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The concept of affordances was introduced by J. J. Gibson to explain how inherent "values" and "meanings" of things in the environment can be directly perceived and how this information can be linked to the action possibilities offered to the organism by the environment. Although introduced in psychology, the concept influenced studies in other fields ranging from human–computer interaction to autonomous robotics. In this article, we first introduce the concept of affordances as conceived by J. J. Gibson and review the use of the term in different fields, with particular emphasis on its use in autonomous robotics. Then, we summarize four of the major formalization proposals for the affordance term. We point out that there are three, not one, perspectives from which to view affordances and that much of the confusion regarding discussions on the concept has arisen from this. We propose a new formalism for affordances and discuss its implications for autonomous robot control. We report preliminary results obtained with robots and link them with these implications.

Keywords affordance · autonomous robots · control architecture · formalization · perception

1 Introduction

The concept of *affordances* was introduced by J. J. Gibson to explain how inherent "values" and "meanings" of things in the environment can be directly perceived, and how this information can be linked to the action possibilities offered to the organism[1] by the environment. Although J. J. Gibson introduced the term to clarify his ideas in psychology, it turned out to be one of the most elusive concepts that influenced studies ranging from human–computer interaction to autonomous robotics.

The affordance concept, from its beginnings, has been a hazy one. Despite the existence of a large body of literature on the concept, upon reviewing the literature, one encounters different façades of this term, sometimes contradictory, rather like the description of an elephant by the six blind men in the famous Indian tale.

In the MACS (Multi-Sensory Autonomous Cognitive Systems interacting with dynamic environments for perceiving and using affordances) project,[2] we, as roboticists, are interested in how the concept of affordances can change our views about the control of an autonomous robot and so we set forth to develop an affordance-based robot control architecture. In our quest, we reached an understanding of this elusive concept, such that it can be formalized and used as a

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base for autonomous robot control. The formalization presented in this article summarizes our work on this quest which was developed within the MACS project, but included additional aspects of the affordance concept that went beyond the core work.

In the next section, we review the concept of affordances and affordance-related literature in different fields. We then summarize different formalizations of the affordance concept in a common framework. We point out three different perspectives through which affordances can be viewed and propose a new formalism that could form a base for an affordance-based control architecture.

2 The Concept of Affordances and Affordance-Related Research

In this section, we first describe the concept of affordance, as originally proposed by J. J. Gibson, and then review affordance-related studies in different fields.

2.1 J. J. Gibson's Affordance Concept

J. J. Gibson (1904–1979) was one of the most influential psychologists of the 20th century, who aimed to develop a "theory of information pick-up" as a new theory of perception. He argued that an organism and its environment complement each other, and that studies on the organism should be conducted in its natural environment rather than in isolation, ideas that later formed the basic elements of ecological psychology. The concept of affordance was conceived within this context.

In his early studies on visual perception, J. J. Gibson tried to understand how the "meanings" of the environment were specified in perception for certain behaviors. To this end, he identified optical variables in the perceptual data that are meaningful. He gave one such example for a pilot landing a plane. The meaningful optical variable in that example was the *optical center of expansion* of the pilot's visual field. This center of expansion, according to J. J. Gibson, was meaningful for a pilot trying to land a plane, indicating the direction of the glide and helping him to adjust landing behavior.

In his book J. J. Gibson (1986) also stated that he was influenced by the Gestalt psychologists' view which pointed out that the meanings of things are perceived just as immediately as other seemingly meaningless properties such as color. In that book, J. J. Gibson quotes from Koffka:

> Each thing says what it is … a fruit says "Eat me"; water says "Drink me"; thunder says "Fear me"; and woman says "Love me". (Koffka, 1935)

Hence, the value of the things in the environment are apparent to the perceiver just like other properties.

Based on these studies of meaningful optical variables and the Gestaltist conception of the immediate perception of meanings of the things, J. J. Gibson built his own theory of perception and coined the term *affordance* to refer to the action possibilities that objects offer to an organism in an environment. The term affordances first appeared in his 1966 book (J. J. Gibson, 1966), and is further refined in a later book (J. J. Gibson, 1986). In the later book, affordances were discussed in a complete chapter, which laid out the fundamental aspects of affordances.

Probably his most frequently quoted definition of affordances is:

> The affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill. The verb to afford is found in the dictionary, but the noun affordance is not. I have made it up. I mean by it something that refers to both the environment and the animal in a way that no existing term does. It implies the complementarity of the animal and the environment. (J. J. Gibson, 1979/1986, p. 127)

For instance, a horizontal and rigid surface affords walk-ability, a small object below a certain weight affords throw-ability, and so forth. The environment is full of things that have different affordances for the organism acting in it. Although one may be inclined to talk about affordances as if they were simply properties of the environment, they are not:

> … an affordance is neither an objective property nor a subjective property; or both if you like. An affordance cuts across the dichotomy of subjective-objective and helps us to understand its inadequacy. It is equally a fact of the environment and a fact of behavior. It is both physical and psychical, yet neither. An affordance points both ways, to the environment and to the observer. (J. J. Gibson, 1979/1986, p. 129)

J. J. Gibson believed that affordances are directly perceivable (a.k.a. *direct perception*) by the organism, thus the meaning of the objects in the environment are directly apparent to the agent acting in it. This was different from the contemporary view of the time that the meaning of objects were created internally with further "mental calculation" of the otherwise meaningless perceptual data.

> The perceiving of an affordance is not a process of perceiving a value-free physical object to which meaning is somehow added in a way that no one has been able to agree upon; it is a process of perceiving a value-rich ecological object. (J. J. Gibson, 1979/1986, p. 140)

Discussions on the perception of object affordances naturally had some philosophical consequences on the much debated concept of "object."

> The theory of affordances rescues us from the philosophical muddle of assuming fixed classes of objects, each defined by its common features and then given a name. You do not have to classify and label things in order to perceive what they afford. (J. J. Gibson, 1979/1986, p. 134)

However, to date, there has been much confusion regarding the concept of affordances. We believe that there are a number of reasons for this confusion, and that an explicit statement of these reasons is essential for a healthy discussion of the concept:

- J. J. Gibson's own understanding of affordances evolved over time. As pointed out by Jones (2003), J. J. Gibson always considered his ideas on the concept as "subject to revision":

  > What is meant by an *affordance*? A definition is in order, especially since the word is not to be found in any dictionary. **Subject to revision**, I suggest that *the affordance of anything is a specific combination of the properties of its substance and its surfaces taken with reference to an animal.* (J. J. Gibson, 1977, p. 67)

  As a consequence of this evolution, different quotations of J. J. Gibson can be seen to support contradictory views of the concept. An excellent review of the evolution of the concept, dating back to even before the conception of the term, was written by Jones (2003, p. 112).
- J. J. Gibson's own ideas on the concept were not finalized during his lifetime, as Jones (2003) concludes. We believe that the evolution of the term should continue, and that discussions should be led toward the point he indicated, rather than return to the point he had already reached. This is the view that we have taken in this article.
- J. J. Gibson's idea of affordance can be fully understood only in contrast to the background of contemporary ideas on perception, rather than in isolation. One can read J. J. Gibson's writing to understand the background where the concept of affordances was born, and how the concept of affordances radically challenged existing views:

  > Orthodox psychology asserts that we perceive objects insofar as we discriminate their properties and qualities. … But I now suggest that what we perceive when we look at objects are their affordances, not their qualities. We can discriminate the dimensions of difference if required to do so in an experiment, but what the object affords us is what we normally pay attention to. (J. J. Gibson, 1979/1986, p. 134)

- J. J. Gibson defined affordances as a concept that relates the perception of an organism to its action, whereas his main research interest lay in the perception aspect. Although he explicitly pointed to other aspects of affordances, such as action and learning, he did not conduct any research along these lines.
- J. J. Gibson's own discussions on affordances were often blended with his work on visual perception. As a result of this blending, early studies of affordances in ecological psychology, as will be reviewed below, concentrated on visual perception of the world, with particular emphasis on optical flow. Therefore, when reading J. J. Gibson's ideas on affordances, it is important to keep in mind that the concept provides a general theory rather than a specific theory of visual perception.

After J. J. Gibson, discussions on the concept of affordances, and on its place in ecological psychology have continued. Also, a number of attempts to formalize the concept have been made, because its description as J. J. Gibson left it was ambiguous. These studies will be reviewed in Section 3. But first we will review affordance-related research in different fields, with particular emphasis on its application and its relation to existing concepts in autonomous robot control.

2.2 Affordance-Related Research

2.2.1 Ecological Psychology J. J. Gibson's view of studying organism and environment together as a system (including the concept of affordances) has been one of founding pillars of ecological psychology. Following the formulation of the theory of affordances, the ecological psychology community started to conduct experiments in order to verify that people are able to perceive the affordances of the environment, and to understand the mechanisms underlying this perception. These experiments (Chemero, 2000; E. J. Gibson et al., 1987; Kinsella-Shaw, Shaw, & Turvey, 1992; Mark, 1987; Warren, 1984; Warren & Whang, 1987) aimed to show that organisms (mostly human) can perceive whether a specific action is *do-able* or *not-do-able* in an environment. This implies that what we perceive is not necessarily objects (e.g., stairs, doors, chairs), but the action possibilities (e.g., climbable, passable, sittable) offered by the environment. Although the number of these experiments is quite high, their diversity is rather narrow. They constitute a class of experiments characterized by two main points: taking the ratio of an environmental measure and a bodily measure of the human subject; and, based on the value of this ratio, making a binary judgment about whether a specific action is do-able or not.

The first point indicates how the experimenters interpreted affordances. Since affordances were roughly defined as the properties of the environment taken relative to the organism acting in it, the goal was to show that the ratio between an environmental measure and a bodily measure of the organism have consequences for behavior. This ratio must also be perceivable, so that the organism is aware of this measure which, in a way, determines the success of its behavior. Thus, this relativeness of environmental properties was incorporated into the experiments simply as a division operation between two metrics, one of the environment and one of the organism. From a conceptual point of view, this is a crude simplification of the relation between the properties of the organism and the environment that comprise an affordance, but for the particular actions and setups used in the experiments, it seemed sufficient.

