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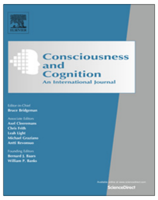

Body-scaled affordances in sensory substitution

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A B S T R A C T

The research field on sensory substitution devices has strong implications for theoretical work on perceptual consciousness. One of these implications concerns the extent to which the devices allow distal attribution. The present study applies a classic empirical approach on the perception of affordances to the field of sensory substitution. The reported experiment considers the perception of the stair-climbing affordance. Participants judged the climbability of steps apprehended through a vibrotactile sensory substitution device. If measured with standard metric units, climbability judgments of tall and short participants differed, but if measured in units of leg length, judgments did not differ. These results are similar to paradigmatic results in regular visual perception. We conclude that our sensory substitution device allows the perception of affordances. More generally, we argue that the theory of affordances may enrich theoretical debates concerning sensory substitution to a larger extent than has hitherto been the case.

1. Introduction

1.1. Body-scaled affordances in sensory substitution

A sensory substitution device (SSD) allows the substitution, or enhancement, of the capabilities of a particular perceptual system through an alternative one. Since pioneering devices such as the OPTACON (Linvill & Bliss, 1966) and the TVSS (Bach-y-Rita, Collins, Saunders, White, & Scadden, 1969), technological advances have progressively improved the portability and usability of SSDs (Dakopoulos & Bourbakis, 2010; Jones & Sarter, 2008; Visell, 2009). Even so, a wide generalization of the use of SSDs has not occurred (Spence, 2014).

The majority of SSDs substitute vision through either the tactile or the auditory modality. In these devices, the light intensity detected by a camera is transduced to stimulation patterns ranging from electrotactile or vibrotactile intensity to pitch range. An outstanding example of an auditory SSD is the vOICe (Auvray, Hanneton, & O'Regan, 2007; Proulx, Stoerig, Ludowig, & Knoll, 2008; Striem-Amit, Guendelman, & Amedi, 2012). The vOICe transforms information about the orientation and position of visual edges detected by a camera into sounds with different onsets and pitches.

Beyond the scientific and technical challenge of developing and implementing SSDs, the possibility of substituting a perceptual system raises questions concerning theories of perception and perceptual consciousness. One of the classic questions that have been raised in this regard refers to the conceptual boundary between true sensory substitution and cognitive aids. In true sensory substitution users report perceiving objects out there, in the environment, rather than attending to the stimulation on the sensory surface. The term distal attribution is devoted to this conscious experience of external objects. On the

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contrary, a cognitive aid is a device that translates information about the external world into arbitrary signs. In this case, users perceive the signs and infer the objects through association. Whereas cognitive aids require explicit learning of signs, codes, and the corresponding meanings, true substitution is intended to make distal attribution emerge through a lawful coupling of perception, action, and sensorimotor information, without the explicit learning of codes.

Several authors have claimed that their SSDs elicit distal attribution. Such claims can be found, for example, in the contributions of Guarniero (1974, 1977) with the original TVSS, in several studies with the vOICe (Auvray, Hanneton, Lenay, & O'Regan, 2005; Proulx, 2010; Ward & Meijer, 2010), and in studies with other visuo-tactile SSDs (Segond, Weiss, & Sampaio, 2005; Siegle & Warren, 2010). Other authors have explicitly considered their SSDs to be cognitive aids, as is the case, for example, for the NavBelt (Johnson & Higgins, 2006) and the NAVIG (Kammoun et al., 2012). However, in a large number of cases no clear-cut distinction is made between these two categories. In addition, no generally agreed-upon sensorimotor behavior or technical feature of the SSD has been proposed that allows one to unambiguously differentiate true sensory substitution from cognitive aids.

Distal attribution may be argued to be the result of the mastery of certain sensorimotor contingencies (Auvray, Hanneton, Lenay, & O'Regan, 2005; O'Regan & Noë, 2001). However, given that the majority of SSDs allow an active control of the sensor component and the effector component is lawfully coupled to the sensor component, according to such criteria the majority of SSDs may produce distal attribution. A related criterion to classify a device as to belonging to the true substitution category or the cognitive aid category is the analysis of *how* the sensory information is transformed in stimulation. In true substitution, one may argue, the contingency of the perceiver's movements and the stimulation should be derived from certain physical laws, such as the laws of optics or acoustics, whereas this is not the case for the relation between external objects and the (arbitrary) codes of cognitive aids. Emphasizing the importance of physical laws for perception and action is reminiscent to an approach that, we believe, is of broader relevance to the main theoretical debates in sensory substitution: ecological psychology.

