Quantifying affordances through information theory

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Abstract

Affordances are directly perceived environmental possibilities for action. Born within ecological psychology, they have been proposed to be one of the main building blocks to explain cognition from and embodied and situated perspective. Despite the interest, a formal definition of affordances in information theory terms that would allow to exploit their full potential in models of cognitive systems is still missing. We explore the challenge of quantifying affordances by using information-theoretical measures. Specifically, we propose that empowerment (i.e., information quantifying how much influence and control an agent has over the environment it can perceive) can be used to formally capture information about the possibilities for action (the range of possible behaviors of the agent in a given environment), which in some cases can constitute affordances. We test this idea in a minimal model reproducing some aspects of a classical example of body-scaled affordances: an agent passing through an aperture. We use empowerment measures to characterize the affordance of passing through the aperture. We find out that empowerment measures yield a similar transition to the one found in experimental data in humans in the specialized literature on ecological psychology. The exercise points to some limitations for formalizing affordances and allows us to pose questions regarding how affordances can be differentiated from more generic possibilities for action.

Introduction

Ecological psychology and affordances

According to ecological psychology, affordances are possibilities for action that we directly perceive in our environments. These possibilities for action emerge from the relations between the capacities of agents and elements of the environment. The term 'affordance' was coined by J. J. Gibson and refers to the complementarity of organism and environment (Gibson, 2014, 119).

Ecological psychology is an embodied, situated, and non-representational approach to cognition that presents itself as an alternative to behaviorism and cognitivism. The way ecological psychology traditionally analyzes perception is not by focusing on how nervous systems work, but on how organisms explore the environment so as to find opportunities for acting (the above-mentioned affordances). In this view, affordances are key objects of perception from an embodied and situated approach to cognitive science, since they are relations between the bodily capacities of agents and certain environmental elements (Chemero, 2009; Heras-Escribano, 2019). These relations can sometimes be mathematically quantified or measured in agent-related units (Warren, 1984; Warren and Whang, 1987), which means that it is possible to offer a scientific account of these relations that can be useful for other embodied and situated approaches (the enactive approach, dynamical systems theory, etc.).

While affordances are defined as 'possibilities for action', not all possibilities for action are affordances. For example, since affordances need to be perceived, activities like abstract thinking or calculating are not considered as such. On the other side, not all perception is of affordances: colours or sensations are not affordances either. Thus, affordances are opportunities for action in the sense that certain aspects of the environment that we perceive are in relation to our movement or to our bodily features, like a bottle to grab, a doorknob to turn, or a door to pass through. In the following sections, we will call 'possibilities for action' or 'range of possible actions' to those movements that the agent can perform (exploration, deambulation, etc.). Note that this range of movements may include those that the agent performs when taking advantage of a directly perceived affordance.

Affordances are usually classified either as action-scaled or body-scaled affordances (Fajen et al., 2009). Action-scaled affordances are those opportunities for acting that depend on the behavior of the agent. For example, how fast an organism moves in a particular location determines the possibilities for acting for that organism (e.g., whether the organism is capable of avoiding moving obstacles). On the other hand, body-scaled affordances relate a particular dimension of the body of an organism to a particular environmental element. Although there are many examples of body-scaled affordances in the literature, here we are going to focus on the contributions of W. Warren and colleagues (Warren, 1984; Warren and Whang, 1987) for describing experimentally the affordance of climbability and that of passing or walking through apertures.

A particular aspect of Warren's contributions is that they explain how we perceive these affordances from an ecological perspective. Based on the active capacities of the organism as a whole, using an agent-related metric, they highlight the relational or complementary aspect of the organism-environment engagement.

Warren (1984) provided one of the first experimental accounts of the body-scaled affordance of *climbability*, one that allows organisms with legs to step on obstacles. He arrived to the conclusion that a step is climbable for a human if its height is less than 0.88 times the height of that human's leg regardless their body size (Heras-Escribano, 2019, 53). This way of describing that a step is climbable for a human emphasizes the agent-environment interaction inasmuch as it does not rely on absolute metric (meters, inches) for explaining in mathematical terms the affordance of climbability, but on agent-related metric; that is, the specific leg size of each agent.

