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To afford or not to afford: A new formalization of affordances towards affordance-based robot control

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This page contains a Turkish translation of the title and the abstract of the report. The report continues on the next page.

Sağlamak ya da sağlamamak: Sağlarlık-tabanlı robot kontrolüne yönelik yeni bir sağlarlık biçimlendirmesi

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Öz

Sağlarlık (ing. affordance) kavramı J.J. Gibson tarafından ortaya atılmış ve bir canlının çevresini oluşturan şeylerin "değerlerinin" ve "anlamlarının" o canlı tarafından nasıl doğrudan algılandığını ve bu bilgilerin, çevrenin canlıya sağladığı eylem olanaklarıyla nasıl ilişkilendirilebileceğini açıklamak için kullanılmıştır. İlk olarak psikoloji alanında ortaya çıkmış olsa da, sağlarlık kavramı insan-bilgisayar etkileşimi'nden otonom robotbilime kadar çeşitli değisik alanlardaki çalışmaları etkilemiştir. Bu raporda, ilk olarak sağlarlık kavramını J.J. Gibson tarafından tasarlandığı şekliyle sunuyor ve terimin değişik alanlardaki kullanımını otonom robotbilim alanına özel bir önem vererek inceliyoruz. Daha sonra, sağlarlık terimi için ortaya atılan dört ana biçimlendirme önerisini özetliyoruz. Sağlarlığa bir değil üç farklı açıdan bakılabileceğini, ve kavram üzerine yapılan tartışmalardaki karısıklıkların pek çoğunun nedeninin bu olduğunu işaret ediyoruz. Son olarak, sağlarlık için, robot kontrolüne daha uygun olacağını iddia ettiğimiz yeni bir biçimlendirme öneriyoruz.

Contents

Abstract

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 that 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 report, 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 to 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 to view affordances and that much of the confusion regarding the discussions on the concept has arisen from this. Finally, we propose a new formalism for affordances which we claim to be more suitable to be used in robot control.

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 that 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 robotics.

The affordance concept, starting from its conception by J.J. Gibson, has been a misty one. Despite the existence of a large body of literature on the concept, upon reviewing the literature, one would front with different façades of this term, sometimes contradictory, more like the description of an elephant by the six blind man 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 view to the control of an autonomous robot and 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 formalized and be used as a base for autonomous robot control. The formalization presented in this report 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. Then, we summarize different formalizations of the affordance concept in a common framework 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) is one of the most influential psychologists of 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

[1] In this report, 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, whereas the use of *agent* to discussion related to robotics.

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

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. For this aim, 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 visual field of the pilot. 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 the landing behavior.

In his late book [1] J.J. Gibson also stated that he was influenced by the Gestalt psychologists' view that points out that the meaning of things are perceived just as immediately as other seemingly meaningless properties like color. In that book J.J. Gibson quotes from Koffka (Koffka, 1935):

> "Each thing says what it is . . . a fruit says 'Eat me'; water says 'Drink me'; thunder says 'Fear me'; and woman says 'Love me' "

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 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 [2], and is further refined in his later book published in 1979 [1]. In his 1979 book, the description of the affordance concept was discussed in a complete chapter, which generally 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 it, a small object below a certain weight affords throw-ability, etcetera. The environment is full of things that have different affordances for the organism acting in it. Although one may be inclined to talk about the 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 were directly perceivable (a.k.a. *direct perception*) by the organism, thus the meaning of the objects in the environment were 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)

The discussions on the perception of object affordances naturally had some philosophical consequences on the much debated object concept.

> "The theory of affordances rescues us from the philosophical muddle of assuming fixed classes of objects, each defined by it 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 explicit statement of these reasons is essential for a healthy discussion on the concept:

- J.J. Gibson's own understanding of affordances has evolved over time. As pointed out by Jones[3], J.J. Gibson have 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 even before the conception of the term, is written by Jones in [3].

- J.J. Gibson's own ideas on the concept were not finalized during his lifetime, as we agree with Jones' conclusion in [3]. We believe that the evolution of the term should continue, and that the discussions should be led towards where he pointed at, rather than end where he left. This is a view that we have taken in this report.

