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Traces of Our Past: The Social Representation of the Physical World

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Abstract
How do humans build and navigate their complex social world? Standard theoretical frameworks often attribute this success to a foundational capacity to analyze other people's appearance and behavior to make inferences about their unobservable mental states. Here we argue that this picture is incomplete. Human behavior leaves traces in our physical environment that reveal our presence, our goals, and even our beliefs and knowledge. A new body of research shows that, from early in life, humans easily detect these traces—sometimes spontaneously—and readily extract social information from the physical world. From the features and placement of inanimate objects, people make inferences about past events and how people have shaped the physical world. This capacity develops early and helps explain how people have such a rich understanding of others: by drawing not only on how others act but also on the environments they have shaped. Overall, social cognition is crucial not only to our reasoning about people and actions but also to our everyday reasoning about the inanimate world.

Keywords
artifacts, social cognition, physical reasoning, theory of mind

In the summer of 2008, a seemingly unnatural vulture's wing bone was discovered in a German cave (Fig. 1): It had a *V*-shaped notch in one end and five pairs of evenly rounded perforations and notches. A high-fidelity replica later showed that blowing air through one end while covering different holes produced recognizable musical notes, suggesting this bone was a 40,000-year-old flute, among the oldest musical artifacts of human culture (Conard et al., 2009).

Archeologists' ability to recognize this bone's cultural significance attests to the sophisticated ability that humans have to extract social information from the physical world. However, this success reflects a fully institutionalized form of scientific inquiry developed over generations and requiring years to master. This might tempt us to conclude that any untrained capacity in humans is limited and of little practical use. Perhaps without formal training, any social inferences we make from the environment are nothing more than unreliable guesses.

Such a conclusion makes initial sense from the standpoint of cognitive science. Social reasoning in humans appears to be specialized for processing observable *agents*—not their inanimate traces. Our perceptual systems first detect direct agency cues like bodies and faces, separate them from inanimate object representations, and then feed them into a system that extracts mental states from observable behavior (Pitcher & Ungerleider, 2021). Thus, this architecture might lead us to expect that humans are not well equipped to read social information from the physical world. Here we argue that this view is incorrect. Instead, social and physical reasoning are deeply integrated from early in life, allowing the physical world to serve as a rich and omnipresent source of social information. This allows people to build richer social representations than what would be available by attending to observable action alone.

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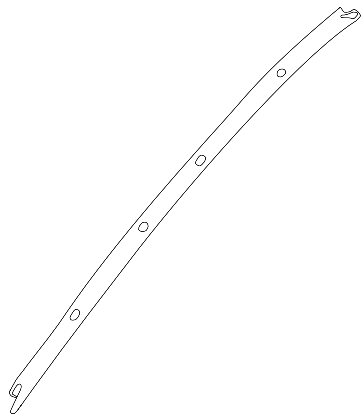

Fig. 1. Schematic of a 40,000-year-old flute made from a vulture's wing bone, discovered in the Hohle Fels cave in southern Germany.

In order to read social information from the physical world, we propose that the mind must achieve three interrelated subgoals (at a computational or functional level of analysis; Marr, 1982). From observations of the physical environment, people must be able to (a) detect when a person or other agent had been present, in the past; (b) determine what happened; and (c) explain why the agent did what they did, for example, by using mental states to explain the inferred behavior (Fig. 2). Here we review evidence of each of these abilities and show how they allow people to read and write social information from the physical world.

For each of these three computational goals, we also aim to characterize the cognitive representations and processes that contribute to human reasoning. We propose that people—even children and possibly infants—can seamlessly integrate social and physical knowledge to reason about behavior as the link between the mental and physical worlds. This *sociophysical interface* allows people to integrate expectations about how mental states guide behavior and how behavior leaves observable traces in the world. This integrated causal theory structures many of our inferences and is supplemented by learned associations between agents and physical cues, and low-level perceptual systems that help draw our attention to traces of agency. Together, these processes allow people to extract social information from their environment, giving rise to otherwise impossible forms of social intelligence and behavior.

Detecting People From Inanimate Traces

Not every component of the physical world calls for social reasoning: Much of the natural world occurs through purely physical-mechanical processes. In order to read social information from the physical world, a cognitive system must therefore detect when the environment has been shaped by a person and social information might be available.

What cognitive processes allow us to detect agency from inanimate scenes? First, low-level features of the physical environment help us notice that an agent was involved. In particular, from infancy, people associate the creation of order with the presence of an agent (Ma & Xu, 2013; Newman et al., 2010; Fig. 3a). However, this form of indirect agency detection is thought to be innately hyperactive (Barrett, 2000), such that we attribute agency even when we have no clear way of explaining phenomena—leading people to posit supernatural agents (the creationist "argument from design"; Kelemen, 2004).

Our ability to detect social information goes beyond a simple association between agency and order to incorporate other cues as well. One critical feature of humans is that the way we shape our environment is fundamentally constrained by our competence. Humans are famously imperfect: Our hands slip, we lose focus, and we make mistakes. Thus, the detection of human intervention should also depend on the detection of flaws that are well explained by human cognitive and motor limitations. Indeed, in visual search tasks, people more quickly and accurately detect block towers with small humanlike errors versus perfectly aligned towers (Lopez-Brau et al., 2021; Fig. 3b), in line with faster detection of animate versus inanimate stimuli in other tasks (Pratt et al., 2010). The speed of these detections opens the possibility that they may be supported purely through low-level attentional processes.