Warren's (1984) stair-climbing experiments have generally been accepted as a seminal work on the analysis of affordances, constituting a baseline for later experiments which seek to understand affordance-based perception. In these studies, Warren showed that organisms perceive their environment in terms of *intrinsic* or *body-scaled* metrics, not in absolute or global dimensions. He was able to calculate the constant π proportions that depend on specific properties of the organism-environment system. For instance, a human's judgment of whether he can climb a stair step is not determined by the height of the stair step, but by its ratio to his leg-length. The particular value of these ratios that signaled the existence of an affordance were called the *critical points*, whereas the ratios which determined whether an action can be performed with minimum energy consumption and maximum ease were called the *optimal points*.

Warren and Whang (1987) showed how the perception of geometrical dimensions such as size and distance is scaled relative to the "perceived eye height"[3] of the perceiver, in an environment where the subjects were to judge the affordance of walking through an aperture. Mark's (1987) surface sitting and climbing experiments also incorporated a similar approach. Some of these studies (E. J. Gibson et al., 1987; Kinsella-Shaw et al., 1992) criticized former studies for limiting themselves to only one perceptual source, namely visual information. Instead, these studies reported experiments related to haptic perception in infant traversability of surfaces and critical slant judgment for walking on sloped surfaces. While in these experiments human subjects were asked to judge whether a certain affordance exists or not in a static environment, Chemero (2000) conducted other experiments in order to prove that changes in the layout of affordances are perceivable in dynamic environments, and found that the results are compatible with *critical ratio* values. Another important work is the study by Oudejans, Michaels, VanDort, and Frissen (1996) of *street-crossing behavior* and perception of a *critical time-gap* for safe crossing. This work is novel, since it shows that not only the static properties of the organism, but also its dynamic state is important when deciding on its actions.

All these experiments were performed in a *one shot* manner, and the subject is either stationary or moving (Warren & Whang, 1987), has either monocular or binocular vision (Cornus, Montagne, & Laurent, 1999), uses either haptic or visual information (E. J. Gibson et al., 1987), determines either the critical or optimal points (Warren, 1984), or examines either searching for affordance or change in the layout of an affordance (Chemero, Klein, & Cordeiro, 2003).

An overview of the experiments mentioned shows that they are mostly focused on the perception aspect of affordances. Other cognitive processes such as learning, high level reasoning and inference mechanisms are not the subjects of these experiments, and the link between affordances and these higher level processes is not discussed. In the following, we will try to close this gap, by presenting some existing studies on the learning of affordances, and the relation of affordances to high-level perception.

2.2.2 Cognitive Science E. J. Gibson studied the mechanisms of the *learning of affordances* and used the ecological approach to study child development. She stated that J. J. Gibson was not particularly interested in development and that "his concern was with perception" only (Szokolszky, 2003, p. 271). As a result, he did not discuss the concept of affordances from a developmental point of view, and only mentioned that affordances are learned in children (J. J. Gibson, 1986).

E. J. Gibson defined learning as a perceptual process and named her theory of learning "perceptual learning." She argued that learning is neither the construction of representations from smaller pieces, nor the association of a response to a stimulus. Instead, she claimed, learning is "discovering *distinctive* features and *invariant* properties of things and events" (E. J. Gibson, 2000, p. 295) or "discovering the information that specifies an affordance" (E. J. Gibson, 2003, p. 283). Learning is not "enriching the input," but discovering the critical perceptual information in that input. She named this process of discovery *differentiation*, and defined it as "narrowing down from a vast manifold of (perceptual) information to the minimal, optimal information that specifies the affordance of an event, object, or layout" (E. J. Gibson, 2003, p. 284). E. J. Gibson suggested that babies use exploratory activities, such as mouthing, listening, reaching and shaking, to gain this perceptual data, and that these activities provide "information about changes in the world that the action produces" (E. J. Gibson, 2000, p. 296). As development proceeds, exploratory activities become performatory and controlled, executed with a goal.

Studies on affordance, reviewed so far, have not provided any ideas regarding its relation to other higher-level cognitive processes. The process of recognition is an example: A subject may indeed seek for sittability when all he needs is to sit, but what would he do when he needs to recognize *his* chair, and how far can affordances help him in this context? In his "Cognition and Reality" book, Neisser (1976) tried to place affordances and direct perception into a complete cognitive system model and tried to link them with other cognitive processes such as recognition. According to him, J. J. Gibson was right in stating that the meanings of the environment are directly available. Invariance attuned detectors are used for this purpose. However, he claimed, the Gibsonian view of affordances of perception is inadequate, since "it says so little about perceiver's contribution to the perception act" (p. 9). Instead, he suggests a perceptual system where a cyclic activity, continuous over time and space, occurs. This cycle "prepares the perceiver to accept certain kinds of information … At each moment the perceiver is constructing anticipations of certain kinds of information, that enable him to accept it (information) as it becomes available" (p. 20). Since every natural object has an infinite number of affordances, this cycle could also be employed to prepare the perceiver to search for particular affordances at each moment, and attune specific detectors to perceive these affordances.

Neisser tried to integrate both *constructive* and *direct* theories of perception. As a result, in a later paper Neisser (1994) constructed a three-layered perceptual system, whose first and third layers correspond to direct perception and recognition, respectively.[4] While the direct perception system is identified by the perception of the local environment, recognition refers to identification of familiar objects and situations.

2.2.3 Neurophysiology and Neuropsychology

J. Norman (2002, p. 25), in a similar vein to Neisser, "attempted to reconcile the constructivist and ecological approaches" into one bigger system, using studies from neurophysiological and neuropsychological studies. Based on evidence from human dorsal and ventral systems, he suggested a perceptual system where two different and interacting visual systems work. While the dorsal system is mainly responsible for the pickup of information from light which is used to modulate actions, the ventral system is concerned with high level perceptual tasks, such as recognition and identification. Thus, according to J. Norman (2001), it is straightforward to conclude that "the pickup of affordances can be seen as the prime activity of the dorsal system." To support his two-perceptual-systems idea he presents examples from a patient who lacks a ventral system (J. Norman, 2002). The patient is able to successfully avoid obstacles, or insert mail into slots in correct orientation using her dorsal system. However, while performing actions successfully, she does not recognize the objects she is interacting with, and thus cannot report them.

Another set of findings of neurophysiological and neuropsychological research that is also associated with the idea of affordances came from studies on *mirror* and *canonical neurons* which were discovered in the premotor cortex of the monkey brain. During experiments with monkeys, mirror neurons fired both when the monkey was grasping an object and when the monkey was watching somebody else do the grasping (Rizzolatti, Fadiga, Gallese, & Fogassi 1996; later similar findings were also found for human subjects by Fadiga, Fogassi, Pavesi, & Rizzolatti, 1995). These findings implied that the same neurons were used both ways: for the execution of an action as output of the system, and also for perceiving that action as an input to the system (Gallese, Fadiga, Fogassi, & Rizzolatti, 1996). Their discovery supports the view that says action and perception are closely related. These neurons, which are located in the premotor cortex of the monkey brain, are thought to be responsible for the motor activation of prehension actions such as grasping and holding.

Rizzolatti and Gentilucci (1988) discovered that canonical neurons, normally considered to be motor neurons for grasping actions, would fire when the subject does not execute a grasping action, but only sees a graspable object. Their activity on such a purely perceptive task that included an object that affords the particular action the motor neurons were responsible for, indicated that they may be related to the concept of affordance. The resulting conclusions are interestingly similar to those of the ecological approach:

> This process, in neurophysiological terms, implies that the same neuron must be able not only to code motor acts, but also to respond to the visual features triggering them. … 3D objects are identified and differentiated not in relation to their mere physical appearance, but in relation to the effect of the interaction with an acting agent. (Gallese, 2000)

Humphreys (2001) showed that, when presented with a tool, some patients, who lacked the ability to name the tool, had no problem in gesturing the appropriate movement for using it. According to Humphreys, this suggested a direct link from the visual input to the motor actions that is independent of more abstract representations of the object, for example, its name. In another study that Humphreys presented, two groups were shown object pictures, non-object pictures, and words. One of the groups was asked to determine if some actions were applicable to what had been presented. The other control group was asked to make size judgments. The brain activities in both groups were compared using functional brain imaging. It was observed that a specific region of the brain was activated more in the first group who were to make action judgments. It was also seen that this specific region was activated more when the subjects were presented with pictures of the objects rather than with the name. This showed that action related regions of the brain were activated more when the visual input was supplied, rather than just naming it. All these findings suggest that there is a strong link between perception and action in terms of neuropsychological activity.

2.2.4 Human–Computer Interaction The concept of affordance has influenced other, seemingly unrelated, disciplines as well. One of these is the human–computer interaction (HCI) domain. The concept was introduced to the HCI community in D. A. Norman's (1988) popular book, *Psychology of Everyday Things* (POET). In his book, D. A. Norman discussed the perceptual information that can make the user aware of an object's affordances. In this context, he defined affordances as follows:

> …affordance refers to the perceived and actual properties of the thing, primarily those fundamental properties that determine just how the thing could possibly be used. (p. 9)

Unlike J. J. Gibson however, D. A. Norman was interested in how "everyday things" can be designed such that the user can easily infer what they afford. He analyzed the design of existing everyday tools and interfaces, identifying design principles. In this respect, his discussion of affordances deviated from the Gibsonian definition of the term (McGrenere & Ho, 2000). D. A. Norman (1999) writes:

> The designer cares more about what actions the user perceives to be possible than what is true. (p. 39)

Since POET, the term affordance has been used in many ways in the HCI community, some in the sense that D. A. Norman introduced, some being more loyal to J. J. Gibson's definition, and others deviating from both of these and using the term in a totally new way (McGrenere & Ho, 2000).

