Geometry-based Affordances

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Abstract

A representational approach to ecological psychology is presented. This paper identifies a computational-level commonality in ecological psychology research related to passability of apertures. It is argued that a cognitive mechanism capable of comparing the geometric properties of an environment and the geometric properties of the agent can be used to support judgments for action in space.

Keywords: affordances; ecological psychology; spatial representation.

Introduction

Two of the most central proposals in ecological psychology are the concept of *affordances* and the theory of *direct perception.* Gibson describes an *affordance* as properties that objects offer to animals that have the capacity to perceive it (Gibson, 1986). This position, shared with Michaels and Carello (Michaels & Carello, 1981), maintains that the semantics of an action, by which I mean how an agent knows what actions can be performed given the objects in its environment, are properties of that object. Because the action semantics are encoded in the environment, they are claimed to be directly perceived.

Chemero & Turvey (2007) divide ecological psychologists into two camps: Gibsonian and representationalist. Gibsonians maintain that affordances are directly perceived, while representationalists (e.g. Vera & Simon, 1993) maintain that affordances (the actions an object affords) are inferred. This paper presents a representationalist position that is inspired by affordance research. However, the representations proposed in both theory and model are non-static and do not include semantically-laden representations of the environment. An example of a semantically-laden representation, with respect to action, is to label a feature of the environment as a 'doorway', such that doorways are features of the environment that can be passed-through.

The representationalist approach presented here is not necessarily inconsistent with a Gibsonian approach. The aim of the theory presented is to leverage the appropriate framework to make use of the computational cognitive architecture, ACT-R (Anderson & Lebiere, 1998), in order to identify a plausible set of information processing steps involved in an aperture-passage affordance.

Gibsonian Positions

There are two main theoretical positions in favor of direct perception. The first, Gibson's own theory, has already been described above. Although I will provide no argument against this position here, I agree with Chemero (2003), that Gibson's position represents a non-standard ontology, in which the environment is not simply made up of physical properties but also semantic properties. I will assume that this alternative ontology is sufficient to reject Gibson's position for the purposes of this paper. For an argument against Gibson's position and related affordance-as-property positions, I refer the reader to Chemero (2003).

The second Gibsonian position is that action semantics are emergent properties which arise from the interaction between an animal and its environment (Chemero, 2003; Chemero & Turvey, 2007; Stoffregen, 2003). While Chemero (2003) differs slightly in the terms he uses (*relations* instead of *properties*, to avoid certain philosophical problems), neither author's version addresses *how* the emergent properties or semantic-laden relations arise.

The theory presented here, the theory of geometric affordances, is inspired by research on aperture passage but also attempts to be commensurate with traditional representationalist views popular in the cognitive sciences. Briefly, this paper proposes that one of the mechanisms which can inform action properties (such as *passability*) is a geometric comparison between the features of the environment and current or possible future geometric properties of the body.

The aim of this paper is to illustrate, by way of example, how a represenationalist approach, which posits cognitive mechanisms, leaves open the possibility to develop unifying theories about different experimental findings within the affordance literature. The research reviewed in the following section is ecological psychology research regarding the affordance of *passability* of an aperture. The purpose of this brief review is to illustrate how a representationalist approach can posit a cognitive mechanism that compares the geometric properties of an environment with the geometric properties of the agent. I term these affordances, geometry-based affordances. I maintain that geometry-based affordances are only one class of possibly many types of affordances.

Aperture Passability Research

Research into the passability of apertures, such as door-ways, has shown that there is a body-size/aperture-width ratio at which apertures are judged to be passable (Fath & Fajen, 2011; Higuchi, Seya, & Imanaka, 2012; Wagman & Taylor, 2005; Warren & Whang, 1987). With different degrees of commitment, the central aim of that research is to show that a *passability* affordance can be directly perceived.

In Warren and Whang (1987), for example, they show that people judge apertures as passable only when the ratio between the aperture width and body width is greater than 1. Warren and Whang argue that we perceive the width of apertures in units of body width. The theory they propose is that we see the width of the doorway in units of eye-height. Since eye-height is in a constant proportion to shoulder width, we are effectively perceiving in units of shoulder-width. Instead of seeing a doorway, estimating its width, estimating body width, and making a determination regarding passability; we simply perceive apertures as either passable or impassible.