- J.J. Gibson's idea of affordance can only be fully understood only when it is contrasted to the background of the 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 were born, and how the concept of affordances radically challenges the existing views:

  > "Orthodox psychology asserts that we perceive objects insofar as we discriminate their properties and qualities. ... But what 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'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 than a specific theory of visual perception.

- J.J. Gibson defined affordances as a concept that relates the perception of an organism to its action, however his main research interest lied in the perception aspect. Although he explicitly pointed out to other aspects of affordances, such as action, learning, he did not conduct any research along those lines. As an indirect consequence of this, much of the research on affordances focused more on perception, making the action aspect of the concept neglected.

After J.J. Gibson, discussions on the concept of affordance and on its place in Ecological Psychology have continued. Also attempts to formalize the concept has been made, since it had an ambiguous description as J.J. Gibson had left it. 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 in the next section.

2.2 Affordance Related Research

J.J. Gibson's view of studying organism and environment together as a system (including the concept of affordance) has been one of founding pillars of Ecological Psychology. Following the formulation of the theory of affordances, 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 [4, 5, 6, 7, 8, 9] 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 are not necessarily objects (e.g. stairs, doors, chairs), but the action possibilities (e.g. climbable, passable, sittable) in the world. Although the number of these experiments is quite high, the diversity in them 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 of whether a specific action is possible or not.

The first point gives us a clue about 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 effort 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 its behavior's success. Thus this relativeness of the 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 stair-climbing experiments [4] 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, so called π proportions, that depend on specific properties of the organism-environment system. There exists one such ratio per each affordance, and they solely depend on the functionally relevant variables of corresponding actions. For instance, a human's judgment of whether he can climb a stair step is not determined by the global dimension of 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*.

In [5], Warren and Whangs showed how the perception of geometrical dimensions such as size and distance is scaled relative to the "perceived eyeheight" [3] of the perceiver, in an environment where the subjects were to judge the affordance of walking through an aperture. Marks' surface sitting and climbing experiments [6] also incorporated a similar approach. Some of these studies[7, 8] criticized former studies because they limited themselves to only one perceptual source, namely visual information. Instead of limiting themselves to visual perception, they studied haptic perception in infant traversibility 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 et. al. [9] conducted other experiments, in order to prove that changes in the layout of affordances are perceivable in dynamic environments, and found out that the results are compatible with *critical ratio* values. Another important work is Oudejans et. al.'s [10] study of *street-crossing behavior* and perception of *critical time-gap* for safe crossing. This work is novel since it shows that not only static properties of the organism, but also its dynamic state is important when deciding on its actions.

All referred experiments are performed in *one shot* manner, and either the subject is stationary or moving [5], either monocular or binocular vision [11] is employed, either haptic or visual information [7] is used, either the critical or optimal points [4] are determined, either searching for affordance or change in the layout of an affordance [12] is examined. In all cases, subjects were asked to judge whether the environment affords a particular action or not, and that the effect of all other cognitive processes that may have contributed to the decision were not properly discussed.

An overview of the related experiments shows that they are mostly employed only as test-beds to validate the existing ideas, and

The scope of the studies reviewed above are limited by the *perception* of affordances. Other cognitive processes such as learning, high level reasoning and inference mechanisms are simply untouched, and the link between affordances and these higher level processes is not established. In fact this is one of the criticisms directed at the Ecological Psychology approach; that it neglects

[3] In [5], eyeheight is defined 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

cognition[13].

E.J. Gibson studied the mechanisms of *learning of affordances* and used the ecological approach to study child development. She stated that[13] J.J. Gibson was not particularly interested in development and that "his concern was with perception" only. 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 [1].

