Reasoning about perception*

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Abstract

This paper focuses on the uncouscious mechanisms underlying the process of acquisition of belief through perception. We outlines the basics of a formal theory of belief that is sensitive to the way in which beliefs are formed through perception. The process of formation of beliefs involves a form of inference that is defeasible. We represent this kind of inference by means of well-known techniques of non-monotonic reasoning. In addition, we provide an account of perception that is consistent with the commonsense intuition for how perception functions, i.e., causality.

1 Introduction

By perceiving, intelligent agents become aware of their surroundings, and form beliefs about objects and events in their perceptual space. The dependence of perception on the sensory input differentiates perception from other forms of belief acquisition, like inductive generalization or communication with other agents: the latter forms of belief acquisition are indirect ways of becoming aware of the surrounding environment, perception is a direct source of information about the physical properties of the environment.

While there has been a great deal of work in AI on communication and belief, and on induction, learning, and belief revision, relatively little attention has been paid to the problem of describing the effects of sensing on beliefs, and to integrate perception with symbolic reasoning [Davis 1988, 1989], [Reiter and Mackworth 89], [Shoham and Del Val 91]. This is not because the problem is simple and has an obvious solution; on the contrary, the nature of perception is intrinsically complex, as it is testified by the iterated attempts of philosophers and cognitive scientists to provide a coherent and complete account. In particular, explaining how it is possible to acquire information about the physical world on the basis of sensing (i.e., explaining the nature of the connection between the *appearance* of an object or situation and *reality*) has long been a puzzling problem for any theory of perceiving. This problem is further stressed by the fact that perception may be illusory, that is perception may attribute a property to the environment that does not reflect the true state of the environment. For example, a white surface may appear grey if it is

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observed when it is in shadow. In this case, simply on the basis of the sensory information, a perceiving agent might come to believe that the surface actually is grey, and behave accordingly. Experiments conducted on human agents show that we do as well as possible, given the knowledge we have, to discriminate between illusory and veridical perception (e.g., see [Rock 83] and [Flavell 86]). Therefore, understanding the nature and the limits of human perception can provide useful insights for modelling and building autonomous agents that appropriately act in the environment.

The theory proposed by the philosopher [Pollock 74] provides at least a partial solution to the problem of perception, and we draw from it. According to such a theory, perceiving that something is the case gives us a *logical* [1] presumption for assuming that what is perceived is really occurring in the physical world. Such a logical presumption leads us to acquire a belief, provided that we do not simultaneously hold additional information that constitutes a *defeater* for the logical presumption (see Section 2). Therefore the process of acquisition of belief through perception is seen as a particular kind of defeasible inference. This process seems effortless to us only because, unlike other forms of reasoning, it is primarily an *uncouscious* process.

This paper describes our attempt to formalize such a theory of perceiving within a theory of belief, and to integrate the formal account so derived with the commonsense intuition for how perception works (i.e., the *causal* nature of perception [Grice 61], [Cox 85]). The focus of the paper is therefore on *normative* questions about what are the aspects of our perceptual experience that justify us in believing. At the same time, the present discussion provides a *descriptive* account of those aspects of our experience that make perception a source of evidence about the external world.

[1] The term *logical* is used as opposed to *contingent*.

2 Modeling perception

The following example illustrates the crucial aspects that must be taken into consideration to provide a realistic model of perception.

Suppose that an agent S sees that a statue is red. Then, simply on the basis of the sensor information he acquires, S might come to believe that the statue actually is red. This, in practice, occurs whenever S does not hold any additional belief concerning the color of the statue and/or the conditions of observation. However, if S also has information that there is a red light shining on the statue, then even though the statue appears red to him, he may be unwilling to believe that the statue is red, knowing that a white statue would still appear red under a red light. Similarly, if S has good reasons to believe that the color of the statue is white (e.g., because S has been told this way by someone on whom he relies), then even if the statue appears red to him, he is unwilling to ascribe to the statue a color other than white. In this case S rejects the content of perception as illusory, and acquires the belief that the conditions of observation are abnormal.

Therefore, perceiving gives to S a *prima facie* reason for believing that what he observes reflects the true state of the environment. However, since beliefs are not acquired in isolation, S accepts the content of perception as a belief only if he does not believe something that may constitute a *defeater* for the prima facie reason represented by perception. In particular, S may recognize the presence of such a defeater on the basis of his knowledge of the relevant causes of perceptual error, and on the reasons he has for trusting his current beliefs.

This character of the perceptual process is summarized by the following principle:

Default Perceptual Rule *I normally believe in the content of my perception, unless I have reason to believe that there is something causing an abnormality in the perceptual process.*

The full formalization of this principle would involve understanding and representing the nature of causation, and in our preliminary work we have not attempted to do this. Rather, we have left causation as an informal concept, and given a simple translation into a nonmonotonic logic of belief, autoepistemic logic [Moore 87].