In a related study by Fath and Fajen (2011), participants view simulated environments while wearing a headset. In a set of experiments, Fath and Fajen modified the visual properties available to the participants. For example, they eliminate the ground plane, making the estimate of eye-height implausible. They argue that the visual properties related to body-width-scaled units are not the only properties that can be used to make passability judgments. They propose that visual information related to head-sway and stride length (both while walking towards the aperture) can be calibrated to body-width and used in lieu of eye-height, to directly perceive passability.

Other studies such as those by Higuchi, Seya, and Imanaka (2012) and Wagman and Taylor (2005) have participants holding objects. Chang, Wade, and Stoffergen (2009), furthermore, studied passability for people grouped in dyads. Higuchi, Takada, and Matsuur (2004), finally, studied passability for novel wheelchair users.

When taken together, it is not clear whether a direct perception account can extend to situations such as dyads. Judging aperture passage for yourself plus another individual seems to require the building of a representation of the total width of yourself and your compatriot. Especially considering the methodology in Chang et al. (2009), where participants are paired with different people during the course of the experiment. Because the optical information from the environment does not change, then another source of information seems modulate judgment. Regardless of the source, it seems as though two pieces of information are used to make a passability judgment: optical information and some-as-yet-to-be-determined source. It is unclear how the ecological psychologist can maintain that the judgment is direct.

A second, perhaps more important, aspect to consider is the methodology used in, for example, Warren and Whang (1987) and Higuchi et al. (2012). The experiments in these studies include a methodology where participants walk through the apertures of various sizes, rotating their shoulders as needed. In Warren and Whang there is also a condition where participants judge whether they can pass through apertures, without rotating their shoulders. In all of these cases what the participant seems to be doing is making a judgment about passibility with respect to a future configuration of their body. Judgment in these cases does not seem to be based upon their current body width but, rather, the width of their body after they have rotated their shoulders. If that is the case, then it is not clear that passability can be directly perceived in these cases. Instead, it seems as if the passability judgment is based upon a representation of the future state of the body. Such a representation can be plausibly drawn from memory or the result of a simulation.

A Representation-Based Theory

The theory being presented is an information processing theory about the steps involved in passability judgments of the kind exhibited in previous aperture passage research. At a functional level the theory of geometric affordances posits a geometric comparison process that compares the geometric properties (width, depth, height) of an aperture against a current or stored body posture. The geometric comparison is used both when judging whether an aperture is passable as well as a top-down metric to control shoulder rotation during passage.

The information relevant to body postures is derived from body schemas. Although previous affordances research have rejected the notion of body schemas (e.g. Carello, Grosofsky, Reichel, Solomon, & Turvey, 1989) there reasonable evidence for their existence and their role in motor planning and performance.

Evidence for Body-Schemas

Schwoebel and Coslett (2005) identify three types of body representations: *body schemas* that represent the positions of the body parts and is used to plan motor movements, the *body structure* that is a topological map of body part locations, and a *body image* which is a lexical-semantic representation of the body detailing body part names, their function, and their relationship to related artifacts. Since body schemas are central to the information processing theory being proposed, a brief summary of evidence for the existence of body schemas will be presented in this subsection.

Neural evidence provides support for the functional role of body schemas as real-time representations of the body. Firing-rates in parietal area 5 of primates supports the idea of encoding arm postures both when the arm is occluded and when a realistic, fake arm is visible, suggesting both somatosensory and visual input is used to create body schemas (Graziano, Cooke, & Taylor, 2000).

There is strong evidence for the use of body schemas in motor simulation. For example, the hand laterality paradigm has been used to study the link between imagined movement and actual movement (e.g. Parsons, 1987). There are two aspects of the laterality paradigm. The first involves making judgements of laterality (left vs. right) and the second involves simulating arm orientations. The reaction time for both tasks was relative to orientation differences between the participant's arm and the target arm. Simulated movements were strongly correlated with actual movements.

There is also evidence of a physiological overlap between imagined and actual movements (Decety, 1996; Lotze et al., 1999). The fMRI work by Lotze et al. (1999) also supports the view that the main difference between imagined and actual motor movements is inhibitory signals from cortical motor areas to cerebral regions, inhibiting actual movements. Sirigu et al. (1996) also show that only patients with parietal damage do not show a correlation between the times for actual and imagined finger movements.