Warren and Whang (1987) used the same agent-related metric for explaining how humans perceive the affordance of walking or passing through apertures. They determined that an agent can perceive the possibility of walking through an aperture if the aperture is at least 1.3 times the human's width for shoulder rotation regardless their body size (Warren and Whang, 1987, p. 381). Again, the authors offer an agent-related metric for quantifying the possibility for acting of a particular agent.

Exploring affordances with information theory

Although there is experimental evidence in favor of the quantification of affordances, there is still an open debate regarding their ontological status.[1] This has certain impact in the scientific practice, since there is no unique or single formal definition of affordances that is widely shared by the scientific community. In particular, a quantitative formal definition of affordances suitable to be applied to modelling simulations is lacking.

Here, we explore the challenge of interpreting affordances formally by characterizing the possibilities for action that constitute affordances using measures from information theory. Ecological information is crucial for the notion of affordance, as it allows embodied agents to perceive affordances. Take, for example, the case of vision: from an ecological perspective, light becomes ecological information when it forms a heterogeneous structure or pattern caused by the reflections and reverberations in the environment. Regarding the source of light and the position of the agent, there are differences of intensity in that pattern that, in turn, produce differences in what the organisms perceive (Gibson, 2014, 45-46). This structure of ecological information shows the agent the available affordances of the environment as the agent explores it (Heras-Escribano, 2019, 30-45). Given the complexity of the light patterns and the variety of elements and variables that we can find in our natural environment, it is almost impossible to reproduce in the exact same terms all these aspects of ecological information and affordances in modelling simulations. However, we can reproduce some minimal aspects of it in information-theoretic terms (as when objects get bigger as they get closer to the visual field of the modelled agent, for example).

We aim to explore what an information-theoretic interpretation of affordances would imply, and what possibilities and limitations are entailed by such an interpretation. This exploration will use minimal models reproducing some aspects of well-known experimental setups, which means that what we offer here is a simplification of real life situations that also lacks of several aspects taken into account within the ecological approach. Nevertheless, we think such models are still able to offer both some of the relevant aspects about the proposed problem and important insights about the idea of interpreting affordances in information-theoretic terms.

Gibson claimed that Shannon's information theory (Shannon, 1948) was inadequate to capture ecological information (Gibson, 2014, 231-232). Nevertheless, we understand that what he rejected was a particular version of information theory that included the channel metaphor, because he interpreted that it implied a tacit commitment to representationalism and cognitivism. In addition, since Shannon's information measures are based on correlational regularities between variables (they cannot directly capture causal relations), they seem to be limited for measuring ecological information about causal effects of an agent's actions. However, there are modern formulations of information theoretic measures that are more adequate to describe possibilities for action in an agent. In this vein, we suggest that an interventionist notion of causality in the sense of Pearl (2009) and the notion of causal information flows (Ay and Polani, 2008) are better suited for characterizing ecological information.

Specifically, we propose that there is an information-theoretic measure that is able to capture possibilities for action that constitute affordances: the measure of empowerment. Empowerment (Klyubin et al., 2005; Salge et al.,

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[1] There is a long debate regarding the ontological status of affordances. For example, Reed (1996) considered that they were aspects of the environment that exert selective pressure, while Chemero (2009) claims that affordances are relations between the abilities of agents and some environmental aspects. Here we offer a neutral approach to the ontology of affordances, although we could claim that affordances here could be understood as being part of a dispositional pair that include the agent's abilities and certain environmental aspects. This dispositional approach makes it partially compatible with Chemero's (2009) approach because an ingredient of a dispositional approach is a relation as such, but a disposition is more than a relation: it includes a dimension of actualization that alters the organism-environment system, which with time it may lead to unexpected changes that may affect the history of the system (Heras-Escribano, 2019; Heras-Escribano and De Pinedo-Garca, 2018). For further discussions on the ontology of affordances, see (Heras-Escribano, 2019, Chapter 3)).