E.J. Gibson defined learning as a perceptual process and named her theory of learning as "perceptual learning". She argued that, learning is neither construction of representations from smaller pieces, nor association of a response to a stimulus. Instead, she claimed, learning is "discovering *distinctive* features and *invariant* properties of things and events" [14], "discovering the information that specifies an affordance" [15]. Learning is not "enriching the input", but discovering the critical perceptual information in that input. She also named the method to make this discovery: *differentiation*, which she defined 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" [15]. E.J. Gibson suggested that babies use exploratory activities, such as mouthing, listening, reaching, shaking etc., to gain this perceptual data, and that these activities bring about "information about changes in the world that the action produces" [14]. 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 can be an example: One can indeed seek for sittability when all he needs is to sit, but what would he do when he need to recognize *his* chair, and how far affordances can help him in this context? Neisser, in his "Cognition and Reality" book[16] [17], tried to placed affordances and direct perception into a complete cognitive system model and tried to link it with other cognitive processes such as recognition. According to him, J.J. Gibson was right in stating that meanings of the environment were directly available, and "information is not processed, but it is directly picked up since it is already there (in the light)". The invariance attuned detectors are used for this purpose. However, he claimed, the Gibsonian view of affordances of perception was inadequate, since "it says so little about perceiver's contribution to the perception act". Instead, he suggests a perceptual system where a cycling continuous activity 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." Since every natural object has 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 [17], he constructed a three-layered perceptual system, whose first and third layers correspond to direct perception and recognition, respectively [4]. While direct perception system is identified by the perception of the local environment, recognition refers to identification of familiar objects and situations.

In a similar vein to Neisser, in [18], J. Norman "attempted to reconcile the constructivist and ecological approaches" in one bigger system, using studies from neurophysiological and neuropsychological studies. Based on evidences 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 from pickup of information from light to modulate actions, the ventral system is concerned with high level perceptual tasks, like recognition and identification. Thus, according to J. Norman, 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 system idea, he, in [18], presents examples from a patient, who lacks a ventral system. The patient is able to successfully avoid obstacles around, or insert mails into slots in correct orientation using her dorsal system. However, while performing actions successfully, she is not recognizing the objects she is interacting with, thus cannot report them.

Another set of findings of neurophysiological and neuropsychological research that were also associated with the idea of affordances are the studies on *mirror* and *canonical neurons* which

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

were found in the premotor cortex of the monkey brain. During experiments with monkeys[19] (later similar findings were also found for human subjects[20]), *mirror neurons* fired both when the monkey was grasping an object, as well as when the monkey was watching somebody else do the grasping. These findings implied that 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 [21]. Their discovery supports the view that says action and perception are related closely. These neurons, which are located in the premotor cortex of the monkey brain, are thought to be responsible from the motor activation of prehension actions like grasping and holding.

In [22], it was found out that *canonical neurons*, normally considered to be motor neurons for grasping actions, were observed to fire when the subject does not execute a grasping action, but only see a graspable object. Their activity on such a purely perceptive task that included an object that affords that 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." ([23])

In [24], Humphreys showed that, when presented with a tool, some patients, who lacked the ability to name the tool, had no problem of gesturing the appropriate movement in using it. According to Humphreys, this suggested a direct link from the visual input to the motor actions that is independent from more abstract representations of the object, e.g. 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 have been presented. The other control group was asked to make size judgments. The brain activity in both groups were compared through functional brain imaging. It was seen that a specific region of 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 the pictures of the objects rather than the name. That 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 neuropsychological activity.

The concept 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 by D. Norman's popular book, *Psychology Of Everyday Things* (POET)[25]. In his book, D. Norman discussed the perceptual information that can make the user aware of affordances. In this context, he defined affordances as:

> "... 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."

Unlike J.J. Gibson however, D. 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 that respect, his discussion of affordances, deviated from Gibsonian definition of the term[26]. In [27], D. Norman writes:

> "The designer cares more about what actions the user perceives to be possible than what is true".

After POET, the term affordance has been used in many ways in the HCI community, some in the sense that D. Norman used, 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[26].

In a later article[27], D. Norman, 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 calls "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'."

The concept of affordances is highly related to autonomous robot control and 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 be noted first. An early discussion of this relationship was made by Arkin (p. 244, [28]) and our discussion partially builds on it.

The concept of affordances and behavior-based robotics emerged in very similar ways as opposing suggestions to the dominant paradigms in their fields. J.J. Gibson constructed his theory based on the criticism of the then dominant theory of perception and cognition, which favored modeling and inference. Likewise, behavior-based robotics was motivated by the 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 (p. 244, [28]; [29]).

Opposing to 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 the modeling and internal representation[30].

J.J. Gibson, suggested that only the relevant information is picked up from the environment, saying "perception is economical". In robotics a behavior is a sensory-motor mapping, and 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 aggreement of economical perception concept of the affordance theory.

