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Exploratory movement and affordances in design

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Abstract

The design community has growing familiarity with the concept of affordances, and with the utility of this concept in many areas of design. Less emphasis has been placed on natural processes by which people acquire knowledge about affordances. Consequently, little is known about how design might be optimized to enable users to detect the actions that are available in a given human-machine system. We review scientific research about what people do to obtain information about affordances. We discuss implications of this research for design.

1. INTRODUCTION

The concept of affordance is widespread in the design community. The concept has its origins in behavioral science, where it has given rise to active literatures in terms of both theory (e.g., Gibson, 1979; Stoffregen, 2003; Turvey, 1992) and empirical research (e.g., Mark, 1987; Warren, 1984). In this article, we describe a relatively new area of affordance research in the behavioral sciences, and discuss some possible implications of this research for the design community.

2. AFFORDANCES AND EXPLORATORY ACTIVITY

In this section, we briefly review the nature of affordances, in general, that is, affordances as they exist outside of (and prior to) artifacts or design. We then discuss how affordances are perceived. We understand perception as being active; it is something that people do, rather than something that happens to them. Laboratory research shows that the perception of affordances is strongly dependent upon movement of the perceiver. We review some of this research as it relates to the perception of affordances outside the laboratory.

2.1 Affordances as emergent, relational properties

Affordances are opportunities for action: They are the things that a given animal can do in a given environment or situation. In general theory, affordances are not properties of objects, as such, nor are they properties of the environment, as such. Rather, affordances are relational (or

emergent) properties of the animal-environment system (Stoffregen, 2003). Relational or emergent properties differ qualitatively from the properties of underlying components. As an example, consider Figure 1. In Figure 1A there are three lines. A scientist might analyze these lines, counting them, measuring their length, color, and so on. A designer might modify the lines, making one longer and another shorter, one lighter and another one darker, and so on. Figure 1B also contains three lines. As lines, the lines in Figure 1B are identical to the lines in Figure 1A. The only difference between the lines in Figures 1A and 1B is their relation to one another. But because of this difference, Figure 1B contains something (a triangle) that is not present in Figure 1A. When the lines have a particular arrangement relative to one another, a triangle comes into existence. When that relation is broken the triangle ceases to exist. Triangularity is not a property of the lines, per se, and it cannot be intuited or even detected by any analysis that is limited to properties of the lines, as such.

The concept of affordances has acquired currency within the design community (e.g., Maier & Fadel, 2009a; Norman, 1988; Stoffregen, Bardy, & Mantel, 2006; Torenvliet, 2003; Vicente & Rasmussen, 1992). In the case of design, affordances are not properties of the user as such, nor are they properties of the artifact as such. Rather, affordances are relational properties of what we call the user-artifact system. Consistent with this description, Maier and Fadel (2009b, p. 226) defined affordance as “a relationship between two subsystems in which a potential behavior can occur that would not be possible with either subsystem in isolation”. A potential behavior that would not be possible with either subsystem in isolation is equivalent to the triangle in Figure 1B; the potential behavior is an emergent property of relations between subsystems.

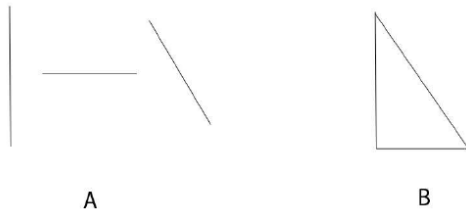


Figure 1. The whole often differs from the sum of the parts. A. Lines that do not form an emergent property. B. The same lines, arranged differently, give rise to an emergent property (a triangle).

As the above discussion illustrates, affordances as relational properties of user-artifact systems are logically distinct from the properties of users, as such, and from the properties of artifacts, as such. The opportunity to climb a stair emerges out of the relation between the height of the stair and the length of a person's leg (Warren, 1984). The distance to which a person can throw a ball emerges out of relations between the size and weight of the ball and the size of a person's hand and the strength of their arm (Bingham, Schmidt, & Rosenblum, 1989). The opportunity safely to cross a busy street emerges out of relations between the time available (the "time gap" between the passage of successive cars) and the time needed (how long it takes the individual to cross the street); (Lee, Young & McLaughlin, 1984; Plumert, Kearney, & Cremer, 2004).

As a general concept, affordances exist in animal-environment systems. For example, the affordance for throwing an object to a maximum distance applies to natural objects (e.g., rocks) as well as to artifacts (e.g., balls). As a matter of practice, the majority of scientific research on the perception of affordances has been conducted in the context of user-artifact systems. Warren (1984) asked whether participants could perceive their ability to climb built staircases, rather than (for example) natural ledges in a rock face. For this reason, much of the research on affordance perception is directly relevant to the perception of affordances in user-artifact systems, which is convenient for the present analysis. In reviewing the literature, we distinguish between studies that were intended to illuminate general or basic aspects of affordance perception, and studies that were intended to illuminate the perception of affordances in specific user-artifact systems. In many cases, this distinction is arbitrary, and relates more closely to the interests of the reader than to the interests of the scientists who conducted the research.