In a later article D. A. Norman (1999), uncomfortable with the misuse of the term in the HCI community, distinguished between "real affordances," indicating the potentials in the environment independent from the user's perception, and what he called "perceived affordances" stating:

> When I get around to revising POET, I will make a global change, replacing all instances of the word "affordance" with the phrase "perceived affordance." (p. 39)

2.2.5 Autonomous Robotics The concept of affordances is highly applicable to autonomous robot control and it has influenced studies in this field. We believe that, for a proper discussion of the relationship of the affordance concept to robot control, the similarity of the arguments of J. J. Gibson's theory and reactive/behavior-based robotics should first be noted. An early discussion of this relationship was made by Arkin (1998, p. 244) and our discussion partially builds on his.

The concept of affordances and behavior-based robotics emerged in very similar ways as opposing suggestions to the then dominant paradigms in their fields. J. J. Gibson constructed his theory based on criticism of the then dominant theory of perception and cognition, which favored modeling and inference. Likewise, behavior-based robotics was motivated by criticism of the then dominant robotic architectures, which favored modeling and inference. This parallelism between the two fields suggests that they are applications of the same line of thinking to different domains (1998, p. 244; Duchon, Warren, & Kaelbling, 1998).

Opposing modeling and inference, J. J. Gibson defended a more direct relationship between the organism and the environment and suggested that a model of the environment and costly inferential processes were not needed. In a similar vein, behavior-based robotics advocated a tight coupling between perception and action. Brooks, claiming that "the world is its own best model," suggested an approach that eliminated all modeling and internal representation (Brooks, 1990, p. 13).

J. J. Gibson suggested that only the relevant information is picked up from the environment, saying "perception is economical" (p. 135). In robotics a behavior is a sensory-motor mapping which can often be simplified to a function from certain sensors to certain actuators. In this sense, the perceptual part of a behavior can be said to implement *direct perception* by extracting only the relevant information from the environment for action, without relying on modeling or inference. Such a minimality is also in agreement with the economical perception concept of the affordance theory.

As discussed above, most of the concepts within affordance theory are inherently included in reactive robotics. The behaviors should be minimally designed for the task, taking into account the niche of the robot's working environment and the task itself. This is in agreement with the arguments of ecological psychology. Some roboticists have already been explicitly using ideas on affordances in designing behavior-based robots. For example, Murphy (1999) suggested that robotic design can benefit from ideas in the theory of affordances such that complex perceptual modeling can be eliminated without loss in capabilities. She studied three case studies and drew attention to the importance of the ecological niche in the design of behaviors. Likewise, Duchon et al. (1998) benefited from J. J. Gibson's ideas on direct perception and optic flow in the design of behaviors and coined the term *Ecological Robotics* for the practice of applying ecological principles to the design of mobile robots.

The use of affordances within autonomous robotics is mostly confined to behavior-based control of the robots, and its use in deliberation remains a rather unexplored area. This is not a coincidence, but a consequence of the shortfalls in J. J. Gibson's theory. The reactive approach could not scale up to complex tasks in robotics, in the same way that the theory of affordances in its original form was unable to explain some aspects of perception and cognition.

In cognitive science, some cognitive models associated affordances only with low-level processes (J. Norman, 2002), others viewed affordances as a part of a complete cognitive model (E. J. Gibson, 2000; MacDorman, 2000; Neisser, 1994; Susi & Ziemke, 2005). Similarly, in robotics, some hybrid architectures inherit properties related to affordances only at their reactive layer (Arkin & Balch, 1997; Connell, 1992), while others study how the use of affordances may associated with high-level processes such as learning (Cooper & Glasspool, 2001; Cos-Aguilera, Canamero, & Hayes, 2004; Fitzpatrick, Metta, Natale, Rao, & Sandini, 2003; MacDorman, 2000; Stoytchev, 2005b), decision-making (Cos-Aguilera, Canamero, & Hayes, 2003), and planning (Stoytchev, 2005a).

Recently a number of robotic studies focused on the learning of affordances in robots. These studies mainly tackled two major aspects. In one aspect, affordance learning is referred to as the learning of the consequences of a certain action in a given situation (Fitzpatrick et al., 2003; Stoytchev, 2005a, 2005b). In the other, studies focus on the learning of the invariant properties of environments that afford a certain behavior (Cos-Aguilera et al. 2003, 2004; MacDorman, 2000). Studies in this latter group also relate these properties to the consequences of applying a behavior, but these consequences are in terms of the internal values of the agent, rather than changes in the physical environment.

Cooper and Glasspool (2001) referred to the learning of action affordances as the acquisition of environment–action pairs that result in successful execution of the action. Their paper associated the affordance to the whole perceived situation of the environment and asserted the consequences of actions, rather than learning them, by judging the outcome of actions as to reinforce successful ones.

Cos-Aguilera et al. (2003) used affordances in action selection by learning the relation between perceived features of objects and the consequence of performing an action on the object, where the consequence is judged by the robot in terms of the change in homeostatic variables in its motivational system. In a later study (Cos-Aguilera et al., 2004) they gave more emphasis to learning the "regularities" of objects and relating them to the outcome of performing an action.

Similarly, MacDorman (2000), extracted invariant features of different affordance categories. In his study, the invariant features are defined as image signatures that do not vary among the same affordance category but vary among different affordance categories. However, his affordance categories were defined in terms of internal indicators, such as tasty or poisonous, and were not directly related to the actions.

Stoytchev (2005a, 2005b) studied learning for the so-called "binding affordances" and "tool affordances," where learning binding affordances corresponds to discovering the behavior sequences that result in the robot arm binding to different kinds of objects whereas learning tool affordances corresponds to discovering tool–behavior pairs that give the desired effects. In this study the representation of objects is said to be grounded in the behavioral repertoire of the robot, in the sense that the robot knows what it can do with an object using each behavior. However, in this study, object identification was done by assigning unique colors to each object, hence leaving no way of building associations between the distinctive features of the objects and their affordances. Therefore, a generalization which would make the robot respond properly to novel objects was not possible.

Fitzpatrick et al. (2003) studied the learning of object affordances in a robotic domain. They proposed that a robot can learn what it can do with an object only by acting on it, "playing" with it, and observing the effects in the environment. For this aim, they used four different actions of a robot arm on four different objects. After applying each of the actions on each of the objects several times, the robot learned about the roll-ability[5] affordance of these objects, by observing the changes in the environment during the application of the actions. Then, when it needs to roll an object, it uses this knowledge. However, as in Stoytchev's study, Fitzpatrick et al. did not establish any association between the visual features of the objects and their affordances, giving no room for generalization of the affordance knowledge to novel objects.

Finally we would like to note that affordance theory has mostly been used as a source of inspiration in robotics. Most of the studies reviewed above preferred to refer to J. J. Gibson's original ideas as formulated in his books, ignoring modern discussions on the concept. As a result, only certain aspects of the theory have been used, and no attempts to consider the implications of the whole theory toward autonomous robot control have been made.

3 Prior Formalizations of Affordances

Following J. J. Gibson's work, there have been a number of studies which attempted to clarify the meaning of the term affordances and to create a common understanding on which discussions can be based (Chemero, 2003; Greeno, 1994; Michaels, 2003; Sanders, 1997; Steedman, 2002b; Stoffregen, 2003; Turvey, 1992; Wells, 2002). We will now review four of the proposed formalisms.

3.1 Turvey's Formalization

One of the earliest attempts to formalize affordances came from Turvey (1992). In his formalism, Turvey defined an affordance as a *disposition*. Here, a disposition is a property of a thing that is a potential, a possibility. These potentials become *actualized* if they combine with their complements (e.g., "solubility" of the salt is its disposition, and if it combines with its complement, which is water's property of "being able to dissolve," then they get actualized, resulting in the salt getting "dissolved"). Therefore, dispositions are defined in pairs, and when two complement dispositions meet in space and time, they get actualized. Basing his views on this account of dispositions, Turvey defined affordances as dispositions of the environment, and defined their complement dispositions as the "effectivities" of the organism. He provided this definition:

> An affordance is a particular kind of disposition, one whose complement is a dispositional property of an organism. (p. 179)

Later in his discussion, Turvey formalized this definition as follows:

> Let W_{pq} (e.g., a person-climbing-stairs system) = $j(X_p, Z_q)$ be composed of different things Z (person) and X (stairs). Let p be a property of X and q be a property of Z. Then p is said to be an affordance of X and q the effectivity of Z (i.e., the complement of p), if and only if there is a third property r such that:
>
> - $W_{pq} = j(X_p, Z_q)$ possesses r [where $j(\cdot)$ is the juxtaposition function that joins X_p and Z_q].
> - $W_{pq} = j(X_p, Z_q)$ possesses neither p nor q.
> - Neither Z nor X possesses r. (p. 180)

Here, when the physical structure that renders the stairs climbable (X_p), and the effectivity of the agent (W_q) that makes it able to climb come together ($j(\cdot)$), new dynamics – the action of climbing – (r) arise.

In this formalism, although the actualization of affordances requires an interaction of an agent on the environment to produce a new dynamics, Turvey explicitly attached affordances to the environment that the organism is acting in.

3.2 Stoffregen's Formalization

A criticism of Turvey's formalism came from Stoffregen (2003). According to Stoffregen, there are two main views about affordances. The first view places affordances in the environment alone, while the second view places affordances in the organism–environment system as a whole. Stoffregen adopts the latter view and argues that affordances *cannot* be defined only as properties of the environment, as Turvey did. From this point of view, Stoffregen (2003) described affordances as:

> Affordances are properties of the animal–environment system, that is, that they are emergent properties that do not inhere in either the environment or the animal. (p. 115)

He claimed that attaching affordances to the environment was problematic for their specification to the organism. The reason was that if affordances belong to the environment only, and if what the organism perceives are affordances, then the organism perceives things that are only about the environment but not about itself. If this is the case, then the agent has to do further perceptual processing to infer what is available *for him*. However, this goes against the basic notion of *direct perception*.