Finally, Schwoebel, Coslett and Buxbaum (Coslett, Buxbaum, & Schwoebel, 2008; Schwoebel, Coslett, & Buxbaum, 2001) provide evidence for Forward Modeling. Forward Models have been theorized to be used to develop representations of body schemas based partially from efferent copies of planned motor movements. What is particularly interesting in their work is the dissociation exhibited by a patient (JD) between body schemas due to purposeful movement and body schemas for passive movement. JD had accurate reach and pointing ability when moving her hand to a target in both occluded-hand and non-occluded hand conditions, suggesting that she had an accurate representation of the position of her arm and hand. However, JD's pointing and reaching ability were impaired when her arm was moved by an experimenter (passive movement), suggesting that, in those cases, she did not build an accurate representation of her arm posture. As pointed out by Schwoebel and Cosslett (2005), this dissociation suggests that JD had an intact ability to generate posture representations from an internal model based on predicated movements (Forward Model).

The above findings in combination imply that humans have representations of the biomechanical constraints of our bodies. If reaction times for imagined movements mimics reaction times for actual movement, then this suggests that the simulated movement has similar kinematic and biomechanical properties as real movements. The fact that there is a strong neurological overlap between simulation areas and areas responsible for actual movements suggests that motor movements are encoded in the same format for simulation as they are for actual movements. It can be inferred that some form of biomechanical representation has to exist to support biomechanically-accurate simulations. This offers compelling evidence that the biomechanical constraints of the body are also likely represented (in order to support simulation). It stands to reason that simulation can produce predictions of body posture in simulated motor planning in much the same was as forward modeling does for active motor behavior.

The theory being forwarded here assumes that we store body schemas of biomechanical constraints. This would be useful for motor planning because it would reduce the complexity of choosing a goal posture. For example, shoulder rotation would require only three representations: a body schema for relaxed, non-rotated posture; and a body schema for full rotation to the left; and full rotation to the right. Although the body is capable of rotating any angle between constraints, it would be costly to store them all. Instead, biomechanical constraints can provide sufficient conditions for an action (fully rotated shoulders might be sufficient for passing through an aperture), which is suitable for planning. Online motor control during action could then be used to control and produce only the necessary motor movements to carry out the action for a particular circumstance.

Information Processing Theory

It is useful to divide the processes proposed in this theory into two phases: the judgment phase and the performance phase. In the judgment phase, we first determine if we can pass through an aperture at all. The performance phase occurs once we have judged an aperture as passable and begin to walk through it. The performance phase can be subdivided further into three sub-phases: rotation initiation, rotation, and rotation termination. The following section will outline how body schemas are used in the passability judgment.

Judgment Phase

Although it is discussed very little in the previous aperture-passage literature, before we ever attempt to pass through an aperture, we must first make a judgment of whether passage is at all plausible. Anecdotally, this must be the case because we simple do not often find ourselves trying to squeeze through apertures smaller than our bodies. This process has to be more complex than the direct perception theory proposes because passage cannot be judged purely on current posture. That is, optical information tuned to a non-rotated posture can only inform passibility judgments where no postural change is required. However, in order to judge passability in the condition where some degree of shoulder rotation is required, the optical information would somehow have to be tuned to a future state of the shoulders. It is unclear how a direct perception approach could account for this.

Geometric affordance theory proposes that a positive passability judgment results from two possible cases. In the first case, body geometry is estimated from a body schema of the current body posture. This information can then be used top-down in a visual search to find apertures of an appropriate size. If the vision system is able to return a feature in the environment that meets those constraints, the returned apertures are considered passable. In this case, the agent can simply walk through the aperture. If no environmental feature is returned by the vision system, the second case proceeds. Note that the representations used in this phase are non-static: they are current (based on current body posture) and can include other sources of information including visual or proprioceptive (such as estimates of body size while carrying objects, or in a dyad).

In the second case, a potential series of memory requests are made for stored body schemas that closely match the current body posture (e.g. standing) and current action capabilities (e.g. supportive of walking action) but are relaxed on an increasing number of postural details (e.g. no need to match with respect to the upper-half of the body). In the case of a simple doorway-like aperture, a reasonable memory request would be for a posture that affords walking (e.g. a standing posture) but allows for variation in torso posture (such as shoulder rotation). As discussed in the previous subsection, storing only the biomechanical constraints vastly reduces the search space for a suitable posture. If a suitable schema is returned, the geometric properties of that schema are used to filter visual results in the same manner described above for the for the first case. In the second case, the retrieved body schema functions as a goal state for the motor system during the rotation phase. That is, the motor system will try to achieve the posture at the biomechanical constraint (e.g. shoulders fully rotated) regardless if that posture is necessary for the desired action.