1.2. The control of action and body-scaled metrics

One of the theoretical and empirical fields that have received wide attention from ecological researchers is that of affordances. The concept of *affordance* was coined by Gibson (1979). Affordances for a particular perceiver are the possibilities for action for that perceiver. This means that affordances are environmental properties that are relevant to the perceiver. Proponents of the ecological approach hold that affordances constitute the object of perception.

According to Fajen, Riley, and Turvey (2008), five main features characterize affordances. First, affordances are real. That is, ontologically, affordances are actual properties of the organism-environment system. Second, affordances are animal-specific. This means that they are not intrinsic properties of objects, but relational properties defined with respect to a perceiver. Third, affordances capture the reciprocity of perception and action, meaning that the perception of the environment is in terms of the possible actions that the perceiver can produce and, at the same time, affordances are perceived through active exploration of the environment. Fourth, affordances allow the prospective control of action. That is, by making use of affordances, a perceiver can adjust her behavior to a future state of the environment, lawfully predicted from the current state. Fifth, affordances are meaningful, so that instead of perceiving the environment in neutral terms as extent, mass, and so forth, affordances are perceiver-relevant properties as climbability, catchability, etc.

Fajen et al. (2008) distinguished *body-scaled* and *action-scaled* affordances. The latter concept refers to possibilities for action that are made possible by dynamic action-capabilities of the perceiver. Tasks that have been used to study this type of affordance include the control of braking (Lee, 1976), catching fly balls (Fajen, Diaz, & Cramer, 2011; Oudejans, Michaels, Bakker, & Dolné, 1996), and walking through sliding doors (Fajen & Matthis, 2011; Fajen et al., 2011). Body-scaled affordances refer to properties that are scaled to anthropometric dimensions. Research concerning this type of affordance has addressed stair climbing (Konczak, Meeuwsen, & Cress, 1992; Mark, 1987; Warren, 1984; Wraga, 1999), prehension (Newell, McDonald, & Baillargeon, 1993; Newell, Scully, Tenenbaum, & Hardiman, 1989; Van der Kamp, Savelsbergh, & Davis, 1998), sitting (Mark, 1987), passing under a barrier (Van der Meer, 1997), fitting the hand through an aperture (Ishak, Adolph, & Lin, 2008), and walking through apertures tightly scaled to the inter-shoulder dimension (Warren & Whang, 1987).

How may the key ecological concepts relate to the theoretical debates in sensory substitution and, more particularly, to the debate concerning distal attribution? First, distal attribution is most commonly suggested to concern properties of the world that are independent of the observer, such as the distance or the dimensions of an object as measured in metric units. Because these properties are distal properties (i.e., exclusively belonging to the external world), the distal part of the term distal attribution makes sense. Given that this view is the dominant one in the debate on distal attribution, it is not typically questioned that awareness should eventually be of distal properties.

The ecological shift away from the claim that perceivers are aware of perceiver-independent properties and toward the claim that perceivers are aware of relational properties may reorient the debate concerning distal attribution in the field of sensory substitution. As mentioned, in the ecological view one perceives properties that are best described in terms such as "an aperture that I can pass through" and "a step that I can climb". Because these properties are not exclusive of the external world, the *distal* part of the term *distal attribution* looses part of its meaning. Although a deeper analysis of the concept of affordance is beyond the scope of our article, it is important to note that affordances are instantiated in ecological properties that are scaled to the perceiver. It is also interesting to note that similar claims concerning relational properties have been made in other scientific areas (e.g., in quantum physics; Gomatam, 1999).

A second key claim of the ecological approach is that affordances are perceived in a direct manner, meaning that perception is not mediated by mental representations, inferential processes, or other computational processes (Gibson, 1979; Michaels & Carello, 1981). Although relevant to the debate, this claim cannot be verified empirically. Nevertheless, we believe that it would be illustrative to analyze perception with SSDs using the tools that are typically used in the ecological literature. Such an analysis may confirm that canonical results of the ecological approach in regular perception are also obtained with SSDs. Showing that empirical results with SSDs mirror key empirical results for regular perception may be interpreted as tentative support for the claim that the main theoretical claims of the ecological approach for regular perception are valid also for perception with SSDs. To exemplify this reasoning, the present study aims to replicate Warren's (1984) classic results concerning the stair-climbing affordance with an SSD.