In the general case, affordances are defined in terms of the animal-environment system. Within the design

community discussions of affordances often substitute the artifact for the environment; an example is the treatment of Maier and Fadel (2009b). This formulation can work well for user-artifact systems that are relatively self-contained, such as a person using a desktop computer. However, in many cases the phrase user-artifact system does not adequately capture the true nature of the system. We often use artifacts to effect some change on or within the larger environment. Consider the interaction between a driver and an automobile's brakes; we do not use the brakes for their own sake but, rather, to control the motion of the automobile relative to the broader environment (e.g., stop signs, or other vehicles). For this reason, in this article we sometimes refer to user-artifact-environment systems. Our formulation parallels the proposal to consider artifact-artifact affordances alongside user-artifact affordances (Maier & Fadel, 2009b). Our formulation indicates that artifact-artifact pairs are, in fact, user-artifact-artifact triads. As one example, the ability to stack one chair on another chair depends on the user's ability to lift and maneuver the chairs.

2.2 We perceive affordances, as such

How do we know about affordances, that is, how do we know what actions are available to us in a given situation? In principle, we might obtain information about the environment and information about ourselves and perform an internal computation to obtain the relevant self-environment relations. But another possibility exists. Empirical research in the behavioral science community supports the idea that, rather than computing affordances through internal processing people can perceive affordances. Effects of this kind have been observed in the context of affordances for an individual's own behavior (e.g., Ramenzoni, Riley, Davis, & Shockley, 2008; Warren, 1984; Yu, Stoffregen, & Bardy, 2011), for the behavior of others (Mark, 2007; Stoffregen et al., 1999), or for the behavior of pairs or groups of people (e.g., Chang, Wade, & Stoffregen, 2009; Richardson, Marsh, & Barron, 2007). Children can perceive affordances (e.g., Johnson & Wade, 2009; Plumert et al., 2004), as can infants (e.g., Adolph, 1995; Yonas & Hartman, 1993).

Of critical importance is the finding that people detect the affordance, as such (analogous to the triangle in Figure 1B), without needing to detect the underlying subsystems (analogous to the lines in Figure 1A). Mark (1987) provided a clear example of this effect. Mark asked participants to judge whether a chair was low enough for them to sit upon. He found that people gave accurate judgments, that is, people judged the chair to be "sit-on-able" when the ratio of chair height to leg length was below a critical threshold, and they judged the chair not to be sit-on-able when that ratio exceeded the critical threshold. Then, Mark changed

the actual affordance. He did this by attaching wooden blocks to the soles of the feet (more or less equivalent to donning platform shoes). The blocks increased participants' actual sitting ability (they could now sit on higher chairs). Critically, participants were not permitted to see or look at the blocks at any time and they were not permitted to practice sitting while wearing the blocks. Mark found that participants rapidly adjusted their judgments so that they accurately reflected the changed affordance. Then, Mark asked his participants to indicate the height of the blocks. Astonishingly, they could not do this; their estimates of block height were grossly inaccurate (for a similar effect, see Yasuda, Wagman, & Higuchi, 2014). They had detected the (changed) relation between themselves and the chair, but they had not detected the metric properties of the underlying subsystems.

2.3 Active perception of affordances

How is it that we can perceive emergent, relational properties of the animal-environment system, or of user-artifact systems? How does this information get into our heads? Part of the answer lies in the design of information that is available to users. This issue has been addressed at length, both theoretically and empirically, by Vicente in the context of Ecological Interface Design (Burns & Hajdukiewicz, 2004; Vicente, 2002; Vicente & Rasmussen, 1990; see also Torenvliet, 2003). We take Vicente's work as given, that is, we assume that 1) an artifact has certain affordances (for a given user) and 2) those affordances "show up", somehow, in aspects of the artifact that structure ambient arrays that are available to the user (e.g., optics, sound).

Ecological interface design has focused on sit-down, desktop-style human-computer interfaces that are used for the control of large systems, such as power plants, or oil refineries (e.g., Vicente, 2002). In such settings, the relevant properties of the user are either trivially simple (e.g., their ability to operate a cursor that permits them to select elements in a given display) or highly abstract (e.g., domain-relevant expertise). A very different set of constraints applies when the artifacts are objects, such as a hammer (Wagman & Carello, 2003), or when a computer-based system is used to detect physical activity of the user and translate that information into realtime displays of user motion within a virtual world. Common examples of the latter are contemporary gaming systems in which the user's bodily movement (e.g., arm movements, or standing on a force plate) are used to control a humanoid avatar within a virtual world (e.g., Stoffregen, Chen, & Koslucher, 2014). In these types of user-artifact systems, opportunities to achieve system-relevant goals, such as driving a nail, or scoring points in a video game, emerge out of relations between physical (or virtual) properties of objects and

physical properties of the user. In settings such as there, how does the user detect the actions that are afforded?