As discussed above, most of the concepts within the 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 [31] 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 tried to prove her point with three case studies and drew attention to the importance of the ecological niche in the design of behaviors. Likewise, Duchon et al. [29] benefited from J.J. Gibson's ideas on direct perception and optic flow in the design of behaviors and termed *Ecological Robotics* to be 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 that its use in deliberation remains a rather unexplored area. This is not a coincidence, but indeed a consequence of the lackings of 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. The need to hybridize robotic control architectures can be considered similar to the attempts in Cognitive Psychology to view affordances as part of a complete cognitive model. While some cognitive models relate affordances only with low level processes [18], others consider their role in cognitive processes as well [14, 17, 32]. Similarly in robotics, some hybrid architectures inherit properties related to affordances only at their reactive layer [33, 34], while other studies exploit how affordances reflect to high-level processes such as learning [35, 36, 32, 37, 38], decision-making [39], and planning [40].

Recently a number of robotic studies focused on the learning of affordances in robots. Before referring to any of them, we should note that our conception of affordance learning, very much in parallel with E. Gibson's theory, comprise discovering the invariant properties of situations that afford an action with some consequence as well as learning the consequence of an action given the current situation.

These studies can be classified into two groups. In one group, learning of an affordance is taken as the learning of invariant properties of environments that afford a certain behavior. In the other one, affordance learning is referred to as the learning of consequences of a certain action in a given situation. Although some studies challenge both aspects [32, 39, 36, 37], they seem to view only the former as affordance learning, while considering the latter separately. We will now review some of them.

Cooper and Glasspool [35] referred to the learning of action affordances, as the acquisition of environment-action pairs that result in successful execution of the action. It 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. [39] 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 [36] they gave more emphasis on learning the "regularities" of objects and relating them to the outcome of performing an action.

Similarly, MacDorman [32], 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, affordance categories are not related to the actions that exploit the corresponding affordance. Instead, categories are defined in terms of the internal indicators (tasty, poisonous) of exploiting that affordance.

Stoytchev [38, 40] 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 are 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 distinctive features of the objects and their affordances. Therefore, a generalization which would make the robot respond properly to novel objects was not possible.

In [37], Fitzgerald et al. 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, similar to Stoytchev's study, Fitzgerald et al. did not establish any association between the visual features of the objects and their affordances either, giving no room for the generalization of the affordance knowledge for novel objects.

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

3 Prior Formalizations of Affordances

After J.J, Gibson, there has been a number of studies[41, 42, 43, 44, 45, 46, 47, 48] to to clarify the meaning behind the term affordances and to create a common understanding on which discussions can be made. We have reviewed four of the proposed formalisms, and concluded that these formalisms were insufficient to provide a basis for developing an affordance-based robot control architecture.

3.1 Turvey's formalization

The first attempt to formalize affordances came from Turvey [41]. 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.

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

"solubility" of the salt is its disposition, and if it combines with its complement, which is water's property of "being able to solve", then they get actualized resulting in the salt getting "dissolved"). Therefore, dispositions are defined in pairs, and when two complement dispositions meets 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 the definition:

> "An affordance is a particular kind of disposition, one whose complement is a dispositional property of an organism."

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."

Here, when the physical structure that renders the stairs being climb-able (X_p), and the effectivity of the agent (W_q) that makes it able to climb comes together ($J(\cdot)$), a 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 acting in.

3.2 Stoffregen's formalization

A criticism of Turvey's formalism came from Stoffregen [46]. According to Stoffregen, there are two main views about affordances. The first view places affordances to the environment alone, while the second view places affordances to the organism-environment system as a whole. Stoffregen adopts the latter view and argues that affordances *can not* be defined as properties of the environment only, as Turvey did. In this line of view, Stoffregen [46] 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."

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 itself. If this is the case then the agent has to further process his perception to infer what is available *for him*. But this is 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 as:

> "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."

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

3.3 Chemero's formalization

Chemero [47] 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."