Rotation Phase

Another aspect of aperture passage with no known discussion in the affordances literate is the need for some trigger that starts the rotation. One possibility is that the agent plans to rotate at some specific point and initiates rotation upon arrival. A second possibility, and the one explored here, is that there is a bottom-up environment trigger that is responsible for initiating the rotation. The theory proposed here is that the visual system performs bottom-up obstacle avoidance and that the presence of the edges of the aperture triggers the rotation. When the edges of the aperture are within a multiple of the agent's rotation radius, the vision system pushes information into the visual buffer, and the agent can respond by carrying out the motor plan.

Recall that during the judgment phase a stored body schema memory may be recalled and used as a goal state for the motor system to achieve the affordance. In Warren and Whang's (1987) first experiment there is a multi-second delay between what I am describing as the judgment phase and the rotation phase (while the participants walks to the aperture). It is proposed that once a body schema is retrieved it is maintained in working memory. When the presence of the obstacle (aperture edges) is pushed in to the visual buffer, combined with the presence of a body schema in memory, the agent can then carry out the motor rotation plan. Note that for shoulder rotation, the goal state will be a biomechanical constraint, e.g. fully-rotated shoulders. However, we know from Warren and Whang (and intuitively) that we do not rotate our shoulders to maximum rotation every time we rotate. Instead the theory assumes that rotation completion is controlled by a vision-action loop in the dorsal visual stream (Milner & Goodale, 2008).

Rotation Completion Monitoring

In their *Two Visual Streams Hypothesis*, Milner and Goodale propose a functional distinction between the dorsal visual stream and the ventral visual stream (Goodale & Milner, 1992; Milner & Goodale, 2008). They propose that the ventral stream composes what they call *vision-for-perception* and that the dorsal stream composes what they call *vision-for-action*. While the ventral stream is used for planning action and carrying out unpracticed action, the dorsal stream is used for moment-to-moment visual updating of actions that are comparatively more automatized.

The theory proposes that a moment-to-moment visual updating can occur through rapid repetition of the original top-down visual filter process described above (i.e. the current body schema is used in a top-down visual search to determine if there are any environmental features that meet those constraints). This moment-to-moment visual updating continues until (in this case) the shoulders have rotated enough to produce a match between the body-width of the agent and the width of the aperture. Although a biomechanical constraint was originally retrieved in the judgment phase, the agent need not always rotate the shoulders maximally. This process ends once the shoulders have rotated sufficiently to pass through the aperture. In other words, the goal state of the motor system was to fully rotate the shoulders, but a moment-to-moment visual update limits the total rotation by comparing the geometric properties of the current body schema (rotated shoulder in this example) to the geometric properties of the aperture. If an aperture is found as a result of the visual search, that means an aperture with sufficient geometric constraints has been found (for whatever posture the body is currently in). In this way, there can be a limited number of stored biomechanical constraints but a large variance in intermediate postural change (a large variance in shoulder rotation). Note these processing steps are the exact same steps used in the judgment phase.

Computational Model Support

A computational model of the shoulder rotation experiments in Warren and Whang (1987) and in Higuchi et al. (2012) was developed as an initial test of the overall theory. The model was modeled in an extension to Python ACT-R called ACT-R 3D (Somers, 2016). At a high-level, the model follows the information processing description described above. Importantly, with respect to affordance research, the model is not semantically informed about the aperture in its environment.

It would not be atypical for an ACT-R model to be semantically informed. It is fairly customary for a model to use what is termed a 'visual icon' with a chunk identifying to the programmer what visual information the agent is 'seeing.' Although semantic information is not contained in the visual icon, it would not be atypical for a production to be pre-programmed to respond to the contents of the chunk in the visual icon.

The visual system in ACT-R 3D is slightly less informed. There is, in the agent's 3D environment, nothing labeled as an aperture. In fact, an aperture is negative space between environment features (such as walls) and cannot in fact be labelled in ACT-R 3D. Although the walls in the 3D environment are labelled, the agent has no access to those labels.

Instead, the agent has a goal to walk forward and in order to carry out this goal, it looks for obstacles. Upon finding an obstacle (the wall), the agent then uses a top-down visual search for features that might be passable in the manner described in previous sections. Put simply, the agent does a visual search for empty space in front of it that meets the geometric constraints of the agent's body (or an achievable body posture). In this way the agent does not in fact represent the aperture as an aperture. Importantly, this also means that agents of different sizes will make different passability judgments.