1.3. π-numbers in stair climbing

Warren (1984) asked participants to estimate if they felt able to climb a step in a bipedal manner. His experiments used different step heights and two groups of participants: one *tall* and one *short*. As expected, the steps that were judged climbable were higher for the *tall* group than for the *short* group. Warren proposed a simple biomechanical model to describe the expected maximum step height as a function of the length of the leg. This model, illustrated in Fig. 1, is given by the equation

$$R_c = Leg + ULeg - LLeg. \quad (1)$$

In this equation, R_c refers to the critical step height, *Leg* refers to full leg length, *ULeg* refers to upper leg length, and *LLeg* refers to lower leg length. Eq. (1) allows one to derive the value of R_c from anthropometric values. One may assume that the value of R_c corresponds to the step height that leads 50% of affirmative climbability judgments.

Warren (1984) showed that the climbability affordance can be described with a dimensionless number called critical π-number. The critical π-number (π_c) refers to the maximum height that a participant is able to climb in a bipedal manner scaled to her leg length. This number can be defined as

$$\pi_c = R_c/L. \quad (2)$$

Warren observed that the group differences in the climbability judgments disappeared after scaling the height of the steps to the leg length of participants: Both experimental groups showed the expected value of $\pi_c \approx 0.88$.

In the present study, we test if participants using an SSD are able to perceive affordances. More specifically, we test if participants estimate the climbability of steps in the same way as the participants in Warren's (1984) regular visual perception study. We hypothesize that perception with an SSD shares the body-scaled nature observed for visual perception.

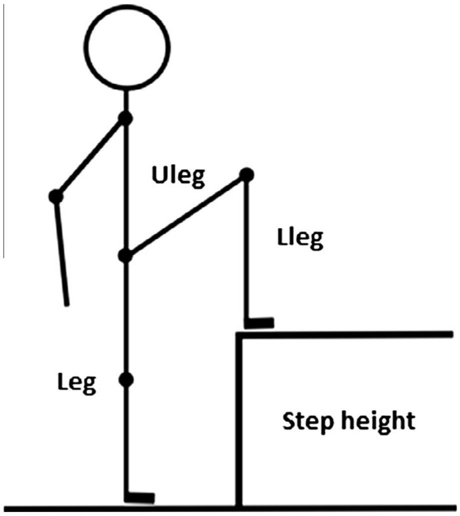

Fig. 1. Biomechanical model of stair climbing. Adapted from Warren (1984).

2. Materials and methods

2.1. Participants

Two groups of eight male participants performed the experiment. Individuals in the *tall* group had a mean height of 182.5 cm (*SD* = 1.3 cm) and were taller than the 75th percentile for height reported in the tables of the Centers for Disease Control and Prevention (CDC, 2002). Individuals in the *short* group had a mean height of 169.1 cm (*SD* = 2.2 cm) and were shorter than the 25th percentile for height (CDC, 2002). All participants signed an informed consent form prior to the experiment. The research program was approved by the local committee of ethical research (CEI 52-957).

2.2. Design

Following Warren's (1984) design, two independent variables were considered. The first independent variable was the height of participants (i.e., the *tall* and *short* groups). The second independent variable was the height of the to-be-judged steps. Seven step heights were used, ranging from 45 to 105 cm. Our steps were similar those used by Warren, who used seven steps heights ranging from 50.8 to 101.6 cm. In our experiment, each step height was used five times, resulting in 7 (step heights) × 5 (repetitions) = 35 trials per participant. The order of the trials was randomized per participant.

2.3. Apparatus and setup

Fig. 2 illustrates the experimental setup. The setup included an exploration area of approximately 400 × 80 cm, a raised platform (i.e., the step) located 50 cm beyond the end of the exploration area, and a four-camera motion-capture system (Qualisys Inc., Sweden).

Participants wore a vibrotactile SSD that was initially designed for previously reported experiments (Díaz, Barrientos, Jacobs, & Travieso, 2012). The SSD consisted of a vertical array of 24 coin motors whose vibration was a function of the distance to the first-encountered object in a frontal body-referenced direction. The vertical array of actuators was located between the top part of the chest and the navel, about 4 cm to the left of the sternum (from the perspective of participants). A rigid body (a piece of cardboard with reflective markers) was also attached to the chest (near the actuators). The motion tracking system continuously registered the position and orientation of the rigid body formed by the reflective markers and exported these measures to Matlab.