The existing literature has mainly focused on the anthropometric properties of the user (e.g., leg length in relation to the design of stairs, or arm length in relation to the physical location of switches in a cockpit), or on mental states of the user (e.g., the user's level of expertise or skill). Less attention has been paid to the fact that the user moves and that these movements affect perceptual stimulation. In the Ecological Approach to Perception and Action, as founded by Gibson (1979) the activity of the human is fundamental to his or her ability to perceive affordances.

A critical discovery was made by Mark, Balliet, Craver, Douglas, and Fox (1990). Following Mark (1987), they asked participants to judge whether a chair was low enough for sitting, and they manipulated actual sitting ability by asking participants (in some conditions) to wear blocks on their feet. The focus of the study was on how participants learned about whether they could sit on chairs of a given height. The situation was both simple and natural: While standing, people looked at a chair and decided whether it was low enough for them to sit on it. We might assume that this perception would be purely visual. However, Mark et al. found that participants were able to give accurate judgments only when they were able to move while looking at the chair. Looking at the chair while walking around it (Experiment 1) was helpful, but only to a limited extent. Remarkably, the data showed that knowledge of sitting ability was dramatically reduced by a very simple manipulation. In Experiment 5, while looking at the chair and making their judgments participants leaned against a wall, such that their head and torso were stationary. This simple, natural manipulation yielded an extraordinary result: In this condition, participants' judgments were degraded to the point of being essentially random. It was as if their eyes were closed and they were simply guessing.

3.1 PERCEIVING AFFORDANCES THROUGH EXPLORATION

A growing experimental literature suggests that our ability to perceive affordances is naturally, routinely dependent upon our own exploratory activity. In plain English, people who want to know what they can do in a given situation engage in actions (i.e., movements) that generate perceptual information about affordances. The use of exploratory activity to generate information about affordances has been documented in a wide variety of situations, and with diverse populations. Exploratory action can include many types of physical interaction with the environment or artifact, including movements of the entire body (as in locomotion, or body sway), movements of limbs, such as the hand in touching an artifact, or even movements of the head and eyes, as in searching a display. The type of

movement(s) that will be relevant to exploration will differ across situations, as suggested in the following examples.

3.1 Exploratory activity generates information about affordances

Even before they learn to walk, crawling infants rely on exploratory activity to determine what surfaces are safe for them to cross. Adolph (1995) presented crawling infants with surfaces that sloped at different angles. Infants were willing to embark upon relatively shallow slopes but refused to cross steeper slopes, even when encouraged by their parents. In making their decisions, infants engaged in systematic exploration of the surfaces, first looking at them, then patting them with one hand, and finally using one or both hands to press down upon them (Adolph, Eppler, Marin, Weiss, & Clearfield, 2000). These exploratory actions were used selectively, on slopes that were near the boundary between crossable and uncrossable. When the slope was very shallow, infants perceived its crossability “at a glance” and immediately embarked upon it. When the slope was very steep, infants refused to embark upon it and, after a quick look, often ignored it. The full range of exploratory actions was deployed mainly for slopes near the can/cannot boundary, that is, slopes that might be crossable.

Bingham et al. (1989) presented adults with a set of objects and asked them to choose the one that they could throw the farthest. When given the opportunity, participants picked up each object and hefted it, using a characteristic pattern of coordinated movements at the wrist and elbow. When allowed to heft the objects, participants gave highly accurate judgments of which one they could throw the farthest, that is, they perceived the affordance for “throwing an object to maximum distance”. Similarly, when a person is allowed to wield a handheld rod (to move the rod by rotating the wrist) they can make extremely accurate judgments about how far they can reach with it, even if they are not allowed to see the rod (e.g., Solomon & Turvey, 1988). On the basis of manual wielding, ice hockey players can accurately select hockey sticks that are best for different types of shots (Hove, Riley, & Shockley, 2006; cf. Carello, Thuot, Anderson, & Turvey, 1999).

The above examples illustrate the use of deliberate movements to learn about affordances. Effects of this kind have led to research on more subtle movements that appear to support the perception of affordances.

It is possible to quantify exploratory movement in ways that permit us to distinguish the characteristics of a given movement that lead to the generation of information about specific affordances. Riley et al. (2002) asked participants to wield a handheld (but unseen) rod. In some conditions, they wielded the rod while judging how far they could reach with it. In other conditions they wielded the rod while judging

the location of their grip (i.e., whether they were holding the end of the rod or the middle), or were asked to wield the rod without making any judgment about it. Measurements of the kinematics of wrist movement revealed that participants systematically used different patterns of wrist movement across these conditions, that is, exploratory wielding was “tuned” to different perceptual tasks. In a complimentary fashion, a priori analysis of particular affordances can make it possible to predict movements that will be effective for exploration (e.g., Mantel, Bardy, & Stoffregen, 2008).