2014) is defined as the channel capacity between an agent's actuators A for a window of time of size n starting at time t, and its own sensors S at time $t+n$

$$\mathfrak{E} = C(A_{[t:t+n-1]} \to S_{t+n}) \tag{1}$$

$$\equiv \max_{p(a_{[t:t+n]})} I(A_{[t:t+n-1]}; S_{t+n}) \tag{2}$$

where $A_{[t:t+n-1]} = \{A_t, A_{t+1} \ldots A_{t+n-1}\}$ and $p(a_{[t:t+n]})$ is a probability distribution of the possible states of $A_{[t:t+n-1]}$. $I(X;Y)$ is the mutual information between X and Y, which is defined in terms of entropy and conditional entropy of the variables

$$I(X;Y) = H(Y) - H(Y|X) = H(X) - H(X|Y) \tag{3}$$

$$H(X) = -\sum_{x \in X} p(x) \log p(x) \tag{4}$$

$$H(X|Y) = -\sum_{y \in Y} p(y) \sum_{x \in X} p(x|y) \log p(x|y) \tag{5}$$

In a deterministic world, i.e., one where each action leads to one specific outcome, we have that $H(S_{t+n}|A_{[t:t+n-1]}) = 0$ and empowerment can be simplified as:

$$\mathfrak{E} = \max_{p(a_{[t:t+n-1]})} H(S_{t+n}) = \log|\mathcal{S}_A| \tag{6}$$

where $\mathcal{S}_A = \{s_{t+n} \in S | \exists a_{[t:t+n-1]} \in A : p(s_{t+n}|a_{[t:t+n-1]}) \geq 0\}$ is the set of different sensor states that can be reached from time t to time $t+n$ with all possible combinations of available actions.

In this article, we propose that empowerment measures can be used to measure possibilities for action that compose affordances, and we test this intuition in a model that replicates the main results from experiments of perception of passability through apertures from Warren and Whang (1987). Still, it should be noted that, in general, empowerment measures are defined by a single value quantifying the possibilities available for an agent. Specifically, empowerment directly quantifies the possibilities for action as the average number of bits that an agent's sensors can perceive as results of its own actions. In contrast, affordances are defined as sets of possibilities related with different objects or parts of an environment. In our comparison with Warren and Whang (1987) this is not a problem, since only one affordance is present and changes in the sensor state of the agent will be related to it. Thus, the mapping between empowerment and affordance becomes straightforward in this case. However, this issue becomes problematic when there is more than one affordance and when the environment has more elements not related to the affordance under study (as the experiments in Figure 4 will show). A more precise relation between empowerment measures and sets of multiple affordances are left as future work, though measures of context-dependent empowerment (Salge et al., 2014; Klyubin et al., 2008) could be used to define sets of possibilities for action related to specific objects in an environment.

Model

Warren and Whang (1987) describe a classical example of body-scaled affordance by using the ability of an agent to perceive whether or not it can pass through an aperture. This ability is related to the capacity of a subject to be sensitive to the relationship of its own body to the objects in its environment. In this work, experimental evidence shows a transition in the perception of 'passability', which is related to the width of an aperture relative to the body of an agent. This transition takes place in humans approximately when an aperture is at least 1.3 times the shoulder width of a person. One of the results of the study, adapted in Figure 2 (top), represents the rate in which subjects with *small* and *large* body sizes judged an aperture of width W as passable (impassable in the original data). The data (Figure 2, top left) shows that each group displays a transition for a different value of W. Nevertheless, when the aperture width is normalized by the subjects' shoulder width, then Figure 2 (top right) displays an invariant transition for both groups around $W/S = 1.3$. This result supports the hypothesis that scale-invariant critical points govern the perception of such affordances.

Furthermore, the authors hypothesize that subjects use eye-height information related to the ground as a source of intrinsic information about their own size to directly perceive the affordance of an aperture from a distance. In an experiment using an Ames room, in which the effective eye-height is distorted, Warren and Whang (1987) show that the self-perceived eye-height is determinant for characterizing the location of the transition in Figure 2 (top).

A minimal model of passability

In this paper we design a minimal model to represent the task described by Warren and Whang (1987), with the aim to quantify the information about the affordances available to an agent by using empowerment measures. In previous work, Slocum et al. (2000) modelled a minimal agent which was evolved to pass through openings wide enough to accommodate its body while avoiding too narrow openings. Agents used proximity sensors in the form of rays that produce a sensor input when intersecting with an object.

Inspired by this work, we present a model (Figure 1) with an agent that can move inside a room with a wall that shows an aperture of width W on one side. The agent is shaped as a rectangular prism of height H and width S, and its length and width are equal. We test agents with different widths, but we always maintain a human-like height-width ratio of $H/S = 4$. In contrast with the model by Slocum et al. (2000), we do not model the neural system of the agents, since it is not necessary for empowerment measures.