Self-developed Matlab routines used the imported position and orientation of the rigid body to compute the position and orientation of the participant, and hence of each actuator. The position and orientation of each actuator, in turn, were used to compute the distance from the actuator to the first-encountered object in the pre-established frontal direction (see Fig. 3). In this experiment, the first-encountered object was either the floor or the step. As mentioned, the driving voltage of each

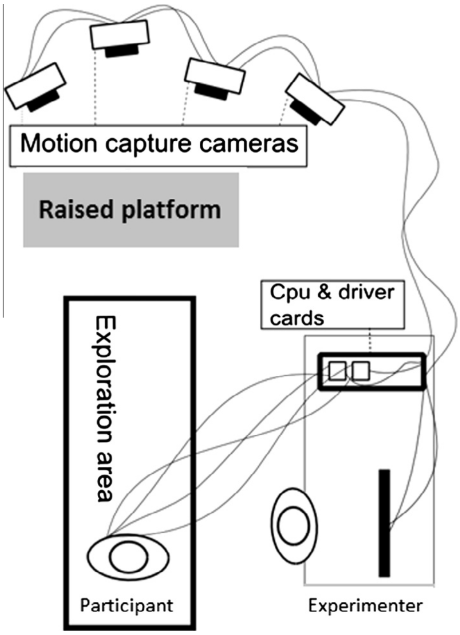

Fig. 2. Experimental setup.

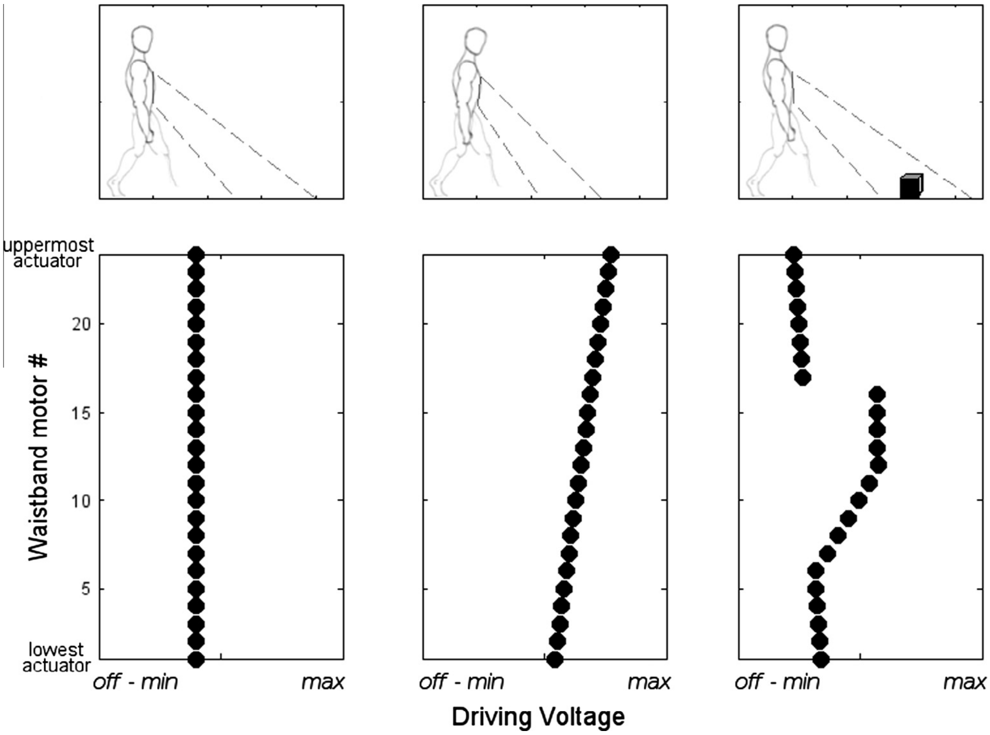

Fig. 3. Schematic representation of the functioning of the SSD. Upper panels show participant positions and the ground range that is "in sight". Lower panels show the corresponding activation of the vibrating motors.

actuator was computed as a function of the distance to the first-encountered object; the nearer the object, the higher the driving voltage. Finally, the driving voltages were sent to the coin motors. The system cycled through the computations with a frequency of about 20 Hz.

