a higher-order bodily experience (Hogendoorn, Kammers, Carlson, & Verstraten, 2009). The explanation of this phenomenon is that the conflict between the updated proprioceptive representation of the limb and the perceived location of the appendage induces distortions in the appearance of the afterimage (Davies, 1973).

In this article, we report a study focused on the latter portion of the observation made by Gregory et al. (1959). In particular, we investigated whether or not objects manipulated by an observer are subject to this "crumbling" effect, as the answer to this question could provide insights into longstanding philosophical and psychological questions. From a philosophical point of view, our study tested the notion that the body schema (Head & Holmes, 1911) can be expanded to include external objects, an idea discussed some time ago by James in his description of a sense of "me" (James, 1918). Notably, the discussion of an extended self continues in the modern philosophical literature (Clark, 1999) and has even expanded into discussions of conscious awareness (Nöe, 2009).

The question of whether or not objects can be assimilated into the brain's representation of the body has also captured the attention of psychologists and neuroscientists (for a review,

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see Maravita & Iriki, 2004). Empirical studies addressing this question, however, have yielded mixed results. On the one hand, behavioral studies and some studies of neurological patients indicate that the brain's representation of external objects is separate from the brain's representation of the body (Bisiach, Perani, Vallar, & Berti, 1986; Guariglia & Antonucci, 1992; Reed & Farah, 1995). In contrast, compelling observational evidence coupled with supporting behavioral findings and other neurological studies indicates that the brain's representation of the body can be extended (Aglioti, Smania, Manfredi, & Berlucchi, 1996; Critchley, 1979; Yamamoto & Kitazawa, 2001). In addition, physiological studies in primates have found that neurons in intraparietal cortex can expand their receptive fields to include tools after the primates engage in goal-directed behavior (Iriki, Tanaka, & Iwamura, 1996). The brain thus appears to have the necessary neural substrates for an extended self.

In the present study, we exploited Davies's (1973) documented interactions between proprioception and vision to gain access to the brain's representation of the body. We used this technique to test if and when objects are incorporated into an extended body representation. The hypothesis that objects can be assimilated makes clear predictions within this paradigm. If the hypothesis is correct, objects manipulated by the observer, like an appendage moved by the observer, will appear distorted in visual afterimages. The results of our study indicate that external objects can indeed be assimilated into an extended self. We further observed that this extended body sense is highly plastic and that physical contact with the object appears to be important for this assimilation to occur.

Method

Subjects

Six males and 4 females with normal or corrected-to-normal vision participated in the study. Three of the subjects were authors of this article (T.A.C., D.W., and G.A.). The other subjects were naive to the purposes of the study. One subject was removed from the study because he did not experience any changes in visual afterimages in response to bodily movements. Davies (1973) reported a similar proportion of subjects (2/24) who did not experience fading of the relocated limb.

Materials

Positive afterimages were induced using a high-intensity flash generated by a Speedotron 4803cx (Speedotron Corporation, Chicago, IL), which produces a 1,000-W flash with a duration of approximately 1 ms. The lamp was oriented toward the ceiling of the room to ensure an even distribution of light in the room.

In all object conditions, two pieces of gray wool were used. These objects were approximately 25 cm long and 8 cm wide, and one was held in each hand. The rationale for using these items as the objects was as follows: (a) The wool was approximately the same luminance (8.4 cd/m^2) as human skin (11.6 cd/m^2) under ambient room lighting, (b) there would be no audible indication of the object making contact with the table in conditions that required dropping an object, and (c) the wool would be easy to grasp with the device used in the mechanical grasping condition.

General procedure

Subjects in all the trials were seated at a table in a light-sealed room. The lights were turned off, and subjects were allowed to adapt to the dark (for 6 min in the initial trial and 2 min in subsequent trials). Before each trial, subjects fixated a point that was roughly half way between their two thumbs. This procedure was in place to ensure that participants did not move their eyes during the afterimage. Although their hands were not visible, subjects reported no difficulties in fixating the unseen location. After subjects received the instructions from the experimenter and indicated that they were ready, the experimenter counted down from 3 and discharged the lamp.