Based on these criticisms, Stoffregen modified Turvey's definition to propose a new one to resolve these problems. He presented it in the following way:

> Let W_{pq} (e.g., a person-climbing-stairs system) = (X_p, Z_q) be composed of different things Z (e.g., person) and X (e.g., stairs). Let p be a property of X and q be a property of Z. The relation between p and q, p/q, defines a higher order property (i.e., a property of the animal–environment

> system), *h*. Then *h* is said to be an affordance of W_{pq} if and only if
>
> - $W_{pq} = (X_p, Z_q)$ possesses *h*.
> - Neither *Z* nor *X* possesses *h*. (p. 123)

Here, affordances are defined as "properties of the animal-environment system," rather than as properties of the environment only.

3.3 Chemero's Formalization

Chemero (2003) also criticized Turvey's view which placed affordances in the environment regarding them as environmental properties. Partially in agreement with Stoffregen's proposal, Chemero suggested that:

> Affordances, are relations between the abilities of organisms and features of the environment. (p. 181)

This definition refines Stoffregen's proposal in a number of ways. First, it states that affordances are "relations within the animal-environment system," rather than "properties of the animal-environment system." Second, it also notes that this relation exists between the "abilities of the organism" and the "features of the environment," as compared with a property (of the system) being generated through the interaction between the "property of the organism" and the "property of the environment."

Formally Chemero proposed that an affordance is a relation that can be represented in the form of:

> Affords-ϕ (feature, ability), where ϕ is the afforded behavior.

Here the term "ability" stands for the functional properties of the organisms that are shaped through the evolutionary history of the species or the developmental history of the individual. In that respect, they are different from simple body-scale measures (e.g., the leg-length), but correspond to more general capabilities of the organism. One of the main differences between the two similar formalisms of Stoffregen and Chemero, which both define affordances at the organism–environment scale, is that while Stoffregen's definition of affordance does not include the behavior exploiting the affordance, Chemero's definition does include it.

3.4 Steedman's Formalization

Independent of discussions in the ecological psychology literature, there have also been other attempts at formalization of affordances. One of these came from Steedman (2002b) who used linear dynamic event calculus to reach a formalization of affordances. Steedman's formalization skips the perceptual aspect of affordances (e.g., the invariants of the environment that help the agent perceive the affordances, and the nature of these invariants and the relation of them to the bodily properties of the agent etc.), but instead it focuses on developing a representation where object schemas are defined in relation to the events and actions that they are involved in. For instance, Steedman suggests that a door is linked with the actions of "pushing" and "going-through," and the preconditions and consequences of applying these actions to the door. The different actions that are associated with a particular kind of object constitute the *affordance-set* of that object schema, and this set can be populated via learning. More formally, in Steedman's formalization, an object schema is a function mapping objects of that kind into second-order functions from their affordances to their results.[6] Thus, an object instance specifies what actions can be applied to it, under which conditions, and what consequences it yields. This makes the formalization also suitable for planning, for which Steedman argues that reactive/forward-chaining planning is the best candidate. Steedman's formalization is, as far as we know, the first attempt to develop a formalization of affordances that allows logical/computational manipulation and planning. Steedman also believes this structure of affordances to have implications for the linguistic capability of humans.

To summarize, it can be said that Stoffregen's and Chemero's formalizations, by defining affordances as a relation on the scale of organism–environment system, differ from Turvey's formalization which defines affordances as environmental properties. But there are also differences between Chemero's and Stoffregen's definitions, one of them being the inclusion of behaviors in the definition of affordances in Chemero's formalization. Steedman's formalization differs from the other three formalizations by providing an explicit link to action possibilities offered by the environment, and by proposing the use of the concept in planning.

We believe that none of the reviewed formalisms can be used as a base to develop an affordance-based robot control architecture. In the next section, we will introduce three perspectives through which affordances can be discussed, to explain the source of confusion in the discussions.

4 Three Perspectives of Affordances

One major axis of discussions on affordances concerns where to place them. In some discussions, affordances are placed in the environment as extended properties that are perceivable by the agent, whereas in others, affordances are said to be properties of the organism–environment system. We believe that the source of the confusion is due to the existence of three – not one! – perspectives to view affordances. We argue that in most discussions, authors, including J. J. Gibson himself, often pose their arguments from different perspectives, neglecting to explicitly mention the perspective that they are using. This has been one of major sources that have made the arguments confusing, and seemingly contradictory at times.

The three different perspectives of affordances can be described using the scene sketched in Figure 1, which consists of a (robot) dog, a human(oid) and a ball. In this scene, a dog is interacting with the ball, and this interaction is being observed by a human, who is invisible to the dog and is not part of the dog–ball system. In this scene, the dog is said to have the *agent* role, whereas the human is said to have the *observer* role. We will denote the ball as the *environment*. We propose that the affordances in this ecology can be seen from three different perspectives:

- *agent perspective*;
- *environmental perspective*; and
- *observer perspective*.

We will now describe how affordances can be viewed from these three different perspectives.

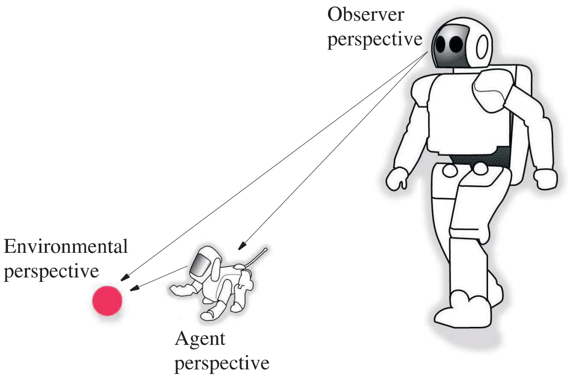

Figure 1 Three perspectives to view affordances. In this hypothetical scene (adapted from Erich Rome's slide depicting a similar scene), the (robot) dog is interacting with a ball, and this interaction is being observed by a human(oid) who is invisible to the dog. (Drawing by Egemen Can Şenkardeş.)

4.1 Agent Perspective

In this perspective, the agent interacts with the environment and discovers the affordances in its ecology. In this view, the affordance relationships[7] reside within the agent interacting in the environment through his own behaviors. In Figure 1, the dog would "say": "I have push-ability affordance," upon seeing the ball.

This view is the most essential one to be explored for using affordances in autonomous robot control, and will be the central focus of our formalization to be developed in the next section.

4.2 Environmental Perspective

The view of affordances through this perspective attaches affordances over the environment as extended properties that can be perceivable by the agents. In our scene, the ball would "say": "I offer hide-ability affordance" to an approaching dog. When interrogated to list all of its affordances, the same ball may say: "I offer, push-ability (to a dog), throw-ability (to a human),..., affordances."

In most of the discussions of affordances, including some of J. J. Gibson's own, this view is often implicitly used, causing much of the existing confusion.

4.3 Observer Perspective

The third view of affordances, which we call the observer perspective, is used when the interaction of an agent with the environment is observed by a third party. In our scene, we assume that the human is observing the interaction of the dog with the ball. In this case, the human would say: "There is push-ability affordance" in the dog–ball system.

In writings of J. J. Gibson, support for the observer perspective can also be seen. While describing the nature of the optical information for perceiving affordances, J. J. Gibson (1986) mentions that it is required for a child to perceive the affordances of things in the environment for others as well as itself:

> The child begins, no doubt, by perceiving the affordances of things for her, for her own personal behavior. But she must learn to perceive the affordances of things for other observers as well as herself. (J. J. Gibson 1979/1986, p. 141)

That is, one must also have the capability of taking the observer perspective when perceiving affordances, at least for the agents of the same species as the observer.

5 An Extended Affordance Formalization

In this section, we develop a formalism to describe our understanding of affordances. Our motivation in attempting this task differs from the prior formalizations studies that we have reviewed, because it stems from our interest in incorporating the affordance concept into autonomous robot control.

In agreement with Chemero, we view affordances as relations within an ecology of acting, observing agents and the environment. Our starting point for formalizing affordances is:

Definition 1. An affordance is a relation between the agent[8] and its environment as acquired from the interaction of the two.[9]

Based on this definition, an affordance is said to be a relation that can be represented as

(*environment*, *agent*).

However, this formalism is too generic to be useful, and needs to be refined. As Chemero also asked in his formalization, "which aspect of the environment is related to which aspect of the organism (agent), and in what way?" Therefore in this relationship, the environment and the agent should be replaced with "environmental relata" and "agent's (organismal) relata" (as in Chemero's terminology), to indicate the relevant aspects of the two.

First, we use the term, *entity*, to denote the environmental relata of the affordance instead of *features* (as used by Chemero) or *object* (as generally used). In our formalism, *entity* represents the proprioceptive state of the environment (including the perceptual state of the agent) as perceived by the agent. The term *entity* is chosen since it has a generic meaning that is less restricting than the term *object*. Although for some affordances the term object perfectly encapsulates the environmental relata, for others, the relata may not be confined to an object and may be more complex.

Second, the agent's relata should represent the part of the agent that is generating the interaction with the environment that produced the affordance. Ideally, the agent's relata should consist of the agent's embodiment that generates the perception–action loop that can realize the affordance. We chose the term *behavior* to denote this. In autonomous robotics, a *behavior* is defined as a fundamental perception–action control unit to create a physical interaction with the environment. We argue that this term implicitly represents the physical embodiment of the interaction and can be used to represent the agent's relata.

Third, the interaction between the agent and the environment should produce a certain *effect*. More specifically, a certain *behavior* applied on a certain *entity* should produce a certain *effect*, for example, a certain perceivable change in the environment, or in the state of the agent. For instance, the *lift-ability* affordance implicitly assumes that, when the *lift behavior* is applied to a *stone*, it produces the effect *lifted*, meaning that the *stone*'s position, as perceived by the agent, is elevated (Figure 2a).