Several studies have shown that the accuracy of affordance perception is related to quantitative details of movements of the head and torso during the process of making affordance judgments (Stoffregen, Wang, Giveans, Flanagan, & Bardy, 2009; Yu, Bardy, & Stoffregen, 2011; Yu & Stoffregen, 2012). We return to this point in a later section.

3.2 Exploration versus performance

Exploratory movements can closely resemble movements used in actual performance. For example, when purchasing an automobile, customers often do a test drive, in which they learn about “how the car drives” by actually driving it. In such cases, exploratory movements can resemble “trial and error” approaches: If you want to know whether an action is possible, then try it and see what happens. These cases are real but they are not universal. In many natural situations exploratory movements are not performance attempts and, in fact, often do not even resemble movements used in actual performance. Infants who want to know whether a surface will support their weight will look at it, pat it, and lean onto it; none of these are locomotor acts or closely resemble locomotor acts, yet they provide information about whether the surface will support locomotion (Adolph et al., 2000). In adults, manual hefting can be used to perceive the throwability of an object, but hefting movements do not resemble throwing movements (Bingham et al., 1989). Similarly, by wielding a rod using only rotations around the wrist an adult can perceive how far they can reach with it, but the wrist movements do not resemble actual reaching (e.g., Riley et al., 2002). On the basis of manual wielding people can make functional judgments with remarkable accuracy, such as differentiating hockey sticks that are optimal for different types of shots (Hove et al., 2006). In an example from daily life, we often squeeze fruits and vegetables to determine their ripeness, but these exploratory movements bear no resemblance to movements of eating.

3.3 Is exploratory movement necessary?

The existence of these movements and the fact that people choose to use them do not, by themselves, permit the conclusion that the movements are necessary. Researchers have addressed this issue by asking participants to perceive affordances when typical exploratory movements are not available. Mark et al. (1990) asked participants to look at a chair and judge whether the seat pan was low enough that they could sit upon it. Judgments were made while standing, such that judgments were made in the context of whole body postural sway. In ordinary conditions, judgments were accurate. However, manipulations that affected the nature or availability of body movement strongly affected the accuracy of these judgments. In one experiment, participants were required to adopt an awkward stance while making their judgments (they stood with their heels together and their toes pointing outward). In another experiment, participants could see the chair only by leaning forward and looking through a peephole. As noted in an earlier section, in a third experiment participants were stand against a wall, such that their back and head remained in contact with the wall. In each of these experiments, participants' judgments of their ability to sit on the chair were grossly impaired, to the point where their responses were effectively random. Similarly, Mantel, Bardy and Stoffregen (2008) presented virtual objects through a head-mounted display, and asked participants to judge whether a virtual object was within reach. Judgments were more precise and more accurate when participants were allowed to freely explore the virtual scene (i.e., moving their head and torso to change their viewpoint) than when they remained stationary while being projected the same 'movie', played back from earlier (active) trials.

Other research has addressed related issues. Stoffregen, Yang, Giveans, Flanagan, & Bardy (2009) asked healthy adults without prior wheelchair experience to sit in a wheelchair and judge the lowest lintel height under which they could roll. Prior to judgments one group was given 2 minutes of practice with the wheelchair. During this practice participants rolled the chairs up and down a long hallway, but not through any doorways or under any low gaps. After this brief practice judgments were more accurate than among participants who had no practice. Moreover, during judgments movements of the head and torso differed between participants with and without practice.

Exploratory movement is important because it generates perceptual information about the animal-environment system (Mantel et al., 2008; 2010). As noted earlier, hefting generates information about how much the object weighs relative to the strength of the arm. A subtler example relates to ordinary body sway, which typically

consists of oscillations that are slow (about 0.2 Hz) and small (approximately 2 cm). Body sway consists of rotational oscillations around body joints (neck, waist, ankles). These rotations displace the head, causing changes in stimulation of the eyes, the vestibular system, and other sensory receptors. The nature of these changes is a complimentary function of properties of the body (e.g., the distance of the head from the axis of rotation) and properties of the environment (e.g., the shape, arrangement, and distances of objects, relative to the observer). Contemporary motion sensing technology makes it possible to detect these subtle movements and use them as inputs to human-computer interfaces (e.g., Stoffregen, Bardy, & Mantel, 2006). One implication is that designers can manipulate relations between user movements and system function. Another implication is that designers can manipulate relations between user movements and the perceptual consequences of those movements, that is, it is possible, in effect, to design the exploratory movements that will be effective in obtaining particular types of information about affordances for the user-artifact system.