Instead, we design different actions $a(t)$ available for the agent: move forward, move back, move left, move right or stand still. The agent moves in discrete time, moving a distance $s = 0.2$ in the appropriate direction each step. The agent cannot move through walls. As we are interested in studying the perception of the affordance, we restrict the analysis to the inside of the room and assume that the agent never crosses the aperture.

The agent projects seven sensory rays from its upper front, with angles evenly distributed in the horizontal plane between $[-\frac{\pi}{4}, \frac{\pi}{4}]$ (Figure 1, main). The sensors receive a binary input, being active when the ray intersects with a wall, and inactive otherwise. In the example shown in Figure 1, where the three sensors in the right pass through the aperture (0) and the remaining four sensors in the left intersect the wall (1), the sensor state is $(1, 1, 1, 1, 0, 0, 0)$. If the agent moves left, the right sensors will change their state from 0 to 1, until all rays collide with the wall. If it moves right, the left sensors will change from 1 to 0, while the right sensors will switch from 0 to 1 when they hit the right side of the wall. The lateral plane (Figure 1, right box), shows that sensors are projected from the upper front edge of the agent to the ground of the aperture, to represent the effect of the eye-height of the agent in its sensory input, retrieving intrinsic information necessary for performing the task as reported by Warren and Whang (1987). In practice, this implies that the distance traveled by the ray will be of $\sqrt{d^2 + H^2}$, where d is the horizontal distance between the agent and the aperture. Thus, note that the available sensory configurations (and therefore the values of empowerment) will change depending on the height of the agent, since for any agent objects will always be seen from a distance larger than H. This is included as a way for the agent to have perceptual information about its own size in its patterns of sensor activation. Warren reported height information as critical for perceiving passability, and we will see here that it has an important effect.

Empowerment of the agent $\mathfrak{E}(n)$ is computed as follows: an agent starts from a specific location and it is allowed to move n steps. Then, for all the positions available within a distance of n steps the sensory input received at each final location is recorded. Then, following Equation 6, the empowerment of the agent in a deterministic world is equal to the logarithm of the size of the set of perceived inputs.

Results

In order to explore the relationship of empowerment with the size of the agent and the affordances of the environment, we perform two experiments. In the first experiment, we reproduce the results reported by Warren and Whang (1987). Measuring the empowerment of the agent for different sizes of the aperture and different body-sizes of the agent we find a scale-invariant transition very similar to the one shown by Warren and Whang (1987). In the second experiment we compute the empowerment field of an agent in an environment with two apertures, one larger than the agent and thus passable, and another one smaller that the agent cannot go through. In this way, the empowerment can illustrate how regions of sensorimotor viability and possibilities for action arise depending on the agent and its environment.

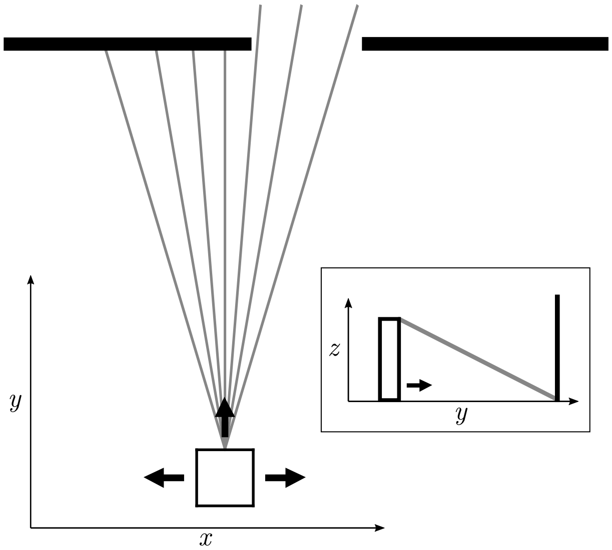

Figure 1: Schema of the agent. An agent interacts with an environment consisting on a wall with an aperture. The agent can perceive using binary sensors shaped as a set of rays arranged in a beam. Each step, the agent can move forward, left or right, or stand still. In the case of the vertical agent (right plot), the rays are not perpendicular to the floor but they are emitted from the top of the agent's body at height H.