Based on these discussions, we refine our first definition as:

Definition 2. An affordance is an acquired relation between a certain *effect* and an (*entity, behavior*) tuple, such that when the agent applies the *behavior* on the *entity*, the *effect* is generated.

We refine our formalization as

(*effect*, (*entity*, *behavior*)).

This formalization explicitly states that an affordance is a relation which consists of an (*entity, behavior*) pair and an *effect* such that there exists a potential to generate a certain *effect* when the *behavior* is applied

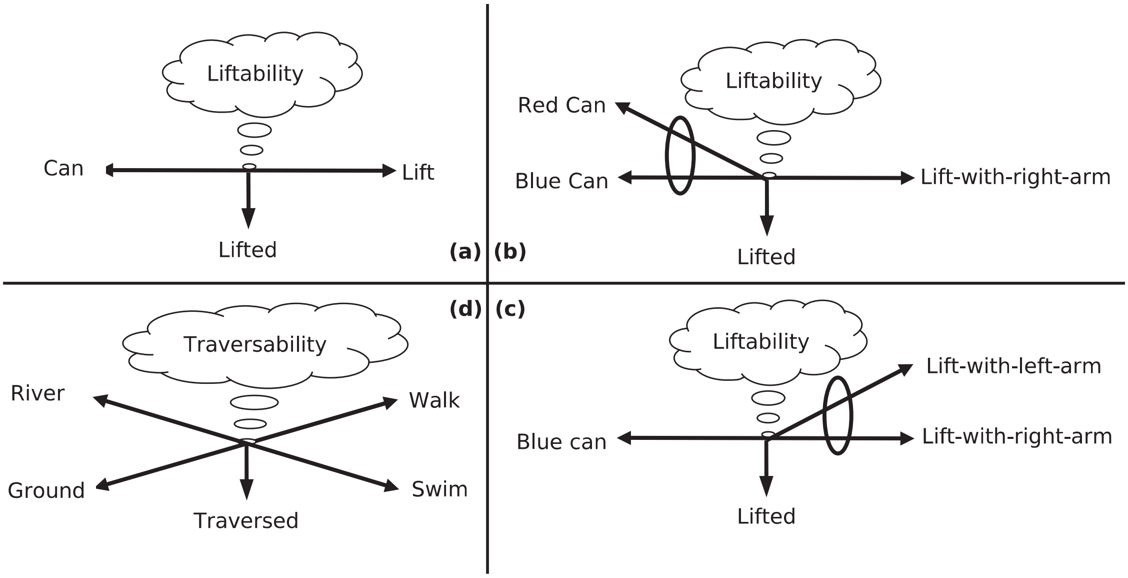

Figure 2 (a) An affordance is a relation between an *entity* in the environment and a *behavior* of an agent, saying that there exists a potential for generating a certain *effect* through the application of that *behavior* on that *entity*. In this example, the application of *lift* behavior on a *can* generated the effect of being *lifted*, and this relation is called *lift-ability*. *Lift-ability* is shown as a "cloud" to indicate that it is just a label for the relation used to make the discussions more clear. (b) Entity equivalence: Many different *entities* (*red-can* and a *blue can*) can be used to generate the same *effect* (being *lifted*) upon the application of a certain *behavior* (*lift*). (c) Behavioral equivalence: More than one *behavior* (*lift-with-right-arm* and *lift-with-left-arm*) can be applied to a certain *entity* (*blue can*) to generate a certain *effect* (*lifted*). (d) Affordance equivalence: Different *(entity, behavior)* tuples [*(river, swim)* and *(ground, walk)*] can generate the same *effect* (*traversed*).

on the *entity* by the agent. In this formalism, we assume that this relation resides within the interacting agent. This means that all three components are assumed to be sensed by the agent. The *behavior* denotes the executed perception-action routine that generated the interaction as sensed by the agent. The *entity* refers not to an abstract concept of an entity (such as a stone) but to its perceptual representation by the agent. Similarly, the *effect* refers to the change inflicted in the environment (including changes in the state of the agent) as a result of the *behavior* acting on the *entity* as perceived by the agent.

The proposed formalization, with its explicit inclusion of *effect*, can be seen as a deviation from J. J. Gibson's view at its outset. It is not. In J. J. Gibson's writings, the issue of effect had always remained implicit. For instance in the definition of the *lift-ability* affordance, the expected effect of *lifted* is implicitly present. Similarly, this has been implicitly included in Chemero's formalism where he named the relation as *Affords-*ϕ to exclude the instances that did not produce the affordance. On the other hand, in both Turvey's and Stoffregen's formalizations, the desired effect is represented as h and r respectively. The proposed formalization differs from these by not only making it explicit, but also putting it on a par with the *entity* and the *behavior*.

The idea of explicit inclusion of a third component into the affordance representation in addition to *behavior*, and *entity* was first set out in Dorffner, Irran, Kintzler, and Poelz (2005) and Irran, Kintzler, and Pölz (2006) within the MACS project. In these studies, the learning of affordances was proposed as the learning of bilateral relations between three components, namely, *entity*, *action* and *outcome* (corresponding to *behavior* and *effect* respectively). The proposed formalization builds on this idea but differs from it in two aspects. First, instead of using *outcome*, which was assumed to be derived from the "time series episode starting after the begin of the application of an action and ending with the end of the action application," we used *effect* as the third component, which can be defined as the change inflicted on the environment. We believe that it is essential for an affordance to have an effect in the environment, and that the issue of change has to be emphasized. Second, *entity* and *behavior* components are grouped into a tuple before being linked to the *effect*. As will become apparent in our discussions later in the article, such a grouping has important benefits.

One question that may be posed is whether this formalism has equated *affordance* with *effect*. This is not the case. The formalism uses *effect* as the index to (*entity, behavior*) tuples. In this sense, given a desired effect to be achieved, the agent can directly access which (*entity, behavior*) can be used to that purpose.

An important aspect of affordances, which is also explicitly stated in our definition, is that they are acquired through the interaction of the agent with the entity. Therefore it is essential to consider the acquisition aspect in order to understand the nature of the three components of our formalism. Note that, whether this acquisition is done through learning, evolution or trial-and-error based design is irrelevant for our discussion.

In the rest of the discussion we will use a hypothetical humanoid robot trying to discover affordances in his operating environment as our guiding scenario. We assume that the robot will experiment with the entities in its environment using its repertoire of behaviors and record the effects as *relation instances* in the proposed formalism. For instance, imagine that the robot applied its *lift-with-right-hand* behavior on a *black-can* and observed the can being *lifted* as its effect. This knowledge can be stored as

$$(\textit{lifted}, (\textit{black-can}, \textit{lift-with-right-hand})). \qquad (1)$$

Here, note that the term *black-can* is used just as a short-hand label to denote the perceptual representation of the black can by the interacting agent. Similarly, *lifted* and *lift-with-right-hand* are labels to the related perceptual and proprioceptive representations. For instance the representation of black can be a raw feature vector derived from all the sensors of the robot looking at the black can before it attempts to apply its *lift* behavior. The naming of such a representation with a label like *black-can*, from the viewpoint of an external observer is merely to make our discussions easier to read.

We call Expression 1, a *relation instance*, to indicate that it contains knowledge obtained from a single experiment and does not have any predictive ability over future experiments, hence is not a *relation*. As the robot explores its environment, it will populate its knowledge database using such relation instances:

$$(\textit{lifted}, (\textit{black-can}, \textit{lift-with-right-hand}))$$

$$(\textit{lifted}, (\textit{blue-can}, \textit{lift-with-right-hand}))$$

$$(\textit{not-lifted}, (\textit{blue-box}, \textit{lift-with-left-hand}))$$

$$(\textit{lifted}, (\textit{black-can}, \textit{lift-with-right-hand})).$$

However, such a database can hardly be called affordances. Affordances should be relations with predictive abilities, rather than a set of unconnected relation instances. In the rest of the section, we will propose four aspects through which relation instances can be bound together toward discovering affordances.

5.1 Entity Equivalence

The class of *entities* which support the generation of the same *effect* upon the application of a certain *behavior* is called an *entity equivalence class*. For instance, our robot can achieve the effect *lifted*, by applying the *lift-with-right-hand* behavior on a *black-can*, or a *blue-can* (Figure 2b). These relation instances can then be joined together as:

$$\left(\textit{lifted}, \left(\begin{Bmatrix} \textit{blue-can} \\ \textit{black-can} \end{Bmatrix}, \textit{lift-with-right-hand}\right)\right).$$

This relation can then be compacted by a mechanism that operates on the class to produce the (perceptual) invariants of the entity equivalence class as:

$$(\textit{lifted}, (<\!*\textit{-can}\!>, \textit{lift-with-right-hand}))$$

where <**-can*> denotes the derived invariants of the entity equivalence class.

In this particular example, <**-can*> means “cans of any color” that can be *lifted* upon the application of *lift-with-right-hand* behavior. Such invariants create a general relationship and enable the robot to predict the *effect* of the *lift-with-right-hand* behavior applied on a novel object, such as a *green-can*. Such a capability offers great flexibility to a robot. When in need, the robot can search and find objects that would provide support for a desired affordance.

We would like to note that the concept of *entity equivalence* is related to the concept *invariance*, defined as "persistence under change" in broad terms by J. J. Gibson. He mentioned the concept in many contexts throughout his book and devoted one section of the Appendices to it. These invariants correspond to the properties which remain constant under various transformations, that is, invariants of optical structure under changing illumination or under change of the point of observation. Although J. J. Gibson did not explicitly define these invariances, he gave some clues about the perception and usage of them.

> … There must be invariants for perceiving the surfaces, their relative layout, and their relative reflectances. They are not yet known, but they certainly involve ratios of intensity and color among parts of the array. (J.J. Gibson, 1979/1986, p. 310)

Entity equivalence can also be related to *matched filters*[10] (Wehner, 1987) which suggests that certain sensor states are equivalent if they induce the same motor response, and there are typically some key features that discriminate the relevant situations for certain motor actions. In this sense, matched filters can also be considered as classifiers of entity equivalence classes.