Many affordances of artifacts are for physical actions, such as whether a tool is within reach, or is too heavy to lift, or whether a pair of gloves will fit. Other affordances are for more cognitive behaviors, such as word processing or other desktop computer applications, or placing a call using a smart phone. In these situations people who want to know what they can do with a device, or who want to find a particular function on a device, will engage in exploratory activity through the designed interface. In these cases

the perceptual consequences of exploratory actions can be part of the design. The designer can choose which user actions will generate information (e.g., tapping or swiping a touchscreen, or tilting a mobile device), and, in a logically distinct operation, can choose the nature of the information that will be generated by any given exploratory act.

4. EXPLORATORY ACTIVITY IN USER-ARTIFACT SYSTEMS

In this section we review examples that illustrate the routine use of exploratory movement in perceiving the affordances of artifacts, using examples drawn from daily life and from the scientific literature. We then discuss some implications that the active character of affordance perception may have for the design of user-artifact systems.

In many cases, users routinely employ exploratory movement to acquire information about the affordances of user-artifact systems. A cook will insert a knife or a toothpick into a cake to see whether it comes out clean (which affords the end of baking) or covered with cake (which affords continued baking). A user interacting with a computer will move the cursor (by moving the mouse or other input device) to a place of interest on the screen, and

will look for changes in the shape of the cursor (to a pointing finger icon, a text entry icon or a prohibited sign icon) to see whether the current cursor location affords clicking, typing text, or something else. When overtaking a car on a highway, a driver will remove her gaze from the road and look successively at the inside and outside rear-view mirrors, then rotate her head to check the blind spot, to see whether the current traffic situation affords a safe lane change. When test-driving a new car, drivers will lightly tap the brake pedal. The purpose of these “test taps” is not to stop the car, or even to slow it down. Rather, the purpose is to obtain information about the brakes. In effect, the driver is asking, “How hard must I push the brake pedal to get this car to stop in a given situation?” The driver is using exploratory movements to obtain information about an affordance of the driver-car system. Similar exploratory actions often are undertaken in a well-known car under adverse driving conditions, such as in the snow. In this case, the implicit question is, “What level of braking capability do I have in this car under these driving conditions?” Again, the driver uses exploratory movements to obtain information about an affordance of the driver-car system.

Fajen (2005; see also Fajen, 2007) asked participants to control a simple driving simulator, which showed the driver (the participant) moving at constant speed toward a stop sign. Participants were asked to use a joystick as a handbrake, and to operate it so as to stop just at the stop sign. Fajen varied the properties of the simulated brakes by varying the gain between the angle of the joystick and the magnitude of negative acceleration (visible slowing down) on the screen. Within a few trials, participants successfully detected the change in braking capabilities. Even when their braking capability was changed on a trial-to-trial basis, participants exhibited partial adaptation from one trial to the next. An implication of these results is that during the act of braking participants were sensitive to relations between their control actions and resulting changes in the on-screen simulation and that they used this information, online and within trials, to adjust their braking behavior.

These examples underline the broad repertoire of exploratory actions that users can deploy to generate information about affordances. At one extreme, users might perform the afforded action itself, either completely (e.g., braking until achieving a complete stop) or in part (e.g., tapping the brake). At the other extreme, users might perform an action that differs qualitatively from the affordance in question (e.g., turning the head toward the car’s dead angle to see if changing lane is afforded). Between these two extremes, exploratory actions can bear a great variety of relationships to the relevant affordance. It is worth noting that while some actions can be purely exploratory, the reverse situation of actions being purely performatory is much less likely.

Michaels, Weier, and Harrison (2007) evaluated exploratory actions that were elicited by different tools in the context of manual welding. They suggested that for some actions actual performatory movements would tend to produce little or no perceptual information about the relevant affordance. For example, when using a handheld rod to poke something we tend to move the rod in a more or less linear manner, that is, toward the to-be-poked object. Angular rotation of a handheld rod generates dynamic information (patterns of pressure at the skin) that provide precise, accurate information about rod length through the inertia tensor of the rod (e.g., Solomon & Turvey, 1988). By contrast, this information is not generated by actual poking movements, which tend toward linear translation rather than rotation. For other affordances manual performatory movements generate haptic information about affordances. An example is hammering, in which performatory movements tend to be angular (swinging the hammer). Michaels et al. observed that exploratory movement not only changed as a function of the affordance investigated, but also as a function of the tool.