The task the model must perform is to walk through an aperture, rotating the shoulders as needed, or avoid walking to apertures that it thinks it cannot pass through. As described above, if the agent does perform shoulder rotation, a moment-to-moment visual update occurs to determine if the agent should stop rotating. A single model is used for both small and large agents in slow and fast walking conditions, walking through apertures of various sizes, modeling experiments in Warren and Whang (1987); as well agents holding bars of various lengths and walking through apertures of various sizes in Higuchi et al. (2012).

The measure of fit to Warren and Whang was with respect to total rotation which is influenced partially by the number of agents who decide to pass through an aperture of a given size, rotation speed, and walking speed. There were four conditions to fit: 2 (size: small vs. large) x 2 (speed: slow vs. fast); with Pearson correlations ranging from 0.91 and 0.98. The same model was then given bars of different sizes and performed the experimental conditions given in Higuchi et al. (2012). Although the fit was not as good in this case, as it showed a strong over-rotation in one condition; the fit was still reasonable, especially with the exclusion of the results for the over-rotated condition. The measure was rotation angle as well as the safety margin made between the end of the bar and the edge of the aperture, producing a Pearson's correlation of 0.84 for absolute rotation and 0.89 with respect to safety margin.

The success of the model is encouraging, given that the accuracy of the results are dependent on the timing involved, which is a product of the information processing steps (in the form of productions) that the agent carries out.

Discussion

There was a number of difficulties pointed out in the first section that affordances based upon direct perception has to contend with. This section will address those difficulties but will also describe an interesting fallout from using an affordance-based approach.

Addressing Difficulties with Direct Perception

The first difficulty pointed out in the first section that *direct perception* has to contend with is a person-plus-other system. In cases like these, there is no invariant property of the body that can act as units to directly perceive: there are measures beyond the body that affect the judgment. The theory presented in this paper also has to be extended to account for situations like these. When an agent is part of a person-plus-other system, the theory proposes that the agent could combine representations, including body schemas, to make a estimation of the total geometric properties. Currently neither the theory nor the model define processes for including accompanying objects (in the bar experiments, the agent has special access to the dimensions of the bar). However, the advantage with the model is that there is a clear question that can be incorporated into a unified theory in the future.

In the same manner the model (and theory) also assumes that the geometric properties of the environment can be suitably perceived. The details of this process are not yet modeled, however, we can assume that aspects such as eye-height, head-sway, and stride-length, can all be combined to creates a representation of the aperture width. In that respect, the model would be very much in line with findings from the aperture-passage literature.

The model can also help answer questions about representational content. The model presented here is part of a series of models that address whether A/S ratio or spatial margin (between edges of the agent and edges of the aperture) might be used as a metric for aperture passage. The model presented here implement an analog of spatial margin to judge the fit between aperture width and body width, supporting Higuchi et al. (2012).

The model also helps explain over rotation evident in Warren and Whang (1987) and Higuchi et al. (2012). Because the processes during the rotation completion monitoring affect timing, they also introduce a degree of variance in the rotation. The model does not rotate perfectly each time and exhibits similar over rotation to human performance.

Extensions

The proposed processing description given above could easily be extended to include other affordances as well. For example, Stefanucci and Geuss (2010) researched aperture passage that required a ducking action. There is no principled reason why the same model could not be used to model those experiments as well. Since the problem is largely geometric, followed by a postural change, there is no principled reason why that postural change could not be for a ducking action. The same process could also be used for any situation that requires a postural change in order to accommodate the size of the body.

Secondly, not all affordances are purely geometric but could involve a geometric comparison process. Grasping, for example, has a number of elements, one of which could involve a judgment of whether the target object would fit in a grasp.

Conclusion

The term 'affordance', though convenient, does not come without certain theoretical baggage. The aim of this paper is not to dismiss or discredit ecological psychology or the notion of direct perception but, rather, to compliment it with an information processing description. The term, 'representation', need not carry the kind of baggage that it may have historically. The representations used in the model are, for the most part, not static and semantically-laden. For example, each agent learns their own body schemas before experiments by performing ‘exercises’, storing and updating new representations for biomechanical constraints. Furthermore, the environment is not labelled in any way. Agents in the simulation have to determine what apertures are passible individually.

Adapting affordance research to a representationalist framework opens some doors for research. This work is mainly philosophical, arguing for the need to unify research in a way that is falsifiable. The theory here presented relies on a cognitive mechanism capable of comparing the geometric properties of an environment with the geometric properties of an agent or agent-plus-object systems. This high-level presentation of the theory does, admittedly, offer very little detail about the working of the mechanism but does so in the hope of inciting research into the area.

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