Transition in the perception of passability

First, we explore the case of an agent moving in a finite room with an aperture. In this case, we assume that the number of steps n is large enough to explore the whole room ($n \to \infty$) and that the positions of the agent are restricted to all the positions available within the room. In this way, we compute the value of empowerment $\mathfrak{E}(n \to \infty)$ assuming the agent can reach all positions in the room. We consider that the agent is on a square room with sides of size 8, and that the side in front has an aperture in the middle of width W.

We compute the empowerment of 5 different agents with width S equal to 0.5, 0.75, 1, 1.25 and 1.5, for aperture widths in the range $[S/4, 4S]$. Empowerment is obtained from the sensory inputs the agent can perceive from all positions of the room. The result is displayed in Figure 2 (bottom).

As we can observe, the value of empowerment $\mathfrak{E}$ presents a transition at different values of W (Figure 2, bottom left). However, if we normalize the values of W by the width of

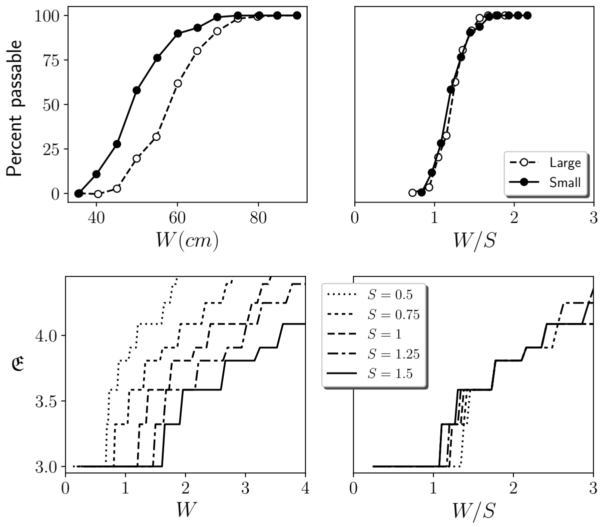

Figure 2: Top: Mean percentage of 'passable' judgments in experimental tests with humans in static viewing condition as a function of aperture width (left) and aperture width normalized for shoulder width (W/S, right). Adapted from (Warren and Whang, 1987). Bottom: value of empowerment $\mathfrak{E}(n)$ of an agent in a room at enough steps n to explore the whole room ($n \to \infty$) as a function of aperture width (left) and aperture width normalized for shoulder width (W/S, right). Note that in both cases we can observe an scale invariant transition for values of W/S slightly larger than 1.

the agent (Figure 2, bottom right) all agents present a transition at the same point (W/S around 1.2), independently of their size[2].

Affordance spaces as sensorimotor regions of viability

In the previous section, we have measured the empowerment of the agent assuming it can perform an infinite number of movements to explore the whole environment. However, if we restrict the number of available movements, we can compute the value of empowerment for specific positions of the environment in a finite number of steps n, which will depend on perceived sensor states in the locations that are accessible from each initial position. This is useful to characterize the affordances that appear in particular regions of the space that an agent can navigate. For an agent of width $S = 1$ with $n = 15$ steps in a 15x60 room with two apertures of widths 2 and 0.5 separated by 20, we observe the distribution of empowerment values shown in Figure 3 (top). High values of empowerment are obtained only around the aperture that is passable by the agent. We can interpret these regions as spaces of viability in which sensorimotor possibilities exist.

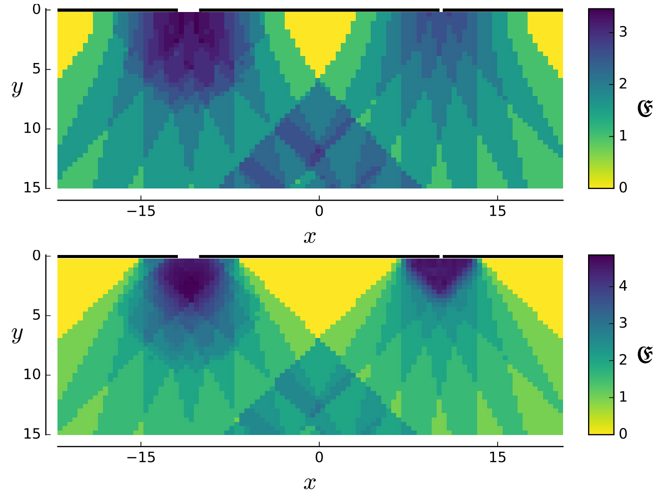

Figure 3: Top: Empowerment of an agent with width $S = 1$ starting at different positions (x, y) for 15 steps in front of a wall with two apertures of different sizes, the left one wider than the agent ($W_L = 2$), and the right one smaller ($W_R = 0.5$). Empowerment around the wide aperture is much larger than around the small one, since they are located at opposite positions of the transition represented in Figure 2, above and below the transition point $W/S = 1$ respectively. Bottom: Same model as in the top figure but with a flat agent ($H = 0$), showing the lack of a clear difference in the empowerment between the wide 'passable' aperture and the small 'not passable' one. In this case we cannot find a difference between the small and large aperture, showing that the height is crucial for the agent to get information about its width.