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 refines that this relation exists between the "abilities of organism" and the "features of the environment", 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 corresponds to more general capabilities of the organism. One of the main differences between the two similar formalisms of Stoffregen and Chemero, which define affordances at the organism-environment scale. 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 from the discussions in the Ecological Psychology literature, there are also other attempts of formalization of affordances. One of these came from Steedman [45] 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 helps the agent perceive the affordances, and the nature of these invariants and the relation of them with the bodily properties of the agent etc.), but instead focuses on developing a representation where object-schemas are defined in relation to the events and actions that they involve in. For instance, Steedman suggests that a door is linked with the actions of 'pushing' and 'going-through', and the pre-conditions 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, on which conditions and yielding what consequences. 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 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 at 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.

[6]The actual formalization of Steedman 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 [45].

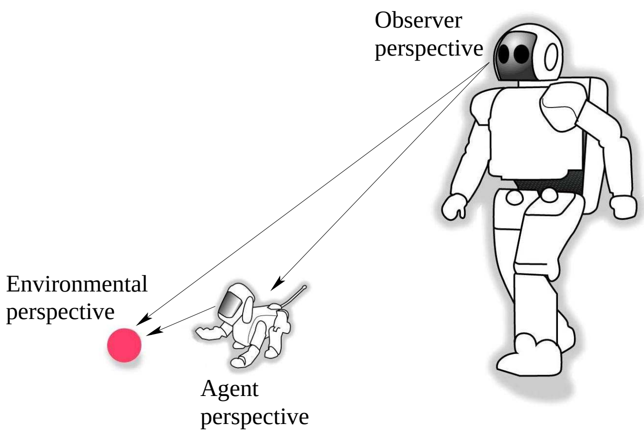

Figure 1: Three perspectives to view affordances. In this hypothetical scene (adapted from Erich Rome's slide depicting a similar scene), the (robot) dog is interacting with a ball, and this interaction is being observed by a human(oid) who is invisible to the dog.

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 first introduce three perspectives through which affordances can be discussed, to explain the source of confusion on the discussions.

4 Three perspectives of affordances

One major axis of discussions on affordances is on where to place it. 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 a 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 making 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 that 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.

4.1 Agent perspective

In this perspective, the agent interacts with 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.

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

4.2 Environmental perspective

This 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. In [1], while describing the nature of the optical information for perceiving affordances, J.J. Gibson mentions that it is also required for a child to perceive the affordances of things in the environment for others as well:

> "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, page 141)

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

5 An Extended Affordance Formalization

In this section, we develop a formalism to describe our understanding of affordances. Different from the prior formalizations studies that we reviewed, our motivation for attempting this task 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 the "environmental relata" and the "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, it represents the perceptual 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 into an object and be more complex.

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

[9] Discussions of affordances also spread onto concepts such as species, evolution and design. This definition can be re-phrased to take those 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.