4.1 Exploration in relation to known versus unknown affordances

Laboratory research has focused on situations in which the experimental subjects have known in advance the affordance to be perceived. Typically, experimenters tell the participants what affordance is relevant, such as the opportunity to climb stairs (Warren, 1984), or to sit (Mark, 1987). Similarly, in the previous section our examples of exploratory movement in user-artifact systems focused on situations in which the users (presumably) knew what affordance they were trying to perceive. In such situations, the question under consideration is of the form, “under current conditions, can I do X?” In many cases designers can assume that the user knows, in advance, the affordance(s) that they are trying to perceive, but this is not always the case. That is, there are many situations in which the effective question in the mind of the user is “what can I do with this object/device?” Laboratory scientists have only rarely given their participants the freedom (or the responsibility) to “figure out” what affordances were available in a given situation (e.g., Adolph, 1995; Ye, Cardwell, & Mark, 2009). Similarly, theoretical discussions of affordances have rarely addressed the fact that multiple affordances exist in any given situation, such that people can (indeed, must) choose among affordances, and may need to differentiate affordances that are compatible with a particular behavioral goal, as opposed to equally available affordances that are not compatible with the goal (e.g., Stoffregen, 2003). To the best of our knowledge few experimental studies have addressed the role of

exploratory movement in differentiating among multiple affordances that are available in a given situation, or in allowing users to answer the question, “what can I do with this object/device?” We believe that exploratory movement will play critical roles in both of these situations. Given our argument that exploratory movement tends to be task-specific (e.g., Riley et al., 2002), it seems likely that the type of question being (implicitly) asked by the user will affect the nature of the exploratory movements that will be useful.

5. IMPLICATIONS FOR DESIGN

We have suggested that affordances exist as properties of systems, that is, we have suggested that affordances are emergent properties, as illustrated in Figure 1b. In Figure 1b, we can think of the three sides as the user’s body (including sensory systems), the user’s mental characteristics (e.g., domain expertise, training, experience), and the artifact. In a literal sense, the designer designs only the artifact. But the design of the artifact necessarily influences the emergent properties (in Figure 1b, the existence and nature of the triangle). For this reason, it is logically possible for the designer deliberately to focus on the design of the system, as such. This is the first and most fundamental implication of affordances for design.

In the present article we have focused on the critical role of exploratory activity in users’ understanding of and ability to exploit affordances of user-artifact systems. We have suggested that the design process should take into account the fact that user-artifact-systems (or, where relevant, user-artifact-environment systems) will include the user’s exploratory activity. A similar point has been made by other scholars (e.g., Schneiderman, 1983; see also Norman, 1988, p. 183, on “explorable systems”). Designers should take into account the likelihood that users will attempt to explore a system separately from their attempts to use or operate the system. In many cases, exploratory movements will differ from performatory movements. When this is true it may be relatively easy to separately design for these different types of interactions. In other cases, exploratory movements may closely resemble performatory movements. In these cases it will be essential for design to include the opportunity to terminate or even reverse (e.g., undo) actions that have not progressed to completion. This is an important point given the prospective nature of exploratory movements. In both types of cases, design should include the provision of perceptual feedback arising from exploratory movement; feedback that is immediate and intuitive (cf. Vicente & Rasmussen, 1992).

Exploratory movements that are utilized by a given user in a given situation are influenced by both the nature of the artifact and by the particular affordance that is at issue

(Michaels et al., 2007; Riley et al., 2002). Given this effect, we suggest that designers should aim to create artifacts that elicit not only the movements that would be used to perform actions but also the exploratory movements that reveal the corresponding affordances. In this context, a design that encourages the user to perform an information-generating action can be understood as adding information to the artifact (Mantel et al., 2012). An important point is that this type of information is not imposed on the user (in the way that a printed label imposes information. Rather, the artifact is designed in such a way that the information can optimally be generated and obtained by the user. In effect, design enables the user to generate information on demand.

Another recommendation is that designers should provide the user with feedback about the consequences of their actions, as these consequences relate to affordances. Hutchins, Holland and Norman (1986) introduced the notions of *gulf of execution* and *gulf of evaluation*. The gulf of execution refers to the difference between the actions intended by the user and the actions allowed by the artifact. The gulf of evaluation refers to the difference between the current physical state of the artifact and the information available to the user about this state. Our approach to perception as an act cuts across the distinction between the gulf of execution and the gulf of evaluation (for a related discussion, see Bennett & Flach, 2011, p. 114). In our framework, the process by which a user might know what the artifact affords is not a cognitive process but, rather, is a series of actions that generate perceptual information. But the ease with which a user can perform a given action depends on the gulf of execution. It follows that the effort associated with perceiving what one can do and how to do it depends both on the gulf of evaluation and on the gulf of execution.

As a general consequence, from perspective the concept of usability does not only concern the cost associated with performatory or executive actions but also includes the cost associated with exploratory actions that reveal affordances. Designers should not only create products that fulfill some of the users’ needs, they should (simultaneously) design for exploratory actions and the perceptual information that such actions generate.