3 A formal theory of perception and belief

A perceptual attribute is any property of physical objects or events whose presence or absence can be detected directly by sensing. Examples of perceptual attributes are *spatial* attributes, like shape, size and location, and *non-spatial* attributes, like color, temperature, and weight. Attributes like "belonging-to", or "flammable", whose presence or absence cannot be judged simply by sensing, are not included in the set of perceptual attributes.

Let α be any atomic statement concerning a perceptual attribute. In particular, α can be any *existential statement*, like: " there is a doorway", "there is an object on my left"-, or any *attributive statement*, like: "the door is open", "the box is close to the wall"-. To express the fact that a statement α is perceived we introduce a modal operator P: the intended meaning of $P\alpha$ is that α is a current perception of the agent. The following axiom holds: $P\alpha \wedge P\alpha' \supset P(\alpha \wedge \alpha')$.

By using epistemic concepts for representing defaults [Konolige 87], the Default Perceptual Rule of Section 2 can be expressed by the following logical statement:

$$P\alpha \wedge \neg def_{P\alpha \supset \alpha} \supset \alpha \qquad (1)$$

where $def_{P\alpha \supset \alpha}$ represents the existence of defeaters for the implication $P\alpha \supset \alpha$. There are two classes of defeaters for the implication $P\alpha \supset \alpha$ [Pollock 74]: (i) the belief that $\neg\alpha$, and (ii) the belief that there are abnormal conditions in perceiving that α. The first is a *type I* defeater because it direct contradicts the conclusion of the statement $P\alpha \supset \alpha$; the second is a *type II* defeater, because it represents a reason for not believing that $P\alpha \supset \alpha$ without contradicting α.

Let ϕ_α denote the presence of abnormal conditions for perceiving that α. An abnormal condition may be either *personal*, i.e. a fact about the agent, like: " I'm partially blind on my lateral side", "I'm moving very fast", "I'm very far from the object that I'm perceiving"-, or *environmental*, i.e. a fact about a specific object or event perceived or about the general circumstances, like: "the view of the object is partially occluded", "the room is illuminated by a blue light"-. The knowledge of the presence of an abnormal condition may be part of the beliefs already held by the agent when he perceives, or may be acquired through current observations. For example, the agent may recognize the presence of an abnormal condition for perceiving the color of an object if he observes that the object is situated behind a colored glass wall, and knows that a filter may produce the appearance of a colored object even when the object is white.

Assume that the agent is aware of the normal causation rule for perceiving that α (see (2) below), and, possibly, of the existence of some specific abnormal condition (say, $\theta_{\alpha,i}$). Then the agent is aware of the following causal rules [Konolige 92]:

$$\alpha \wedge \neg\phi_\alpha \rightarrow P\alpha \qquad (2)$$

$$\theta_{\alpha,i} \rightarrow \phi_\alpha \qquad (3)$$

Here the arrow represents a causal statement, so the first expression could be read as "α, in the absence of defeaters for α, causes the perception of α."

Such causal rules can be mapped into ordinary material implications, as follows (for brevity, we omit the proof):

1. Each abnormal condition rule $\theta_{\alpha,i} \rightarrow \phi_\alpha$ corresponds to the implication $\theta_{\alpha,i} \supset \phi_\alpha$

2. the normal causation rule $\alpha \wedge \neg\phi_\alpha \rightarrow P\alpha$ corresponds to the following set of implications:

   (a) $P\alpha \wedge \neg def_{P\alpha \supset \alpha} \supset \alpha$

   (b) $\neg\alpha \supset def_{P\alpha \supset \alpha}$

   (c) $\phi_\alpha \supset def_{P\alpha \supset \alpha}$

Finally, we need the assumption that in the absence of other information, the normal conditions of perception hold and that no defeaters arise. We can express this in autoepistemic logic by:

$$\neg L\phi_\alpha \supset \neg\phi_\alpha \quad (4)$$

$$\neg L def_{P\alpha \supset \alpha} \supset \neg def_{P\alpha \supset \alpha} \quad (5)$$

To summarize, a logical theory modeling the acquisition of the belief that α by perceiving that α is defined by the following axioms:

1. $P\alpha \wedge \neg def_{P\alpha \supset \alpha} \supset \alpha$
2. $\neg L def_{P\alpha \supset \alpha} \supset \neg def_{P\alpha \supset \alpha}$
3. $\neg\alpha \supset def_{P\alpha \supset \alpha}$
4. $\phi_\alpha \supset def_{P\alpha \supset \alpha}$
5. $\neg L\phi_\alpha \supset \neg\phi_\alpha$
6. $\theta_{\alpha,1} \supset \phi_\alpha$
7. ...
8. $\theta_{\alpha,n} \supset \phi_\alpha$

4 Conflicts

There is always the possibility that different sources of information will be in conflict, e.g., memory and perception; or even that the perceptual process itself will give rise to information that tends to be contradictory. We have formulated the following sets of formal defeat rules to implement the Default Perceptual Rule given in Section 2. As an example, let α be the statement "the wall is blue".