Before beginning the experimental conditions, subjects were oriented to the procedure and screened to determine if they experienced the effects reported by Davies (1973). In a first trial, subjects were allowed to simply experience the afterimage. They then performed either three or four screening trials that replicated the procedure in Davies's (1973) study on the interaction between vision and proprioception. In these trials, subjects held their hands approximately 15 cm above the table's surface, approximately 30 cm apart from one another. Subjects moved either their left or their right hand, randomly selected, toward their body and down to their side after the formation of the afterimage. Nine subjects performed three of these trials; 1 subject performed four trials. One participant did not experience fading of the displaced limb on any of the trials and was dismissed from the experiment. The remaining subjects participated in the four experimental conditions, which were conducted in random order.

In each experimental condition, one of the subject's hands was designated the action hand (AH). Verbal instructions regarding the action to be taken were given to subjects both before the experiment began and before each experimental block. Subjects were instructed to maintain fixation and to carry out the action only after a clear afterimage had formed. They were told that their other hand should mirror the initial configuration of the AH, but not perform the action. The stationary hand (SH) served as a reference for making perceptual comparisons with the AH. This aspect of the procedure also rules out the possible confounding effect of spatial attention being directed to a single object held in the observer's grasp (see Holmes, Sanabria, Calvert, & Spence, 2007). The designated AH alternated between the left and right hands from one trial to the next; the AH for the first trial in each condition was selected randomly. In all experimental conditions, subjects manipulated two objects: the action object (AO) in the AH and the static object (SO) in the SH. These designations changed along with the hand designations.

Subjects performed a minimum of three trials in each condition and were given the opportunity to perform additional trials at their own discretion, to gain confidence in their report. Usually, subjects either performed the minimum number of trials or opted to perform one additional trial. The subjects' task was to report any differences in appearance between the AH and the SH or between the SO and the AO. Reports broadly fell into two categories: Subjects either reported no difference or described the AH or AO as disappearing, prematurely fading, or taking on a ghostly appearance relative to the SH or SO. Davies's (1973) original study included five categories of subjective reports. In the present study, we scored subjective reports of the AH or AO disappearing or fading as positive responses. These descriptions correspond to Davies's subjective descriptions labeled Category 1 (hand or arm disappears) or Category 2 (hand or arm went negative). All other reports were scored as a negative response (i.e., no difference).

For each subject, we computed the proportion of positive responses in each condition. Analyses were performed on the individual proportions to ensure that subjects who performed additional trials were not given greater weight. Prior to conducting statistical analyses, we performed an arcsine transformation on the proportions, so that standard linear statistics (e.g., analysis of variance) could be applied to the bounded (ranging from 0 to 1) proportion data.

Experimental Condition 1: movement of the hand and object. Subjects held their hands in the same position as in the screening. In this condition, however, after subjects indicated that their hands were in position, the experimenter gave them the two objects, one for each hand to grasp. Subjects moved their AH (and the AO) toward their body and down to their side after the formation of the afterimage and then reported differences between the AH and the SH and between the AO and the SO. All 9 subjects performed three trials of this condition.

Experimental Condition 2: release of the object. The configuration was the same in the second experimental condition as in the first, except that the subjects did not move the AH. Instead, they released the object from their grasp, thus allowing the AO to drop to the table surface. Six subjects performed three trials of this condition; 3 subjects performed four trials.

Experimental Condition 3: grabbing of the object. In this condition, the experimenter placed two objects on the table, approximately 30 cm in front of the observers' hands. After the formation of the afterimage, subjects reached forward with their AH and grasped the AO. While holding onto the AO, they moved their AH toward their body and down to their side. Four subjects performed three trials of this condition, 3 subjects performed four trials, 1 performed five trials, and 1 subject performed seven trials.