Fig. 3 illustrates the functioning of the SSD in three situations. The panels on the left illustrate a user standing straight up in a situation without a step. In this situation, the sensory direction of the highest actuator was oriented to a point on the ground 3.0 m ahead, the lowest actuator was oriented to a point on the ground 1.5 m ahead, and the in-between actuators were oriented to in-between points on the ground. The lower left panel illustrates that, in this situation, a constant low voltage level was used for all actuators. When the participant moved, the orientation and position of the actuators and the associated body-referenced sensory directions changed, resulting in changes in the distances to the floor (or to the step) along the sensory direction of the actuators. The middle panels of Fig. 3 show a situation in which the participant leaned slightly forward, resulting in shorter distances and hence higher driving voltages, especially for the higher actuators. The right panels show a situation with a step. In this situation, the distances to the first-encountered object and the associated driving voltages changed in a less homogeneous manner over the actuators than in the situations shown in the left and middle panels.

A more detailed description of the used SSD is provided in Díaz et al. (2012). An alternative (portable) version using a Microsoft Kinect sensor (without the need of external position tracking and virtualization) is described in Cáncar, Díaz, Barrientos, Travieso, and Jacobs (2013; cf. Lobo, Travieso, Barrientos, & Jacobs, 2014).

2.4. Procedure

Participants were first measured anthropometrically, allowing us to calculate the biomechanical model. Then, they received the following instructions: "The vibration of the actuators is a function of the distance to the ground. The vibration is uniform if you are standing straight up and there is a flat surface in front of you. If you lean forward, the vibration becomes more intense because the actuators get closer to the ground; if you lean backward, the vibration becomes less intense because you are not focusing on the ground. Similarly, if an obstacle is present, the area of the array that points toward the object vibrates more intensely because the distance between the actuators and the nearest object is reduced. Now I am going to present you steps of different heights. At the end of each trial, you will be asked to tell me if you think you are able to climb them without using your hands. You should not leave the exploration area during the trial. Once blindfolded I will tell you if you are about to leave the exploration area, so you can avoid leaving it." To clarify the explanation we used the images presented in Fig. 3.

Before the actual experimental trials, nine practice trials were performed with three repetitions of the smallest (45 cm), medium (75 cm), and highest (105 cm) steps. In these trials, a wooden platform that was adjustable in height was used, and participants perceived both through the SSD and through regular vision (i.e., they were not blindfolded). Participants were not allowed to touch the steps at any moment. These practice trials were immediately followed by the 35 experimental trials. Each trial lasted 30 s. Participants started at the furthest end of the exploration area, and they were allowed to walk back and forth in the area. The experimenter warned participants verbally when they closely approached one of the edges of the exploration area, in order to avoid that they left the area. When the 30-s trial ended (i.e., when the vibration stopped), participants made a forced-choice judgment concerning the perceived bipedal climbability. No feedback was given. In the experimental trials participants were blindfolded and virtual steps were used. The virtual steps affected the vibration as described above without being physically present. The physical presence of the steps was not necessary because, during the experimental trials, participants were blindfolded and did not have physical contact with the steps.

3. Results

We performed a two-way ANOVA on the proportion of trials in which participants judged the step to be climbable in a bipedal way. The within-subjects factor was the height of the step (seven levels) and the between-subjects factor was group (tall vs. short). Significant main effects were observed for step height, $F(6,84) = 27.64$, $p < .001$, and group, $F(1,14) = 5.41$, $p = .04$. The interaction was not significant: $F(1,32) = .95$, $p = .34$. As can be seen in Fig. 4, as the steps increased in height, the proportion of steps that were perceived as climbable progressively decreased. The figure also shows that this proportion was higher for the *tall* group than for the *short* group.

To illustrate the stair climbing affordance as done by Warren (1984), it is necessary to establish the height with 50% affirmative judgments (which is assumed to correspond with the critical step height, R_c, as defined in Eq. (1)). To do so, we fitted logistic functions to the probability data, using the equation

$$p_{(\text{climbable})} = \frac{1}{1 + e^{-a+bx}}. \tag{3}$$

Fig. 5 shows the fitted curves for the *tall* and *short* groups. We performed a *t*-test on the critical step heights (R_c) that were obtained from the logistic curves of individual participants. The effect of group was significant: $t(14) = 2.12$, $p = .003$. The *tall* group indeed judged that they could climb higher steps ($M = 84.39$ cm, $SEM = 3.57$) than the *short* group ($M = 74.85$ cm, $SEM = 2.76$).