We argue that the discovery of invariants in entity equivalence classes can also produce abstractions over existing entities. For instance, the invariant <**-can*> denotes a can without color, in an environment where all cans have color. In this sense, if one restricts *entity* to only the perceptual representation of the external world, the component <*entity*> can be referred to as an *affordance cue* (Fritz et al., 2006), which hints at the existence of a potential affordance. We would also like to note that when the term *entity* also includes the perceptual state of the agent itself, the term <*entity*> can be considered to be equivalent to the term *precondition* in deliberative planning. Finally, note that the question of how these invariants can be discovered and represented is a challenge that needs to be tackled.

5.2 Behavior Equivalence

The concept of affordance starts with equi-distance to perception (through the entity in the environment) and action (through behavior of the agent). Yet the role of action is often less pronounced than the role of perception, and most of the discussions concentrate on the perception aspect of affordances. We argue that, if we wish to maintain a fair treatment of the action aspect of affordances, then the same equivalence concept should be generalized to that aspect as well.

For instance, our robot can lift a can using its *lift-with-right-hand* behavior. However, if the same effect can be achieved with its *lift-with-left-hand* behavior, then these two behaviors are said to be *behaviorally equivalent*. This can be represented in our current formalism as:

$$\left(\textit{lifted}, \left(<\textit{*-can}>, \left\{ \begin{matrix} \textit{lift-with-right-hand} \\ \textit{lift-with-left-hand} \end{matrix} \right\} \right) \right)$$

as also shown in Figure 2c. One can join these into

$$(\textit{lifted}, (<\textit{*-can}>, <\textit{lift-with-*-hand}>))$$

where <*lift-with-*-hand*> denotes the invariants of the behavior equivalence class.[11]

We would like to note that, as with the *entity equivalence*, the use of *behavioral equivalence* will bring a similar flexibility for the agent. Through discovery of the perceptual invariants of an *entity equivalence* class, the agent gains the competence to use a different entity to generate a desired effect, even if the entities that had generated the effect in the past are not present in its environment. Such a "change of plan" is directly supported by the *entity equivalence* classes. A similar competence is gained through *behavioral equivalence* classes. For instance, a humanoid robot which lifted a can with one of its arms, loses its ability to lift another can. However, through *behavioral equivalence* it can immediately have a "change of plan" and accomplish lifting using its other hand.

5.3 Affordance Equivalence

Taking the discussion one step further, we come to the concept of *affordance equivalence*. Affordances such as traversability are obtainable by "walking across a road" or "swimming across a river" (Figure 2d) as

$$\left(\textit{traversed}, \left\{ \begin{matrix} (<\textit{road}>, <\textit{walk}>) \\ (<\textit{river}>, <\textit{swim}>) \end{matrix} \right\} \right).$$

That is, a desired effect can be accomplished through different (*entity, behavior*) relations. As a result of this, at a first glance, one is tempted to revise the formalization as:

(*effect*, {(<*entity*>, <*behavior*>)}).

However, we claim that a better and more general formalization that is consistent with the discussions made up to now would be:

(*effect*, <(*entity*, *behavior*)>).

This formalization suggests that the *entity* (the sensory information) is to be concatenated with *behavior* (the motor information) and that the invariances are detected on this combined representation. We would like to note that this formalization is consistent with ideas of effect and behavioral equivalence and that such equivalence classes would emerge as well. An interesting support for this formalization can be drawn from studies of mirror neurons, which are observed to be activated during pure perception as well as during action.

5.4 Effect Equivalence

The concepts of entity, behavior and affordance equivalence classes implicitly relied on the assumption that the agent, somehow, has *effect equivalence*. For instance, applying the *lift-with-right-hand* behavior on a *blue-can* would generate the effect of “a blue blob rising in view.” If the robot applies the same behavior to a *red-can*, then the generated effect will be “a red blob rising in view.” If the robot wants to join the two relation instances learned from these two experiments, then it has to know whether the two effects are equivalent or not. In this sense, all the three equivalences rely on the existence of *effect equivalence* classes.

At its outset, the need for effect equivalence turns the problem into a chicken-and-egg problem. The challenge of discovering effect equivalence classes concurrently with entity and behavioral equivalence classes will be an interesting problem for the learning of affordances by autonomous robots. On the other side, the inclusion of effect equivalence highlights that the invariant detection operation would apply to all three components of the representation and that effect is no exception.

5.5 Agent’s Affordances

Finally, we propose that an affordance can be formalized as:

(<*effect*>, <(*entity*, *behavior*)>).

This formalism represents affordance from an agent’s perspective. We will make this perspective explicit, and revise our definition as:

Definition 3. Affordance (agent perspective): An affordance is an acquired relation between a certain <*effect*> and a certain <(*entity, behavior*)> tuple such that when the agent applies an (*entity, behavior*) within <(*entity, behavior*)>, an *effect* within <*effect*> is generated.

This definition differs from the previous version because it explicitly states that affordance is a *relation* between *equivalence classes*, rather than a *relation instance* between an *effect* and an (*entity, behavior*).

5.6 Observer’s Affordances, and Agent Equivalence

We can now extend the affordance formalization to accommodate affordances from the *observer perspective* as:

(<*effect*>, (<*agent*>, <(*entity*, *behavior*)>)).

where *agent* denotes the perceptual characteristics of the agent that is being observed and <*agent*> represents the *agent equivalence* class. Such an equivalence class can be the basis for the learning of species concepts. That is, after observing what affordances different mice would have in the presence of a stone, the human observer can develop a “mouse” concept. However, we should also note that the affordance would also allow the formation of a “small creatures” class, which would allow the human to predict the behavior of a rat. One would even speculate whether the <*agent*> class for the agent’s own affordances can be linked to the concept of *self* or not. However, this is a controversial issue, and we will not elaborate on it.

We also would like to note that this representation will be different for the human observing a mouse than the human observing his own self. Although not explicitly stated in our formalism, the *behavior* representation included motor information when representing one's own affordances. However, when representing others' affordances, the *behavior* is the behavior of the other agent as perceived by the observer.

We will make this perspective explicit, and revise our definition as:

Definition 4. Affordance (observer perspective): An affordance is an acquired relation between a certain <*effect*> and a certain (<*agent*>, <(*entity*, *behavior*)>) tuple such that when the observed *agent* within <*agent*>, applies an (*entity*, *behavior*) within <(*entity*, *behavior*)>, an *effect* within <*effect*> is generated.

5.7 Environmental Affordances

As we have discussed above, this perspective of affordance exists merely in discussions over the concept, and it is not relevant for affordance-based robot control. However, this perspective can also be formalized. For this, we will assume that the entity being interacted with can also acquire an affordance relation based on its interaction with the agents in its ecology. Under this assumption, an affordance can be formalized as:

(<*effect*>, <(<agent>, < *behavior*>)>).

Note that, the <*entity*> component drops, since we are dealing with a single entity, and that the relation is assumed to reside inside the entity. A definition can be provided:

Definition 5. Affordance (environmental perspective): An affordance is an acquired relation between a certain <*effect*> and a set of (<*agent*>, <*behavior*>) tuples such that when the *agent* within <*agent*>, applies a *behavior* within <*behavior*> on the entity (both taken from the same tuple), an *effect* within <*effect*> is generated.

6 Discussions of the Formalism and Its Implications for Robot Control

We believe that the proposed formalism has laid out a good framework over which the concept of affordance can be utilized for autonomous robot control. Below, we will discuss the major aspects of affordances as proposed within the formalism, and the corresponding implications toward robot control:

- Affordances can be viewed from three perspectives, not one; namely, agent, observer, and environment. In our formalism, we defined affordance from these perspectives with the hope that these different, but related, definitions will be of help in clarifying the discussions of the concept. We consider only the agent and observer perspectives to be relevant and provide the environment perspective only as a means to tie the proposed formalism to some philosophical discussions of the concept.
- Affordances (agent and observer perspective) are relations that reside inside the agent. At first glance, this claim can be seen to go against the common view of affordances in ecological psychology which places affordances in the agent–environment system, rather than in the agent or in the environment alone. However, we argue that representing these relationships explicitly inside the agent does not contradict the existence of these relations within the agent–environment system. As discussed in the previous bullet, we are interested in how the relations within the agent–environment system are viewed from the robot's perspective. We argue that these agent–environment relations can be internalized by the robot as explicit (though not necessarily symbolic) relations and can enable robots to perceive, learn, and act within their environment using affordances.
- Affordances are acquired relations. The acquisition aspect is an essential property of the formalization, yet the method of acquisition is irrelevant. Here, acquisition is used as an umbrella term to denote different processes that lead to the development of affordances in agents including, but not limited to, evolution, learning, and trial-and-error based design. In some discussions, affordances have also been classified based on the process of acquisition leading to: innate affordances (J. Norman, 2001) that are acquired by the species that the organism belongs to through evolution; learned affordances (E. J. Gibson, 2000), that are acquired by the interaction of the organism with its environment during its life-time; and designed affordances (Murphy, 1999) that are "acquired" by the robot through a trial-and-error design phase.

The formalism implies that in order to have robots acquire affordances within their environment, first, relation instances that pertain to the interaction of the robot with its environment need to be populated, and then these relation instances should be merged into relations through the formation of equivalence classes. The issues of how relation instances can be generated, and how relation instances can be merged into affordance relations are open problems that beg to be studied. However, we would like to claim that the acquisition process, regardless of the method being used, would lead to two major gains. First, it should lead to perceptual speed-up: a reduction in perceptual processing requirement after acquisition. This gain has already been mentioned as a major motivation for affordances and E. J. Gibson's studies on the mechanisms of learning of affordances already provide clues to how such a speed-up can be achieved. Second, we argue that acquired relations would naturally be in the so-called *body-scaled* metrics, in agreement with the affordance studies in ecological psychology.