To explore what is the effect of the height of the agent, we compare those results with the empowerment of a 'flat' agent (an agent with $H = 0$). Note that in such agent, objects are perceived to be at a different distance (since the agent perceives objects to be at a distance $\sqrt{d^2 + H^2}$), and thus the agent's sensor will lose any information about the size of the agent. As we can see in Figure 3 bottom, in this case the viability space is ill-defined, and thus the agent is in a state of maladaptation (to the behaviour of traversing an aperture). In this case, both the large and the small aperture show a similar value of empowerment. In contrast, the area of viability in the model with height larger than zero is correctly defined, with large empowerment correlating with the possibility for exploiting the affordance of passing through the aperture.

If we try to extend our minimal model to more complex environments, the relationship between empowerment and possibilities for action is not as easy as in the previous cases. If we analyze a wall with two nearby apertures, we can see that the empowerment measure increases when the sensors

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[2] Note that because of the discrete nature of the model, values of empowerment grows step-wise, and that by transition we refer only to the point where empowerment starts to grow from a flat state).

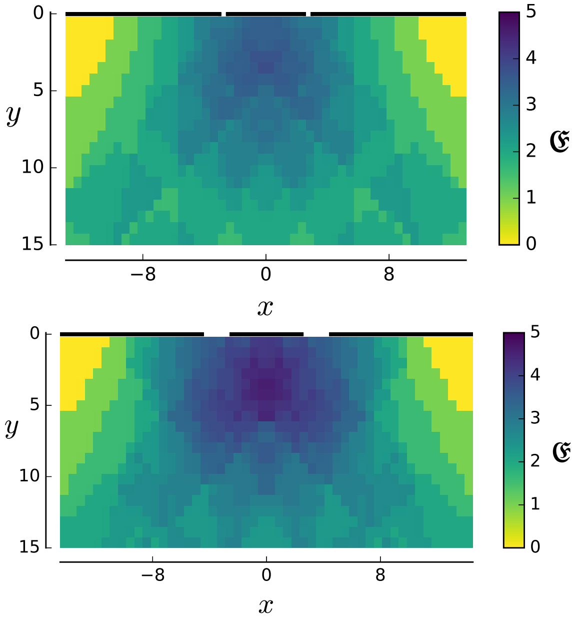

Figure 4: Empowerment of a model with the same parameters as in Figure 3 (top) but with two nearby apertures, small and ‘not passable’ in the top ($W = 0.5$), and larger and ‘passable’ in the bottom ($W = 2$). The empowerment measure shows some limitations when considering more complex environments, yielding high values even in the absence of affordances (top) or mixing the contributions of two affordances (bottom).

have access to both apertures. This increment in empowerment, however, does not always correlate with possibilities of action and affordances. This limitation is illustrated in Figure 4. We can see in the top of this Figure 4 that empowerment is large in the center and relatively close to the apertures, but in this environment there is no affordance available for this agent. In contrast, in the bottom panel of Figure 4 both apertures are wider than the agent and thus they generate two affordances, passing through the left or right aperture. In this cases, thus, it is not clear how to interpret the increase of empowerment, which might be because of a richer environment (even if there is no affordance available) or due to the fact of having two affordances available.

Discussion

In the previous sections we have studied the challenge of interpreting affordances using information theory. We have explored this issue by proposing measures of empowerment as a natural form of quantifying affordances in information theory terms. We have applied this idea to a minimal model reproducing some aspects of Warren’s experiment of perception of passability through apertures. As Figure 2 shows, we successfully reproduced the scale-invariant transition in Warren’s experiment with a measure of the empowerment of the agent. The results are similar since both transitions are body-scaled. This shows that we can use empowerment measures to quantify information about a particular interpretation of the affordance of passing through apertures in information-theoretical terms. Nevertheless, as we claimed before, this interpretation of affordances in information theoretic terms is a simplified simulation of a full-blown scientific, ecological explanation of how we perceive affordances, so it lacks many key aspects from an in vivo scientific explanation, like a realistic model of visual perception.