Experimental Condition 4: mechanical release of the object. Two mechanical grasping arms, each approximately 60 cm in length, were used in this condition. Each device was affixed to the table with the handle in front of the observer. The mechanical claws at the opposite end of the device were elevated 30 cm from the surface of the table to ensure a clear view of the objects from the observer's perspective. The device had a squeeze handle on one end that mechanically applied variable amounts of pressure to a set of mechanical claws at the opposite end. Squeezing the handle allowed the operator to grasp and hold small objects with the device; releasing pressure on the handle opened the mechanical claws. Note that the hand movements necessary to operate the device were similar to the hand movements in the object-release condition.

Subjects began this condition holding the handles of the device without applying pressure. The experimenter then placed one object in each of the device's claws and asked the subjects to apply firm pressure. After verifying that the objects were securely in the grasp of the devices, the experimenter discharged the lamp. Subjects released the handle of the device with their AH after they saw a clear afterimage. Eight subjects performed three trials of this condition; 1 subject performed four trials.

Results

We first replicated Davies's (1973) interaction between vision and proprioception. Nine of the 10 observers reported that the hand that was relocated during the screening trials either faded or disappeared completely in the afterimage. Results for the experimental conditions involving object movement are summarized in Figure 1.

In the first experimental condition, we tested whether external objects could be integrated into the representation of the body. We did this by testing whether the interaction between vision and proprioception we found in the screening trials would extend to objects held in the observers' grasp. Subjects reported that the displaced hand faded in 93% of the trials, but they also reported that the object faded in 78% of the trials. Although the effect appeared to be weaker for the object than for the hand, this difference was not significant, $t(8) = 1.51$, $p = .17$. This observation indicates that the perceived location of the object in the afterimage was in some way in conflict with the brain's updated representation of the object's location in space. Presumably this updating occurred because the object had been assimilated into the brain's representation of the body, as the effect is believed to be derived from an interaction between vision and proprioception (Davies, 1973). An alternative explanation is that the fading occurred as a consequence of high-level knowledge of the displacement of the object or a more general updating of the environment. We favor the first explanation, as the object did not always fade when it was relocated (i.e., it did not fade in the mechanical release condition, as discussed later in this section).

The second condition tested if this extended representation is updated when the object is released from the observer's grasp.