We next rescaled the results as the ratio of step height by leg length. We performed the same logistic fits on the rescaled data as on the original data. Fig. 6 shows the resulting curves. A *t*-test on the individual critical π-numbers (π_c) did not show a significant group difference: $t(14) = 0.75$, $p = .46$. Finally, we performed a *t*-test to check if our overall π_c was different from .88 (the value reported by Warren, 1984). The overall π_c in our sample was not significantly different from .88: $t(15) = 0.99$, $p = .34$. In our case, π_c was 0.91.

In addition to the similarity of the observed values of π_c, it is interesting to note that our response curves and the ones reported by Warren (1984) differed in the sense that our curves were less steep. For example, whereas Warren reported 0%

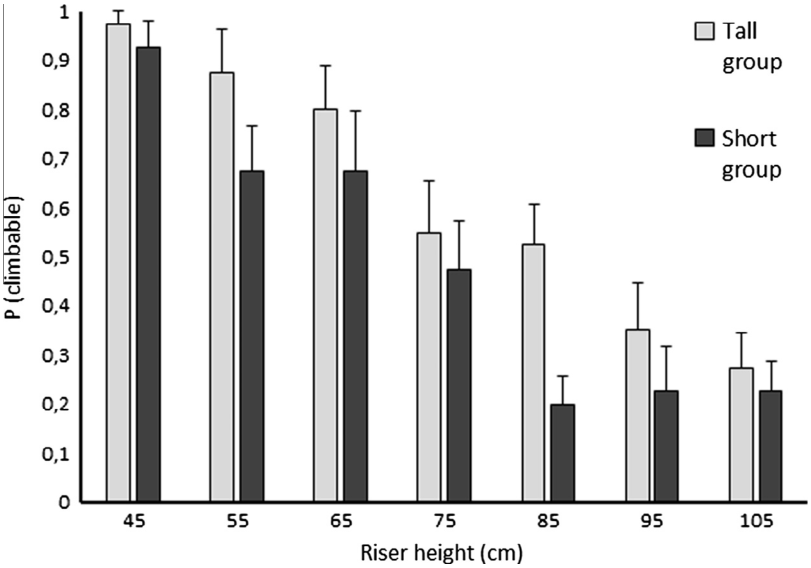

Fig. 4. Proportion of affirmative judgments as a function of step height and group.

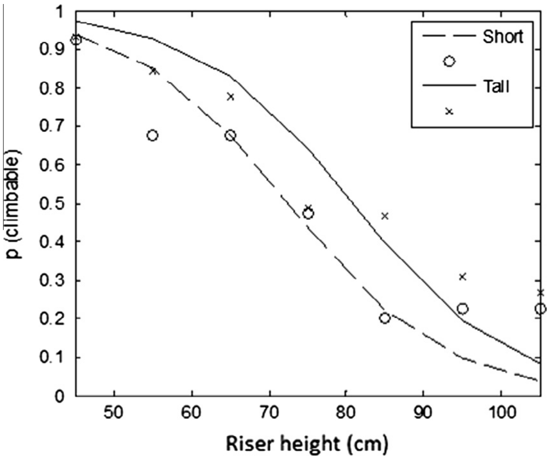

Fig. 5. Logistic fits of p(climbable) as a function of step height for both experimental groups.

and 100% of climbable responses for step heights of 101.6 and 50.8 cm, respectively, we did not observe percentages as low as 0% nor did we observe percentages as high as 100%. This difference can be interpreted as reflecting the lower acuity of perception with an SSD as compared to regular visual perception. Note, finally, that whereas our data show a relatively continuous decline of the percentage of climbable responses with riser high for the *tall* group, the decline seemed to be slightly less continuous for the *short* group. We do not have an explanation for this latter finding.

4. Discussion

The rationale of the present study was to test if SSDs allow the perception of affordances. As a case study, we addressed the perception of climbability through a vibrotactile SSD. It was shown that tall users of our device have a higher mean threshold of climbable steps than short users. However, when the height of the steps is scaled to the length of the leg of the users, then tall and short users do not differ in the height that they perceive as climbable. In sum, perception with our SSD is not of a primary quality of the object, height, but of a relevant relational property, climbability. A similar distinction between primary and secondary qualities, in a different scientific area, was addressed by Gomatam (1999).