6. CONCLUSION

The design community has a good awareness of the existence of affordances and of the fact that it is possible to incorporate specific affordances into the design of user-artifact systems. Designers are aware, also, that affordances can be perceived by users, and that design should be tuned to optimize or simply the perception of an artifact’s affordances. It is equally important, we argue, for designers to understand the active, exploratory nature of human

perception. Humans are not stationary, passive receivers of information. Rather, we are in constant motion and that motion is fundamental to our ability to understand the affordances that are available in any given place and time. Some exploratory acts, such as searching through a folder on a desktop interface, are conscious and deliberate. Other exploratory acts are implicit, outside of deliberate awareness. Both are important, and both can influence design.

REFERENCES

- Adolph, K. E. (1995). Psychophysical assessment of toddlers' ability to cope with slopes. *Journal of Experimental Psychology: Human Perception and Performance*, 21, 734–750.
- Adolph, K. E., Eppler, M., Marin, L., Weiss, I., & Clearfield, M. W. (2000). Exploration in the service of prospective control. *Infant Behavior and Development*, 23, 441–460.
- Bennett, K. B., & Flach, J. M. (2011). *Display and interface design: Subtle science, exact art*. Boca Raton, FL: CRC Press.
- Bingham, G. P., Schmidt, R. C., & Rosenblum, L. D. (1989). Hefting for a maximum distance throw: A smart perceptual mechanism. *Journal of Experimental Psychology: Human Perception and Performance*, 15, 507–528.
- Burns, C. M., & Hajdukiewicz, J. R. (2004). *Ecological Interface Design*. Boca Raton FL: CRC Press.
- Carello, C., Thuot, S., Anderson, K. L., & Turvey, M. T. (1999). Perceiving the sweet spot. *Perception*, 28, 307–320.
- Dainoff, M., Mark, L., Ye, L., & Petrovic, M. (2007). Forget about aesthetics in chair design: Ergonomics should provide the basis for comfort. In M. J. Dainoff (Ed.), *Ergonomics and health aspects of work with computers* (pp. 19–25). Berlin: Springer. DOI: 10.1007/978-3-540-73333-1_3
- Fajen, B. R. (2005). The scaling of information to action in visually guided braking. *Journal of Experimental Psychology: Human Perception and Performance*, 31, 1107–1123.
- Fajen, B. R. (2007). Affordance-based control of visually guided action. *Ecological Psychology*, 19, 383–410.
- Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston, MA: Houghton-Mifflin. [Reprinted in 1986: Hillsdale, NJ: Erlbaum].
- Hove, P., Riley, M. A., & Shockley, K. (2006). Perceiving affordances of hockey sticks by dynamic touch. *Ecological Psychology*, 18, 163–189.
- Hu, J., & Fadel, G. M. (2012). Categorizing affordances for product design.
- Johnson, D. C., & Wade, M. G. (2009). Children at risk for developmental coordination disorder: Judgment of changes in action capabilities. *Developmental Medicine & Child Neurology*, 51, 397–403.
- Lee, D. N., Young, D. S., & McLaughlin, M. (1984). A roadside simulation of road crossing for children. *Ergonomics*, 27, 1271–1281.
- Maier, J. R. A., & Fadel, G. M. (2009a). Affordance based design: A relational theory for design. *Research in Engineering Design*, 20, 13–27.
- Maier, J. R. A., & Fadel, G. M. (2009b). Affordance-based design methods for innovative design, redesign and reverse engineering. *Research in Engineering Design*, 20, 225–239.
- Mantel, B., Bardy, B.G. & Stoffregen, T.A. (2008, November). Intermodal perception of whether an object is within reach. In B. G. Bardy (Chair), *Multimodal Perception- Action Dynamics, Symposium conducted at the 10th European Workshop of Ecological Psychology*, Funchal, Madeira, Portugal.
- Mantel, B., Bardy, B. G., & Stoffregen, T. A. (2010). Locomotor assessment of whether an object is reachable. *Ecological Psychology*, 22, 192–211.
- Mantel, B., Hoppenot, P., & Colle, E. (2012). Perceiving for acting with teleoperated robots: Ecological principles to human–robot interaction design. *IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans*, 42(6), 1460–1475.
- Mark, L. M. (1987). Eyeheight-scaled information about affordances: A study of sitting and stair climbing. *Journal of Experimental Psychology: Human Perception and Performance*, 13, 361–370.
- Mark, L. M. (2007). Perceiving the actions of other people. *Ecological Psychology*, 19, 107–136.
- Mark, L. S., Balliet, J. A., Craver, K. D., Douglas, S. D., & Fox, T. (1990). What an actor must do in order to perceive the affordance for sitting. *Ecological Psychology*, 2, 325–366.
- Michaels, C. F., Weier, Z., & Harrison, S. J. (2007). Using vision and dynamic touch to perceive the affordances of tools. *Perception*, 36(5), 750–772.
- Norman, D. A. (1988). *The psychology of everyday things*. New York: Basic Books.
- Plumert, J. M., Kearney, J. K. & Cremer, J. F. (2004). Children's perception of gap affordances: Bicycling across traffic-filled intersections in an immersive virtual environment. *Child Development*, 75, 1243–1253.
- Ramenzoni, V., Riley, M. A., Davis, T., & Shockley, K. (2008). Tuning in to another person's action capabilities: Perceiving maximal jumping-reach height from walking kinematics. *Journal of Experimental Psychology: Human Perception and Performance*, 34, 919–928.
- Richardson, M. J., Marsh, K. L., & Barron, R. M. (2007). Judging and actualizing intrapersonal and interpersonal affordances. *Journal of Experimental Psychology: Human Perception and Performance*, 33, 845–859.
- Riley, M. A., Wagman, J. B., Santana, M.-V., Carello, C., & Turvey, M. T. (2002). Perceptual behavior: recurrence analysis of a haptic exploratory procedure. *Perception*, 31, 481–510.
- Shaw, R. E., Flasher, O. M., & Kadar, E. E. (1995). Dimensionless invariants for intentional systems: Measuring the fit of vehicular activities to environmental layout. In J. M. Flach, P. A. Hancock, J. Carid, & K. J. Vicente (Eds.), *Global perspective on the ecology of human-machine systems* (pp. 293–357). Hillsdale, NJ: Erlbaum.
- Shneiderman, B. (1983). Direct manipulation: A step beyond programming languages. *Computer*, 16(8), 57–69.
- Smitsman, A. W. (1995). Affordances and the practice of industrial design engineering: Comments on Smets's presentation. *Ecological Psychology*, 7(4), 375–378.
- Solomon, H. Y., Turvey, M. T. (1988). Haptically perceiving the distances reachable with hand-held objects. *Journal of Experimental Psychology: Human Perception and Performance*, 14, 404–427.
- Stoffregen, T. A. (2003). Affordances as properties of the animal-environment system. *Ecological Psychology*, 15, 115–134.
- Stoffregen, T. A., Bardy, B. G., & Mantel, B. (2006). Affordances in the design of Enactive systems. *Virtual Reality*, 10, 4–10.
- Stoffregen, T. A., Chen, Y.-C., & Koslucher, F. C. (2014). Motion control, motion sickness, and the postural dynamics of mobile devices. *Experimental Brain Research*, DOI 10.1007/s00221-014-3859-3.
- Stoffregen, T. A., Gorday, K. M., Sheng, Y.-Y., & Flynn, S. B. (1999). Perceiving affordances for another person's actions. *Journal of Experimental Psychology: Human Perception & Performance*, 25, 120–136.
- Stoffregen, T. A., Yang, C.-M., Giveans, R., Flanagan, M., & Bardy, B. G. (2009). Movement in the perception of an affordance for wheelchair locomotion. *Ecological Psychology*, 21, 1–36.
- Torenvliet, G. (2003). We can't afford it! *Interactions*, 10, 13–17.
- Turvey, M. T. (1992). Affordances and prospective control: An outline of the ontology. *Ecological Psychology*, 4, 173–187.
- Vicente, K. J. (2002). Ecological interface design: Progress and challenges. *Human Factors*, 44, 62–78.
- Vicente, K. J., & Rasmussen, J. (1990). The ecological of human-machine systems II: Mediating "direct perception" in complex work domains. *Ecological Psychology*, 2, 207–250.
- Wagman, J. & Carello, C. (2003). Haptically creating affordances: The user-tool interface. *Journal of Experimental Psychology: Applied*, 9, 175–186.