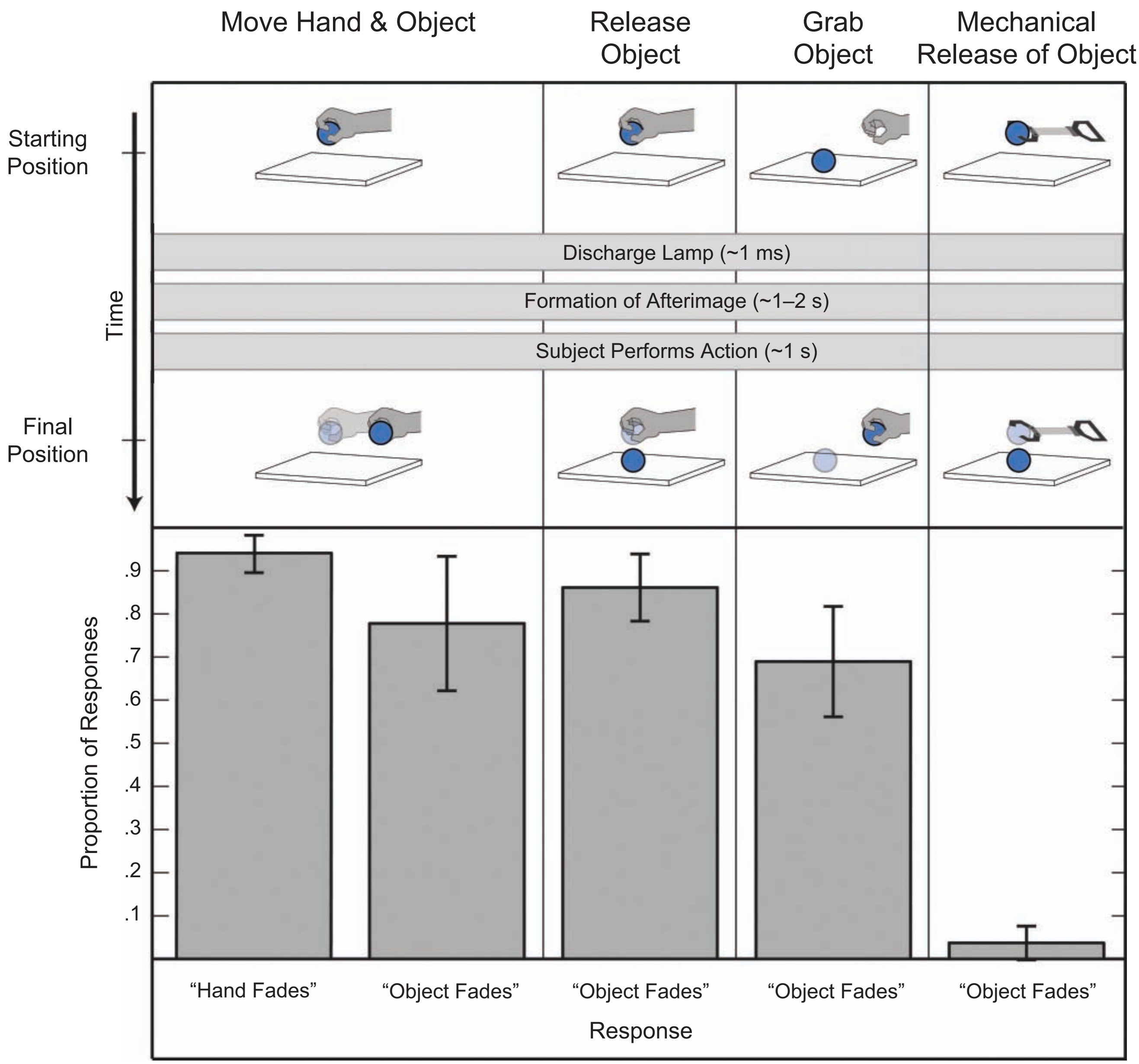

Fig. 1. Experimental results: average proportion of responses in which subjects indicated that the hand or the object faded in the afterimage. Results are shown for the following experimental conditions: movement of the hand and object (subjects held the object and moved their arm after the formation of the afterimage), release of the object (subjects held the object and released the object from their grasp after the formation of the afterimage), grabbing of the object (subjects reached for, grasped, and displaced the object after the formation of the afterimage), and mechanical release of the object (subjects released the object from the grasp of a mechanical device after the formation of the afterimage). The illustrations show the initial position of the hand and object and their final physical location. The perceived location of the hand and object, as seen in the afterimage, is rendered as transparent. Error bars show standard errors.

In this condition, subjects reported that the object faded in 86% of the trials. The fading of the object indicates that it is no longer part of the brain's representation of the body. This suggests that this extended representation is being updated to exclude objects no longer within one's grasp. In the third condition, we inverted the experimental configuration, asking subjects to reach out and grasp one of the two objects. In this condition, the object was reported to fade in 69% of the trials. This finding indicates that the object was assimilated as soon as the observer grasped the object. Taken together, the first through third conditions show that this extended body sense integrates objects in one's grasp, updates to include newly grasped objects, and is updated to exclude objects released from one's grasp. A one-way repeated measures analysis of variance indicated that there was little variation in reports among the first three experimental conditions, $F(2, 8) = 0.857$, $p = .443$.