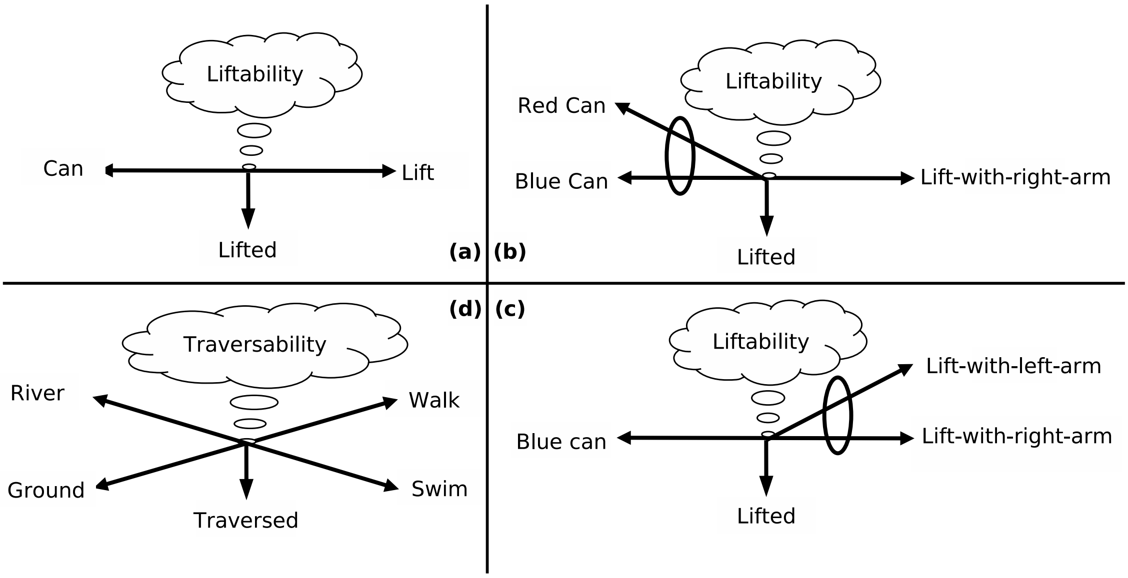

Figure 2: **(a)** An affordance is a relation between an *entity* in the environment and a *behavior* of an agent, saying that there exists a potential for generating a certain *effect* through the application of that *behavior* on that *entity*. In this example, the application of *lift* behavior on a *can* generated the effect of being *lifted*, and that this relation is called as *lift-ability*. *Lift-ability* is shown as a "cloud" to indicate that it is just label for the relation 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* (begin *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*).

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 to use 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*, e.g. 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 on a *stone*, it produces the effect *lifted*, meaning that the *stone*'s position, as perceived by the agent, is elevated (Figure 2(a)).

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

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

and our formalization as

$$(\mathit{effect}, (\mathit{entity}, \mathit{behavior})).$$

This formalization explicitly states that an affordance is 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 on the *entity* by the agent. In this formalism, we assume that this relation resides in the interacting agent. This means, all three components are assumed to be sensed through proprioception of 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 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 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 Turvey and Stoffregen's formalizations, the desired effect is represented as h and r respectively. The proposed formalization is different from these, by not only making it explicit, also putting is 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 forth in [49, 50] 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 on two aspects. First, instead of using *outcome*, which was assumed to be derived from "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 report, such a grouping has important benefits.

One question that may be posed is whether this formalism equated *affordance* to *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

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

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 black can before it attempts to apply its *lift* behavior. The naming of such a representation with a label, such as *black-can*, from the eyes of an external observer is merely to make our discussions easier to read.

We call (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 not a *relation*. As the robot explores its environment, it will populate its knowledge database using such relation instances:

$$
\begin{array}{rll}
(\textit{lifted}, & (\textit{black-can}, & \textit{lift-with-right-hand})) \\
(\textit{lifted}, & (\textit{blue-can}, & \textit{lift-with-right-hand})) \\
(\textit{not-lifted}, & (\textit{blue-box}, & \textit{lift-with-left-hand})) \\
(\textit{lifted}, & (\textit{black-can}, & \textit{lift-with-right-hand}))
\end{array}
$$

However, such a database can hardly be called as 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 towards 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 2(b)). These relation instances can then be joined together as:

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

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" can be *lifted* upon the application of *lift-with-right-hand* behavior. Such invariants, create a general relationship, enable the robot to predict the *effect* of the *lift-with-right-hand* behavior applied on a novel object, like 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 concept *invariance*, defined as "persistence under change" in broad terms by J.J. Gibson. He mentioned the concept in many contexts through his book and devoted one section in Appendices for it. These invariants correspond to the properties which remain constant under various transformations, i.e. invariants of optical structure under changing illumination or under change of the point of observation. Although J.J. Gibson did not explicitly provide what these invariances are, he gave some clues on 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] [51] which suggests that certain sensor states are equivalent if they call for the same motor response and there are typically some key features that discriminate the relevant situations for a 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 represent only the perceptual representation of the external world, the component <*entity*> can be referred as an *affordance cue* [52], which hints the existence of a potential affordance. We would also like to note that when the term *entity* includes also the perceptual state of the agent itself, the term <*entity*>

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

can be considered to be equivalent to the term *pre-condition* 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 that 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:

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

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

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

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

We would like to note that, similar to the *entity equivalence*, the use of *behavioral equivalence* will bring in a similar flexibility for the agent. Through discovery of 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 his other hand.

5.3 Affordance Equivalence

Taking the discussion one step further, we come to the concept of *affordance equivalence.* For affordances like traversibility, it is possible to obtain it by "walking across a road" or "swimming across a river" (Figure 2(d)) as

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

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:

$$(\textit{effect}, \{(<\textit{entity}>, <\textit{behavior}>)\}).$$

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

$$(\textit{effect}, <(\textit{entity, behavior})>).$$

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 the ideas of effect and behavioral equivalence and that such equivalence classes would emerge as well. An interesting support to this formalization can be drawn from the studies of mirror neurons, which are observed to be activated during pure perception as well as during action.