- Affordances encode "general relations" pertaining to the agent, environment interaction, such as: balls are rollable. Naturally, exceptions to these general relations, such as "the-red-ball-on-my-table is not rollable (since it is glued to the table)" do exist. However, unlike affordance relations, these "specific relations" possess little, if any, predictive help over other cases, such as whether the-blue-ball-on-my-table is rollable or not. The proposed formalization, differs from the existing formalizations, by explicitly stating that an affordance is a relation that exists between equivalence classes, rather than a relation instance, and embodies power to generalize into novel situations.

  The implication for autonomous robot control is the existence of two control systems; an affordance-based one that acquires and uses general relations, and a complementary add-on system that complements the affordance-based system by learning its exceptions. It is interesting to note that this implication is also in agreement with Neisser's cognitive model (Neisser, 1976) which suggested an object-recognition system that complements affordances.
- Affordances provide a framework for symbol formation. Symbolic representation and processing are important issues in both cognitive science and robotics. However, the problem of how symbols are related to the raw sensory-motor data of the agent, also known as the symbol grounding problem (Harnad, 1990), still attracts considerable research focus. In the proposed formalism, the categorization of raw sensory-motor perceptions into equivalence classes can be considered as a symbol formation process. We would like to point out that the formation of equivalence classes is intertwined with the formation of relations. In this sense, the formation of symbols is not an isolated process from the formation of affordance relations. Instead, as also argued by Sun (2000), these symbols would be "formed in relation to the experience of agents, through their perceptual/motor apparatuses, in their world and linked to their goals and actions." Finally, it will be an interesting challenge to link the different equivalence classes (entity, behavior, affordance, effect, and agent) with the lexical and semantic types in natural languages.
- Affordances provide support for planning. Planning is described as "an abstract, explicit deliberation process that chooses and organizes actions by anticipating their expected outcomes" to achieve "some prestated objectives" (Ghallab, Nau, & Traverso, 2004). The link between affordances and planning was first noted by Amant (1999) within the human computer interaction domain. Later, Steedman (2002a, 2002b) formalized affordances such that they could be used for planning, as reviewed earlier. Steedman pointed out that planning is closely related to the discussion on affordances, even when they are not directly attainable to the agent. For example, we can perceive the graspability of a mug, even when it is not within our reach and not immediately graspable. Even for a seemingly simple task such as this, a plan (such as stand-up, walk, and bend toward) is needed to make the graspability of the mug evident to us.

  In classical planning, also commonly known as STRIPS planning (Fikes & Nilsson, 1971), systems work with operators which consist of three main components: *precondition*, *action*, and *effect* denoting the initial requirements for the action to be applied, the atomic action to be taken, and the expected changes to be inflicted in the environment, respectively. The planner uses the operators, which are assumed to be pre-coded, to generate a sequence of operators, such that its application would take the system from a given initial state to a desired goal state.

We argue that the proposed formalism creates relations that can also be used as operators for planning. An affordance relation is indexed by its *effect* and include tuples which store how that particular effect can be achieved. For instance, the <*entity*> and <*behavior*> components in the proposed formalism, can be considered to correspond to the precondition and action components in the STRIPS representation. A major difference between the STRIPS representation and the affordance representation is the way the operators are indexed. In STRIPS, operators are indexed by their actions, whereas affordances (as our operators) are indexed by their effects. For instance, the proposed formalism implies that the traversability affordance can be represented as a planning operator:

```
(index: traversed
 effect: traversed
      (entity: river, behavior: swim)
      (entity: road, behavior: walk)
)
```

whereas, the same relations could represented using two different operators in STRIPS as:

```
(index: swim
action: swim
     precondition: river,
     effect: traversed
)
(index: walk
action: walk
     precondition: road,
     effect: traversed
)
```

The different representations of operators have important implications for planning. In STRIPS, the whole environment is assumed to be perceived before the planner can start planning, a plan effectively consists of a sequence of actions (since operators are indexed by their actions), and that any change in the environment during execution may require the plan to be revised by the planner. These are important limitations, which can be addressed by the operator structure implied by the formalism. Not surprisingly, however, these limitations were discussed and addressed by some of the relatively more recent work in robotics, such as Firby's reactive action packages (RAPs; Firby, 1989). Firby defined RAPs as a representation that groups together and describes all known ways to carry out a task in different situations. A RAP is composed of a *success test* and a number of *method*s, with each method consisting of a *context* and a *task network*. The task network denotes a partial plan which may use one or more RAPs, whereas the context specifies the situation that the method is applicable, similar to the precondition component of STRIPS. The success test typically contains an algorithm which judges whether the application of a method was successful or not. Note that all methods are subject to the same success test. The traversability relation can be represented as a RAP as follows:

```
(index: traverse
     (success-test: traversed?)
          (context: river,
           task-network: swim)
          (context: road,
           task-network: walk)
)
```

We believe that the similarity between the RAP representation and the affordance representation is interesting because they were developed in different contexts and that this needs to be further investigated.

Most of the discussions regarding the proposed formalism and their implications toward autonomous robot control highlight the need for further studies on physical robot systems. In the next section, we will briefly report some preliminary results obtained from autonomous robots and link them to the discussions above.

7 Toward Affordance-Based Robot Control: Preliminary Results

We have conducted a number of preliminary experiments with robots to implement and evaluate certain aspects of the proposed formalism. Specifically, we studied how a mobile robot can learn to perceive the traversability affordance in a room filled with spheres, boxes, and cylinders. Uğur, Doğar, Çakmak, and Şahin, (2007; an extended version appears as Uğur, Doğar, Çakmak, & Şahin, 2006), defined traversability as the ability "to pass or move over, along, or through." Hence, the environment is said to be traversable in a certain direction if the robot moving in that direction is not forced to stop as a result of contact with an obstacle. Thus, if the robot can push an object by rolling it away, that environment is said to be traversable even if the object is on robot's path and a collision occurs. In this view, which is different from simple obstacle avoidance, boxes and cylinders in upright positions become non-traversable and spheres become traversable.

The experiments were first conducted in a physics-based robot simulator, and then verified on the real robot. The robot and its simulated model used a 3-D range scanner as the main sensor. The environment typically contained one or more objects, with arbitrary size, orientation and placement, in the frontal area of the robot. The robot used its 3-D range scanner to create a range image. The image was split by a 30 × 30 grid. Thirty-nine low-level feature detectors were applied to each of the grids generating a raw perceptual vector of size 35,100. The robot then executed one of the seven pre-coded movement behaviors, which ranged from turn-sharp-right to turn-sharp-left, and recorded whether it was able to successfully traverse or not, through its odometry. Hence, the robot was able to generate relation instances; *entity* being the raw perceptual vector, *behavior* being the index (range 1–7) of the movement behavior executed, and *effect* being 1 or 0 indicating success or failure. Each experiment consisted of an exploration phase, during which the robot accumulated a number of relation instances, a training phase in which entity equivalence classes were learned from these relation instances, and an evaluation phase for testing. The training phase was carried out in two steps. First, the relevant perceptual features were extracted, and then a classifier was trained using these relevant features to learn the mapping from feature space to the effects.

We will report three experiments and discuss the results with respect to the proposed formalism. In the first experiment, the robot explored traversability in setups where it was faced against a random collection of objects dispersed in the environment. The robot generated relation instances from 2,000 different random setups, and used them to learn the traversability of each movement behavior. After training, the robot was able to predict whether the environment affords traversability for a given behavior with around 95% success in 1,000 random setups generated for evaluation. A sample course of the simulated robot in a room full of different objects is shown in Figure 3.

We would like to discuss a number of points to link these results back to the formalism. First, entity equivalence classes were discovered by the trained classifiers. As a preliminary study, we would like to note that only the formation of entity equivalence classes were studied, while assuming that behavior and effect equivalences are pre-coded. Second, the relations between these three equivalence classes were explicitly represented inside the robot. Third, the acquisition process used, that is learning, generated *perceptual economy* for the robot. Our analysis showed that only 1% of the raw feature vector was relevant for perceiving traversability and that these relevant features were grouped on the range image with respect to the direction of the movement as shown in Figure 4.

In the second experiment, the trained robot was tested in setups that were inspired by Warren and Whang's (1987) study on walking through apertures. Warren and Whang studied the perception of pass-through-ability affordance, where participants, presented with apertures of varying width, were asked whether the apertures afford walking through or not. The results showed that the *aperture-to-shoulder-width ratio* is a body-scaled constant for this affordance, and that a *critical point* existed for the subject's decision. In a similar vein to these experiments, we placed two box-shaped objects in front of the robot and tested the robot's predictions of traversability affordance for apertures with different widths. As shown in Figure 5, the robot is able to correctly perceive the affordances of pass-through-able apertures, where *critical passable width* is clearly related to the robot's width.

