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How active perception and attractor dynamics shape perceptual categorization: A computational model

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ABSTRACT

We propose a computational model of perceptual categorization that fuses elements of grounded and sensorimotor theories of cognition with dynamic models of decision-making. We assume that category information consists in anticipated patterns of agent–environment interactions that can be elicited through overt or covert (simulated) eye movements, object manipulation, etc. This information is firstly encoded when category information is acquired, and then re-enacted during perceptual categorization. The perceptual categorization consists in a dynamic competition between attractors that encode the sensorimotor patterns typical of each category; action prediction success counts as "evidence" for a given category and contributes to falling into the corresponding attractor. The evidence accumulation process is guided by an active perception loop, and the active exploration of objects (e.g., visual exploration) aims at eliciting expected sensorimotor patterns that count as evidence for the object category. We present a computational model incorporating these elements and describing action prediction, active perception, and attractor dynamics as key elements of perceptual categorizations. We test the model in three simulated perceptual categorization tasks, and we discuss its relevance for grounded and sensorimotor theories of cognition.

1. Introduction

Cognitive scientists and neuroscientists have widely studied how the brain categorizes and recognizes objects and entities. Traditional cognitive psychology theories propose that categories are stored in the form of sets of rules that define the category (Trabasso & Bower, 1968), category prototypes that average across category elements (Rosch, 1975), sets of exemplars that correspond to specific category elements (Medin & Schaffer, 1978), or a combination of all them.

More recently, grounded theories of cognition have put categorization research into a broader perspective, arguing how the abilities of perceiving, categorizing, and thinking about objects and events are highly related. According to this view, perceptual and motor processes (rather than amodal symbols) constitute the conceptual content of categories and concepts, including abstract ones. Once acquired through agent–environment interaction, this conceptual content can be re-enacted to support off-line thinking and cognition, determining so-called *situated simulations* (Barsalou, 1999, 2008; Pezzulo et al., 2011, 2013).

Sensorimotor theories stem from similar assumptions but further emphasize the importance of action dynamics. They assume that actions are constitutive of perception and categorization, and describe object perception in terms of interaction dynamics and stable patterns of actions and sensory stimulations, or *sensorimotor contingencies* (O'Regan & Noe, 2001). For example, the sight of a glass produces a coherent pattern of sensory stimulations (as an effect of the eye's actions), and the mastery of such contingencies corresponds to the knowledge of what is a glass. Support from this view comes from experiments showing the importance of action (e.g., eye movement) dynamics in shaping the categorization process (Ballard, 1991; Hayhoe & Ballard, 2005; Rothkopf, Ballard, & Hayhoe, 2007; Yarbus, 1967).

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In a similar vein, action-based approaches emphasize that knowledge of the external world consists in sets of "dispositions to act" as produced by action–outcome mechanisms, and that object knowledge consists in the anticipated patterns of actions and perceptions produced by an interaction with them (Bickhard, 1993; Grush, 2004; Pezzulo, 2008, 2011). For instance, a sponge can be understood in terms of a characteristic (sequence of) action–outcome relation, such as the anticipated softness one expects when squeezing it. These action–outcome relations have been linked to the concepts of internal forward models (Desmurget & Grafton, 2000; Kawato, 1999) and ideomotor codes (Hommel, Musseler, Aschersleben, & Prinz, 2001); see also Maye and Engel (2011), Pezzulo and Calvi (2011) and Roy (2005). Numerous studies support the idea that the same action–outcome links adopted in the on-line interactions can also be reused off-line to *mentally simulate* an interaction, essentially recruiting the same brain mechanisms for *motor cognition* (Jeannerod, 2001, 2006).

In this article we offer a theory of perceptual categorization that distills key concepts of grounded, sensorimotor and action-based theories of cognition and integrates them with dynamic and competitive models of choice. We propose that categories are coded in terms of the associated action–outcome sequences, not in purely sensorial terms. Specifically, an object category is linked to (predictable) sequences of saccades, grasp movements, or a combination of them. This sensorimotor information is firstly acquired during situated agent–object interactions and can be successively re-enacted to guide perceptual processing and categorization, in a process that resembles the sampling of environmental information under the guidance of categorical hypotheses (Barsalou, 1999; Pezzulo et al., 2013).