[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 similar to the discovery of invariants in entity equivalence classes.

5.4 Effect Equivalence

The concepts of entity, behavior and affordance equivalence classes implicitly relied on the assumption that the agent, somehow, has an *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-an-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 on autonomous robots. On the other side, the inclusion of effect equivalence points out that, the invariant detection operation would apply on all the 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 represented 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 a* (entity, behavior) *within* <(entity, behavior)>*, an* effect *within* <effect> *is generated.*

Different from the previous version of the definition, this one explicitly states that affordance is a *relation* between *equivalence classes*, rather than a *relation instance* between an *effect* and a *(entity, behavior).*

5.6 Observer's Affordances, and Agent Equivalence

We can now extend the affordance formalization to accommodate affordances from *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 concept. That is, after observing what affordances would different mouses 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 "small creatures" class, which would allow the human to predict the behavior of a rat. One would even speculate that 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 find it early to elaborate on it.

We also would like to note that this representation will be different for the human observing a mouse than 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 other's 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 a* (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 that it is not relevant for affordance-based robot control. Yet, this perspective can also be formalized as well. For this, we will assume that the entity being interacted 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 Conclusion and discussion

We proposed a new formalism for affordances that, we believe, laid out a good framework over which affordance-based robot control architectures can be developed. Certain aspects of this formalism are worth to be discussed in detail:

- Different from previous formalizations, the proposed formalization provided affordance definitions from three, not one, different perspectives; namely, agent, observer and environmental. We hope that, these different, but related definitions will be of help in clarifying the discussions around the concept.

  Of the three definitions provided, we would like to note that only the two, the ones from the agent and observer perspectives, are relevant for autonomous robot control. The third perspective is provided as a means to tie the proposed formalism to some philosophical discussions on the concept.

- The proposed formalization defines an affordance as a relation between two equivalence classes, namely <*effect*> and <*(entity, behavior)*>, and provides a means for prediction in novel situations. In this sense, affordances encode general relations in the world, such as: balls are rollable (through the use of the roll behavior). However, such relations provide a rough representation of the interactions between the environment and the agent, and that there will always be exceptions. For instance, the knowledge that the-red-ball-on-my-table is not rollable (since it is glued over the table), is a specific knowledge that lacks any generalization. For instance, it contains no predictive help over whether all balls-on-my-table are liftable. We claim that such relation instancess, that is relation between two instances of *effect*, and *(entity, behavior)*, should not be called as affordances. We argue that such relation instances should be handled by a complementary add-on system and that the object recognition system proposed by Neisser in his cognitive model[16] would be in agreement with these views.

- Affordances are acquired relations. We believe that the acquisition aspect is an essential property of affordances. We claim that relations that are acquired through the interaction of the agent with its environment would automatically be in the so-called *body-scaled* metrics, in agreement with the affordance studies in Ecological Psychology as reviewed in Section 2.2.

- The proposed formalism argues that invariance operators should be applied on the concatenated representation of *entity* with *behavior*. Such a representation enables the formation affordance equivalence as well as entity and behavior equivalence classes. Although this choice was made purely to make the formalism accommodate the three types of equivalences, its potential link to the studies on mirror and canonical neurons is interesting. However, we agree that, the actual consequences of such a concatenated representation remains an interesting topic to be analyzed on autonomous robot studies.

- Finally, although we treated an affordance as a discrete rule, and the components of the relation as discrete symbols, the reader should keep in mind that they were merely for presentation purposes. These discretizations occur only through the affordance relationship between non-symbolic representations of <*effect*> and <*(entity, behavior)*>.

The proposed formalism, in certain ways extend the Gibsonian view. Extending an already controversial term such as affordance is open to criticism. One of the previous commentators of our project, had warned us of the dangers of being drawn into an already existing hot debate over the term, and suggested that whether a related-sounding but different term, such as "affoodance", would relieve us from such debates. 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 it to already existing terms, does more harm than good. Instead, in this report, we tried to properly propose our formalization and definition of the our understanding of the concept and leave the final judgement 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 towards this goal, the ideas proposed in this report will be of help to guide us on this quest.

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