In addition, we have shown how empowerment (Figure 3) can describe a field of behavioural possibilities, characterizing the area in which a specific affordance exists in information theoretic terms. We could connect this with more general ideas about the maintenance of regions of viability in adaptive systems. In this work we have not considered the behaviour of the neural system of the agent, but we could think of the family of neural systems that are adapted to a particular affordance as the ones that maintain the state of the agent within a region in which the affordance exists.

Still, the results here present some limitations that should be addressed in further work. First, the empowerment measure is a good description of possibilities for action that generate observable results for the agent. Nevertheless, this information theoretic interpretation of affordances is less restrictive than the original one, since not all possibilities for action are affordances. As we observe in Figure 2 (bottom right), even in the situation when the affordance doesn’t exist ($W/S < 1$) there is some basal level of empowerment (because the movement of the agent can still cause sensations of a small aperture). However, when the affordance appears, it generates a transition in the empowerment metric. Our results suggest that affordances could be quantified by identifying these transitions in the space of possibilities for action. Nevertheless, further work could explore whether this also happens in more complex models and how empowerment metric could be refined to capture more specific aspects about affordances that are not shared by general possibilities for action.

In this line, we made explicit this limitation by showing that the relation between empowerment and affordances in our minimal model holds only for simple environments where either there is one affordance or none. When we analyzed the case of walls with two nearby apertures, we found that the empowerment combines contributions from both apertures, making the absolute value of empowerment not an indicative measure of the presence of an affordance or even of the possibility for action. Even if any of the apertures is wide enough for the agent to pass (Figure 4 top), the empowerment increases around the apertures, but in this case the region of high empowerment does not correlate with a viability region where sensorimotor possibilities arise. Instead, both viability regions overlap, and we cannot disentangle the contributions of each individual affordance.

In order to overcome this limitation, some adaptations might be necessary to extend its usefulness to more complex situations than the one analyzed here. Nevertheless, there are refined versions of the measure, e.g. context-dependent empowerment (Salge et al., 2014; Klyubin et al., 2008), which might sucessfully be used to separate different sources of empowerment.

Our description of affordances shows similarities with some works in the field of robotics that try to simplify action spaces (Guttenberg et al., 2017) and with the concept of 'intrinsic options' developed in the field of reinforcement learning. Options in general are defined as 'closed-loop policies for taking action over a period of time' (Sutton et al., 1999), but this definition can be restricted to policies with a termination condition that meaningfully affect the world, i. e., intrinsic options (Gregor et al., 2016). Therefore, the main goal of learning intrinsic options is not to predict future observations, but to control the environment. Information theory and empowerment measures have also been applied in this context (Gregor et al., 2016), and theoretical work in this field might be useful to extend the validity of our interpretation and overcome some of the difficulties mentioned above.

When computing empowerment there is an important distinction between open and closed-loop measures. The open-loop measure assumes that the action sequence is selected in advance, with each action depending only on the initial state. However, this is not very realistic for noisy or changing environments. When computing closed-loop empowerment later actions can change depending on the current sensor state, allowing the agent to adapt to modifications in the environment during the action sequence. It is important to note that in the model we analyzed the agent moves in a deterministic world, meaning that each action is associated with just one specific outcome. Therefore, the sequence of actions that the agent follows is known in advance, and only depends on the initial state, making both open-loop and closed-loop empowerment measures equivalent in our model.

Another aspect for future exploration is that affordances are described as specific possibilities for action which the agent can perceive *directly*. In our work we have not explored how an agent can perceive information about its empowerment. Future work could explore how information about the presence of an affordance flows through variables of the neural system and the body of the agent in a similar way as the experiments performed by Beer and Williams (2015). Furthermore, as empowerment is defined in terms of entropy (of a channel capacity between actuators and sensors), future explorations could quantify to what extent the information captured by empowerment metric also flows through different variables of the agent. Such an analysis could rigorously determine whether information processing in the neural system of the agent is involved in the perception of a particular affordance, or whether this information is directly available through sensorimotor interaction without internal computation.

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