Warren, W. H. (1984). Perceiving affordances: Visual guidance of stair climbing. *Journal of Experimental Psychology: Human Perception and Performance*, 10, 683–703.

Weast, J. A., Shockley, K., & Riley, M. A. (2011). The influence of athletic experience and kinematic information on skill-relevant affordance perception. *Quarterly Journal of Experimental Psychology*, 64, 689-706.

Yasuda, M., Wagman, J. B., & Higuchi, T. (2014). Can perception of aperture passability be improved immediately after practice in actual passage? Dissociation between walking and wheelchair use. *Experimental Brain Research*, 232, 753-764.

Ye, L., Cardwell, W., & Mark, L. M. (2009). Perceiving multiple affordances for objects. *Ecological Psychology*, 21, 195-217.

Yu, Y., Bardy, B. G., & Stoffregen, T. A. (2011). Influences of head and torso movement before and during affordance perception. *Journal of Motor Behavior*, 43, 45-54.

Yu, Y., Hemingway, L., Bardy, B. G., & Stoffregen, T. A. (2014). Task-specific exploratory movement of the head and body in the perception of affordances. Manuscript submitted for publication.

Yu, Y., & Stoffregen, T. A. (2012). Postural and locomotor contributions to affordance perception. *Journal of Motor Behavior*, 44, 305-311.

Yonas, A., & Hartman, B. (1993). Perceiving the affordance of contact in four- and five month old infants. *Child Development*, 64, 298–308.

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