In this view, agent–object relations can be described as sequences of actions and resulting sensations, or action–outcome pairs. In keeping with grounded cognition theories, we assume that this information is acquired when the agent interacts with exemplars of the category (Barsalou, 1999). For instance, during interactions with a sponge an agent learns action–outcome relations: how a sponge feels when it is squashed, how it looks if it is foveated to the left or right, etc. Once learned, the same sensorimotor processes used to explore (e.g., visually or haptically) and interact with objects also realize the object categorization process; for instance, a sponge is recognized when the agent successfully reuses the stored action–outcome relations associated to earlier sponge uses. The same information can be reused to mentally simulate interactions with the same objects in their absence (Pezzulo, 2011). Action–outcome relations are maintained in the internal models used to interact with objects, in a modal format; more frequently, objects link to multimodal information acquired using different effectors (e.g., eye and hand). Categorization profits from both overt exploration (e.g., physical manipulation of a sponge) and mental simulation (e.g., just anticipating the interaction), which according to grounded theories of cognition recruit the same brain processes.

The pragmatic view of categorization that we propose emphasizes the importance of previous interactions, like exemplar and prototype theories of categorization. At the same time, it reverses the perception–categorization-action pipeline of traditional cognitive theories, and proposes that action is part and parcel of perception and categorization rather than being successive to the categorization. In sum, our approach assumes that action–outcome representations are constitutive of the conceptual content of categories, at least for categories that can be readily mapped to possible interactions.

1.1. *The mechanics of situated categorization*

Up to now we have introduced our proposed theory of categorization by referring abstractly to action–outcome patterns. Now we discuss how this information is elicited during situated interactions with the to-be-categorized object and how it influences the moment-by-moment dynamics of the categorization.

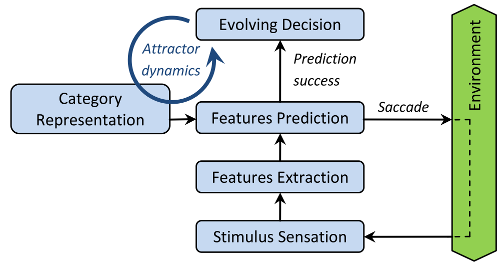

Fig. 1. Proposed dynamic model of perceptual categorization. See main text for explanations.

There is ample consensus that perceptual decision-making and categorization are dynamic and competitive processes in which evidence is accumulated in favor or against the competing alternatives (e.g., deciding if a visual stimulus is a cat or a dog). The widely adopted drift–diffusion model describes choice as a competitive process of accumulation of evidence up to a criterion; when the criterion is reached, action can start (Ratcliff, 1978; Ratcliff & Rouder, 1998); see also Bogacz, Brown, Moehlis, Holmes, and Cohen (2006), Usher and McClelland (2001) and Wang (2002) for descriptions of plausible neural implementations of diffusion-to-bound and related mechanisms. Several models of perceptual categorization invoke the same dynamic mechanisms but differ on what they consider to be the relevant dimensions along which evidence is accumulated. An influential model (Nosofsky & Palmeri, 1997) describes perceptual categorization as a dynamic competition between exemplars, linking to the exemplar models of categories described earlier. Another model (Lamberts, 2000) uses the same principles of dynamic accumulation of evidence, but focuses on competition between stimuli features rather than exemplars.

Diffusion-to-bound models have been extremely successful in explaining behavioral data and map nicely to the brain substrate (Gold & Shadlen, 2001, 2007). This leads to the idea that core mechanisms of decision-making (based on evidence accumulation) could have been preserved to support increasingly more complex and abstract decisions and categorizations (Cisek, 2012; Shadlen, Kiani, Hanks, & Churchland, 2008). However, they largely abstract from the way evidence is accumulated. They often point to a bottom-up process in which a stimulus is repeatedly probed to obtain multiple samples and do not model active perception dynamics or overt exploration (but see Krajbich, Armel, & Rangel, 2010). Our proposed model extends these theories and describes categorization as a dynamic and competitive process that builds on evidence elicited through active perception.

Within the dynamic and competitive categorization process that we discussed, it is often assumed that evidence accumulation follows a sequential sampling rule (Ratcliff, 1978), which corresponds to an optimal statistical test. We assume that active perception dynamics bias the evidence accumulation process; this process is not random but rather it recapitulates the agent–object interactions that firstly created the agent's categorical concepts. In other words, the visual exploration of an object consists in an attempt to re-create and re-elicit the same action–perception patterns that were established when an object category was acquired, and the elicitation of the same (predicted) stimuli counts as evidence for the category. The proposed model (sketched in Fig. 1) is based on three main assumptions that we discuss below.

1.1.1. *Action dynamics shapes the ongoing categorization*

A first aspect that distinguishes our model from previous ones is that it gives motoric and active perception processes a key role