We would like to point out that these results can be viewed from two different perspectives: observer and agent. An observer of this experiment would indeed conclude that the traversability affordance of the robot depends upon the ratio of the aperture width to the robot's width. Although this conclusion would be correct, it bears little relevance to the nature of the

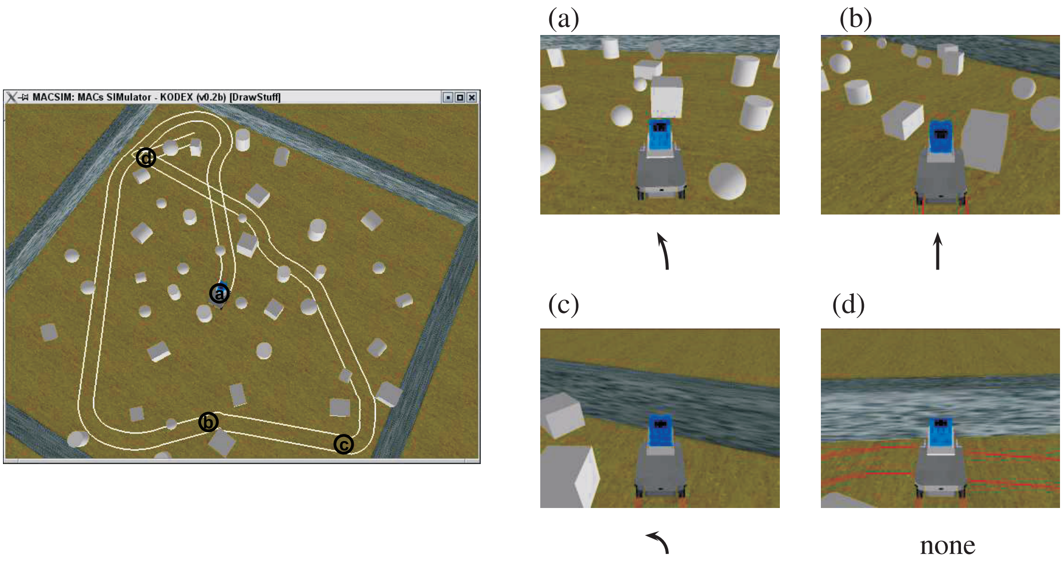

Figure 3 On the left: The course of the trained robot in a virtual room cluttered with 40 objects. The robot tries to go forward while making as few and small turns as possible (Ugur et al., 2007) (©2007 IEEE). On the right: Instances from the trajectory of the robot. In (a) a turn to the left was afforded, and the robot drove toward the spherical object. In (b), although the robot made contact with the box on the right, it selected forward move. In (c), the only behavior that was afforded was turning left sharply. In (d), none of the behaviors were afforded because the robot got too close to the wall and all seven behaviors in the robot's repertoire would have caused a collision. Note the slight difference between (c) and (d), where the robot was able to find the small open-space toward its left in (c).

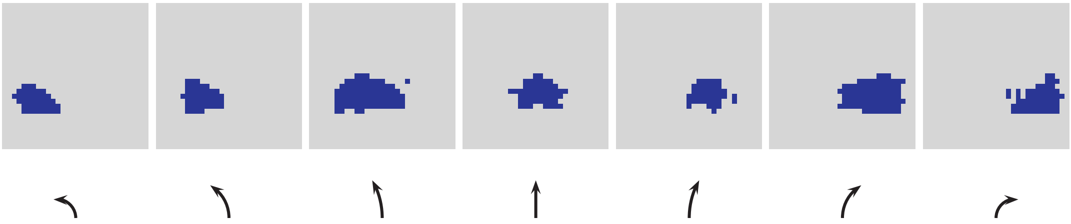

Figure 4 The relevant grids in the range image for each action. A grid is marked as relevant if any of the features extracted from it were learned to be relevant. Note how the relevancy region is correlated with the direction of the movement behavior (Ugur et al., 2007) (©2007 IEEE).

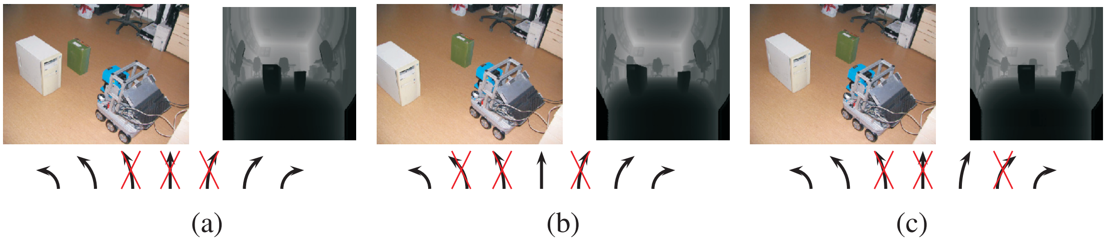

Figure 5 Three experiments for evaluating pass-through-ability for the robot. For each experiment, the view from the observer's and the robot's perspectives are shown. The views from the robot's perspective consisted of range images of the environment as generated by the 3-D range scanner of the robot. In (a) the width of the aperture is too narrow whereas in (b) it is wide enough to support the pass-through-ability. (c) This shows the case where the aperture is slightly toward the right of the robot. In this case, it is important to note that the aperture seen from the robot's point of view is actually narrower than the one in (b). Yet, the robot successfully took this factor into account in its decision.

sensory-motor processing done in the robot. As described above, the robot does not possess the concept of object, aperture or width at any perceptual level and the affordance relation that exists within the robot is different from the affordance relation perceived by the observer. Also, we argue that the existence of a body-scaled relation from an observer's perspective merely indicates that the relation was acquired through the physical interaction of the robot with its environment.

In the third experiment, the robot explored traversability when it was faced with a lying cylinder, which may or may not afford traversability to the robot depending on its relative orientation. After training, the robot was tested with spheres, boxes, and upright cylinders, objects that it had not interacted with before. Yet the robot was able to predict that boxes and upright cylinders were non-traversible (both 100% success), and that spheres were traversible (83% success). We claim that, in this study, the robot learned "general relations" that pertained to its physical interaction with the environment and that these relations were useful for making successful predictions about the traversability of novel objects.

The results reported here were obtained from our preliminary studies, and provide only limited proof for some of the implications discussed in the previous section. A fully-fledged evaluation of all the implications put forward, requires a long-term research effort. Our on-going work has focused on an extended scenario, where the movement behaviors span a continuous range of movements, instead of a discrete set, and where the effects are no longer grouped into success and failure. Also, the use of equivalence classes as a symbols for "affordance-based planning" remains a challenge for future studies.

8 Conclusions

The concept of affordances has been both inspirational and hazy (which may have contributed positively to its influence over a wide-range of fields). In this article, we have reviewed the discussions around the concept and explored how the concept can be formalized to be utilized in autonomous robot control. Toward this end, we have taken the view that our thinking should be led toward the point J. J. Gibson indicated, rather than return to the point that he had already reached. As a consequence, the proposed formalism extended the Gibsonian notion of affordances in two major aspects. First, although the proposed formalism agrees with the Gibsonian view that affordances are relations within the agent–environment system, it differs by arguing that these relationships can also be projected onto the agent. Hence, unlike the prior formalizations, the proposed formalism stops short of providing any "perspective-free" definitions for affordances, since it is not considered to be relevant for using the concept in robot control. The philosophical issue of whether an affordance can be defined without reference to any perspectives is possible or not, and how much such a definition would contribute to the development of a "theory of information pickup" in agents, which constituted J. J. Gibson's main motivation, will remain as topics for further discussion.

Second, the proposed formalism differs from the Gibsonian view because it argues that affordances (for instance, as viewed from the agent perspective) can be internalized and explicitly represented within the agent. The Gibsonian view may reject this extension by arguing that J. J. Gibson had developed the concepts of affordance and direct perception to object the existence of "representations" in the organism. We do not agree with such an argument. In our understanding, J. J. Gibson objected to the view that perception has to create a generic world model, which has been often referred as "representation," over which the organism infers whether an affordance exists or not. He argued that affordances are directly perceivable, that is, without using a world representation and without making inferences. The proposed formalism represents relations, not world models, within the robot and therefore we claim that it does not conflict with the J. J. Gibson's line of thinking.

Extending an already controversial term such as affordance is bound to be subject to criticism. One of the previous commentators on our project warned us of the dangers of being drawn into the heated debate over the term, and suggested that a related-sounding but different term, such as "affoodance," might relieve us from such debates.[12] This difficult dilemma is expressed in our title which begins with "to afford or not to afford." We believe that conceiving new terms without properly relating them to already existing terms does more harm than good. Instead, in this article, we have presented our formalization and definition of the concept according to our understanding of it and leave the final judgment to the readers.

Finally, we would like to note that the implications of the proposed formalism on the development and implementation of an affordance-based robot control architecture is our current and on-going work in the MACS project. Although we believe that there are many challenges ahead toward this goal, the ideas proposed in this article will be of help to guide us on this quest.

Notes

1 In this article, the terms *organism*, *animal* and *agent* will be used interchangeably. The use of *organism* and *animal* will be mostly confined to discussions related to psychology, and the use of *agent* to discussion related to robotics.

2 More information is available at http://macs-eu.org

3 Warren and Whang (1987) defined eye height as the height at which a person's eyes would pass through the wall while walking and looking straight in a natural and comfortable position.

4 The second layer is about inter-personal perception and is not discussed here.

5 What the robot actually learns about objects is the most probable rolling direction of the objects with respect to their principal axis. Hence, after the learning phase, the robot knows that the bottle rolls perpendicular to its principal axis, and the toy car rolls parallel to its principal axis.

6 Steedman's actual formalization requires at least a basic presentation of linear dynamic event calculus and lambda calculus. Since we do not have the space for these here, we restrict ourselves to the prose definition. For a complete account of this formalization, see Steedman (2002b).

7 The formalization of an affordance as a relationship will be developed in the next section.

8 In the rest of our discussions, we will use the term *agent* instead of *organism* or *animal*.

9 Discussions of affordances also spread into concepts such as species, evolution and design. This definition can be rephrased to take such discussions into account, as: An affordance is a relation between the organism (or the species) and its environment as acquired from the interaction of the two, through either learning, evolution or trial-and-error based design.

10 The relationship between affordances and matched filters was questioned/pointed out by Barbara Webb during discussions at the Dagstuhl Seminar "Towards Affordance-Based Robot Control."

11 In robotics, behaviors are often considered to be atomic units, and the invariants of a group of behaviors can sound meaningless. However, if one implements behaviors as a set of parameters whose values determine the interaction, then invariants of behaviors can be discovered on these parameters, similarly to the discovery of invariants in entity equivalence classes.

12 We would like to acknowledge R. Arkin of Georgia Institute of Technology, GA, USA, for this.

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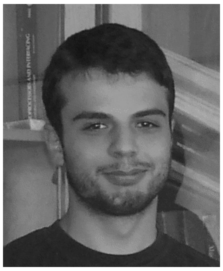

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