With respect to the critical π-number of this affordance, our results for perception with an SSD did not differ significantly from those reported by Warren (1984) for visual perception, establishing the π-number for critical step height around $\pi_c \approx .88$. Given that the proprioceptive components of the tasks are not different, the perception of the steps does not appear to differ between regular vision and SSD perception, at least on the crucial aspect considered in our analysis. Our conclusion, therefore, is that our vibrotactile SSD allows the perception of body-scaled affordances, albeit with less acuity than regular visual perception. The observed similarity between different ways of perceiving is reminiscent to Gibson's concept of

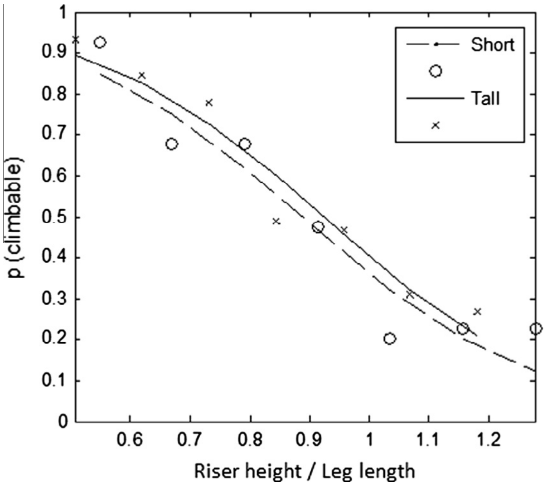

Fig. 6. Logistic fits of p(climbable) as a function of step height divided by leg length for both experimental groups.

perceptual systems and, in particular, with his idea that "the pattern of the excited receptors is of no account" (Gibson, 1966, p. 4).

Relatedly, in the introduction of this article we have argued that adopting key ecological tenets, such as the claim that perception is of affordances, may be of relevance to theoretical debates in the field of sensory substitution. Let us also speculate that an objective measure of π-numbers of either action-scaled or body-scaled affordances may be a useful part of tests that aim to classify SSDs as producing true sensory substitution (i.e. distal attribution) or as being a cognitive aid. Our main argument is that the perception of affordances emerges from active exploration, the resulting sensorimotor contingences, and the biological demand to perceive relevant relational properties. In so doing, a stable objective measurement can be obtained in the form of dimensionless informational numbers that can be tested experimentally. A cognitive aid that, say, indicates the presence of a particular object or letter with a particular vibratory code, might be expected to be less likely to produce the perception of body-scaled affordances.

In addition to concluding that body-scaled affordances are perceived with our SSD, one may consider the question of *how* such affordances are perceived. The main ecological tenet in this regard is that affordances are perceived directly. We are aware, however, that assuming that the observed π-number provides evidence for direct perception might not result convincing to many, as the skeptic argument may always be held. Even in regular vision, the skeptic concerning direct perception may always considered perception a compositional process that starts with minimal units of information that are later integrated and added to secondary properties in an automatic and unconscious manner, perhaps in a computer-like fashion via symbol manipulation. Likewise, possible claims about direct perception with SSDs are always open to criticism, which may mirror the skeptic argument in the case of regular vision (Fodor & Pylyshyn, 1981; cf. Turvey, Shaw, Reed, & Mace, 1981). If, on the other hand, one chooses to place the burden of proof on the skeptic, one may also argue that replicating a sufficient number of key ecological results, such as the observed π-numbers, sets perception with SSDs in reference to direct perception at the same status as regular visual perception.

Although the main topic of the present article is the perception of affordances, we now briefly address another main concern of ecologically inspired research: the informational basis of actions. According to Cesari, Formenti, and Olivato (2003), the perceptual parameter that defines the initiation of the stepping action is the angle between the line from the tip of the foot to the bottom of the step and the line from the tip of the foot to the top of the step. These authors showed that different groups of perceivers with regular visual perception initiated the stepping action when this angle reached the value of 68.3°, which is to say, when the height of the riser was 2.5 times the distance to the step. Such findings, related to the informational basis of actions, may have important implications for the design of SSDs: If one aims to facilitate the control of the stepping action it may be crucial to design SSDs that allow the detection of the angle considered by Cesari et al. An example of an SSD designed for stepping on obstacles—although not inspired by the results of Cesari et al.—can be found in Lobo et al. (2014).

To summarize, we belief that basing further work with SSDs on the conceptual background of the ecological approach to perception, which includes the notion of affordances, may improve both the usability of the devices and the scientific knowledge of the involved perceptual and behavioral processes.

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