The fourth condition tested the limits of this extended body sense. Specifically, we tested the possibility of a second-order extension by asking subjects to hold and then drop the object using a mechanical grasping device. In this case, observers reported that the object faded in only 4% of the trials, a result that stands in stark contrast to the results in the other experimental conditions. Not surprisingly, the proportion of reports of fading was significantly different, $t(8) = 8.24$, $p < .001$, from the proportion in the third condition, in which observers released the object from their hand. The report of little or no fading in this condition is important for several reasons. First, the fading phenomenon is inherently observational, and therefore it is difficult to rule out observer bias. The fact that subjects did not report fading in this condition indicates that they did not simply report fading whenever the object was manipulated. Second, as noted previously, the results of this condition rule out the possibility that general knowledge of the object's displacement was the source of the effect. Observers were clearly aware that the object would fall when released, yet they did not report that the object faded. Finally, the results of this condition suggest that this extended body sense is limited to first-order extensions, which suggests that physical contact with the object may be a critical factor.

Discussion

In summary, we have found evidence for an extended representation of the body. It is noteworthy that afterimages, which are the basis for our findings, persist for 8 to 10 s on average. This places an upper boundary on the time scale of the proprioceptive updating that can be measured using visual afterimages. This timing constraint indicates that the updating occurs within a few seconds at most. Moreover, subjects most often reported that the fading occurred immediately after the movement. Our results, taken together with this time constraint, indicate that objects can be assimilated into this extended representation of the body in a very short period of time.

Our findings are in general agreement with both behavioral and neurophysiological studies indicating that the brain's representation of the body can be extended, but are seemingly incompatible with respect to the necessary conditions for the assimilation and the time scale of plasticity. In a landmark study, Iriki et al. (1996) showed that neurons in intraparietal cortex reshaped their receptive fields to include tools (objects). This reorganization, however, occurred only after extensive training. Similarly, human behavioral experiments suggest that assimilation requires at least some training before objects can be integrated into the brain's representation of the body (Maravita, Spence, Kennetta, & Driver, 2002). In our own study, we found that this assimilation occurred within a matter of seconds, with little or no training. These differences suggest that there are distinct mechanisms that alter the brain's representation of the body. The first mechanism supports the long-term adaptability of the organism by creating a limited number of durable representations that can be refined and rapidly "switched on" (Braun et al., 2001). It is important to note that the extensive training required to form these representations not only serves to refine the skills of the organism, but also may protect stored representations from catastrophic interference. The second mechanism provides the organism with the flexibility to assimilate objects quickly into a highly plastic representation of the body, which could serve as a basis for creating new long-term representations. Notably, the latter mechanism more closely matches both traditional (Head & Holmes, 1911) and modern (Wolpert & Haggard, 2005) definitions of body schema in that it is updated on a short time scale.

The striking difference between the conditions in which observers directly manipulated the object and the condition in which they manipulated the object with the mechanical arm has two implications. First, previous studies examining extended representations of the body suggest that familiarity and training are important factors in altering the representation of the body (Aglioti et al., 1996; Maravita & Iriki, 2004; Maravita et al., 2002). Subjects in our study had little experience with the objects and only a verbal description of the actions. Therefore, familiarity and training likely contributed little to the assimilation process. The fact that assimilation did not occur in the mechanical-arm condition suggests that physical contact is an additional mechanism for assimilation. This mechanism would allow individuals to immediately perform actions with novel objects. Second, our findings indicate that second-order extensions of the body are not possible, at least with respect to the rapid assimilation process that we observed in this study. An intriguing question for future study would be to test whether a more durable first-order extension—one that is based on familiarity and training—would allow for second-order extensions.

In regard to the philosophical question of how far the mind can extend itself beyond the observer into the environment (Clark, 1999), our study shows that the mind can be immediately expanded into the environment. The absence of second-order extensions, however, indicates that this expansion is not without limitation. Our results thus indicate that the body—the mind's interactive interface with the world—can rapidly be extended into the world, but only to that part of the world that is in direct physical contact with the observer.

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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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