R1. [$P\alpha$ while by default $\neg\alpha$]. For example, the agent holds the statement $\neg L\alpha \supset \neg\alpha$ (i.e., "normally a wall is not blue"). In this case, differently from the case in which $\neg\alpha$ is a categorical belief[2], the default assumption that $\neg\alpha$ is not a sufficient reason to deny the acquisition of α by (1). In particular, it does not provide a type I defeater for (1).

R2. [$P\alpha$ while by default β, where β asserts an abnormal condition for observing that α]. For example, the agent holds the statement $\neg L\neg\beta \supset \beta$ (e.g.,"Normally this environment is illuminated by a blue light"), together with the information $\beta \supset \phi_\alpha$. In this case, even if β is only a default assumption, β becomes a reason to deny the acquisition of α by (1). In particular, β provides a type II defeater for (1)[3].

R3. [$P\alpha$ while simultaneously $P\gamma$, where γ asserts an abnormal condition for observing that α]. For example, the agent perceives that "the wall is behind a glass wall" (γ_1) and that "the glass wall is blue" (γ_2). In this case, $P(\gamma_1 \wedge \gamma_2)$ becomes a reason to deny the acquisition of α by (1) [4].

These rules take care of the key cases in which defaults will conflict and the causal structure of the perceptual process can be used to adjudicate among them.

5 Applications

In this paper we have investigated the defeasible nature of the perceptual process. The follow-

[2] A categorical belief is an incorrigible justified belief, whereas a default assumption is only a prima facie justified belief [Pollock 74]. A categorical belief cannot be overridden.

[3] Note that it is immediately obvious that β is a type II defeater for (1) only when β is a categorical belief.

[4] Note that $P\alpha$ cannot be a reason to deny the acquisition of γ_1 by $P\gamma_1$ because of the content of the causal rules.

ing example illustrates that the ability to reason about the defeasible nature of perception may be crucial for autonomous mobile robots operating in real-world unstructured environments.

Let F be a mobile robot that navigates in an office environment. F is equipped with ultrasonic sonar sensors to perceive the environment, and has the goal of entering in a particular office, say office J1. In order to find the target office, F uses a map of the environment, which describes the topology of the building, and senses his surroundings with the sonars to detect openings that correspond to office doors. Due to the physical characteristics of the sonars, F is unable to distinguish whether there is a wall or an open doorway that is occluded by a stationary person: both situations, in fact, produce the same sonar readings that indicate that there is a straight surface in the proximity of F. The errors introduced by the robot movements preclude to F an accurate localization of the door by using the map. Therefore, if there is a person at the entrance of the office J1 when F approaches that office (or if a person is at the entrance of an office that precedes office J1), F may lost his target doorway and fails. To overcome this problem without requiring the intervention of a human agent that points out perceptual errors, F must be endowed with the ability to recognize the possibility of an illusory perception of a wall. This can be accomplished (a) by providing F with explicit information about his own perceptual skills and about the relevant causes of his perceptual errors, and (b) by allowing F to question his perceptions on the basis of additional information he already holds or comes to acquire. In particular, F may use a priori knowledge of the office topology to form the expectation that he will find a doorway when he is in the proximity of the office J1. If he does not perceive the doorway within a certain distance tolerance according to his supposed location, he must replan his activity. For example, F may decide to go back down the corridor to take a closer look at the area in which the doorway was supposed to be, in order to localize the entrance of the office J1 if he recognizes that he has moved too far without perceiving it.

The task described above describes a very complex problem to be performed by real robots or by robot simulation. The insights provided by our research on the problem of acquisition of beliefs through perception, and ongoing experiments being conducted at SRI to integrate action, perception, and planning on the mobile platform Flakey [Saffiotti, Konolige and Ruspini 93], seem to confirm the feasibility of the task, and suggest a cautious optimism.

6 Concluding Remarks

This paper represents an attempt to develop a formal theory of belief that is sensitive to the way in which beliefs are formed through perception. The process of acquisition of beliefs is influenced by the beliefs already held by the agent. This dependency on the epistemic context has not a simple nature, and is investigated in the paper. The formalization uses the autoepistemic logic of [Moore 87] to represent the causal and default connections between belief and perception. The framework we have presented models a rational perceiving agent that, under the appropriate conditions, augments his beliefs on the basis of his perceptions. The conditions considered appropriate by the agent are determined by the agent's awareness of his own perceptual process.

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