However, people are not limited to quick, low-level processes when detecting agents' intervention. We also routinely bring to bear our full naive theories of physics and psychology, and doing so can radically change our intuitions. In contexts where order can be generated through intuitive natural forces, like gravity, this "explains away" the presence of an agent: People's tendency to infer agents from order can be eliminated and even reversed (Schachner & Kim, 2018). The presence of humanlike errors also shapes high-level inferences and value judgments, suggesting this factor is integrated into our causal model of the sociophysical interface. For example, people are more likely to believe that overly perfect objects were factory-made versus handmade (Judge et al., 2020) and value handmade artifacts more highly than factory-produced items (DeJesus et al., 2022).

Reconstructing Past Behavior

To read social information from the physical world, people must do more than detect agents' intervention:

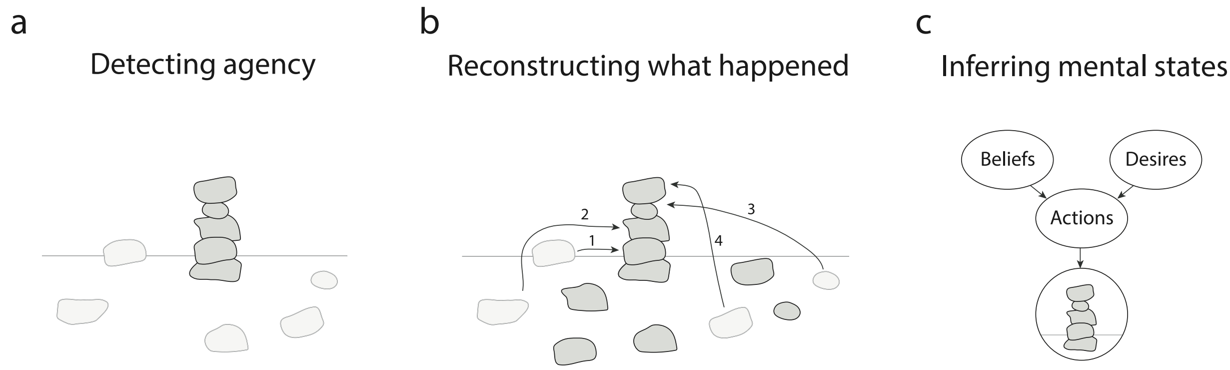

Fig. 2. The three computational goals people solve to extract social information from the physical world. Research suggests that each of these inferences integrates a causal understanding of how physical and social knowledge are integrated, and lower-level attention processes and associations. (a) Identifying what aspects of a scene reflect the involvement of an agent. (b) Explaining the social traces by reconstructing what happened. (c) Reasoning about how an agent's mental states, such as their beliefs and desires, explain the reconstructed actions and the final observed outcome. In this causal model, the causal connections from beliefs and desires to actions emerge from naive psychology, and the causal connection from actions to physical outcome emerge from naive physics.

We must be able to determine the nature of this intervention to glean its meaning. To accomplish this, we engage in *event reconstruction*, inferring the particular past events and actions that shaped the physical features. By reconstructing what happened, human cognition can move beyond an amorphous feeling that an agent was involved to construct a specific hypothesis about what happened and reason about the implications of the inferred behavior.

Here again, humans appear capable of some quick, bottom-up perceptual inferences that rapidly reconstruct what an agent did from specific physical features. For instance, when we encounter a dented can, we "see" its history—a force being applied to dent it (Leyton, 1992)—and this even leads to illusory motion perception (e.g., seeing a discrete change between a complete cookie and one with a bite in it as having occurred gradually; Chen & Scholl, 2016). This perceptual event reconstruction is not specifically social and appears limited to recovering only recent actions (e.g., in the cookie bite case, we see it as a bitten cookie but not as a mixed, molded, and baked combination of flour, butter, chocolate, etc.).

However, people can push beyond the limitations of perceptual inferences through high-level reasoning. Given that both intuitive physics and intuitive psychology instantiate causal reasoning through Bayesian inference (Lake et al., 2017), so might the sociophysical interface. If so, then people should be able to make rational inferences about the events underlying a broad range of physical stimuli, and their judgments should be better predicted by a Bayesian model of reasoning than by models of alternative cognitive processes (e.g., associative learning). This is indeed the case. From simple inanimate traces (such as a small pile of cookie crumbs or an arrangement of blocks), people can reconstruct extended spatiotemporal sequences of actions that an agent took. These event reconstructions can be predicted with quantitative accuracy by a model that uses Bayesian inference to infer what goals would rationally produce some observed behavior, which would then give rise to the observed traces (Lopez-Brau et al., 2022). Critically, people's inferences could not be explained through narrow, associative cognitive mechanisms (i.e., simple heuristic models trained to predict the appropriate inference from superficial features of the stimuli).

In this way, event reconstruction supports what has been termed *intuitive archeology* (Hurwitz et al., 2019; Schachner et al., 2018), allowing even the untrained eye to infer complex aspects of the social past from the physical present. These event reconstructions then unlock a range of powerful inferences that help us understand others: The reconstructed actions reveal the agent's goal, the amount of skill required, the effort they put in, and even whether one or more people were involved (Fig. 3c; Gweon et al., 2017; Lopez-Brau et al., 2022; Yildirim et al., 2019). This broad collection of inferences that people can make—which could not be captured through simpler associative alternative accounts—lend further support to the idea that the integration of social and physical knowledge is Bayesian, helping us make rich inferences from small amounts of data.

Inferring the Causes Behind Behavior

If people can reconstruct what actions explain an observed physical trace, they should be able to reason about the causes behind behavior, as the

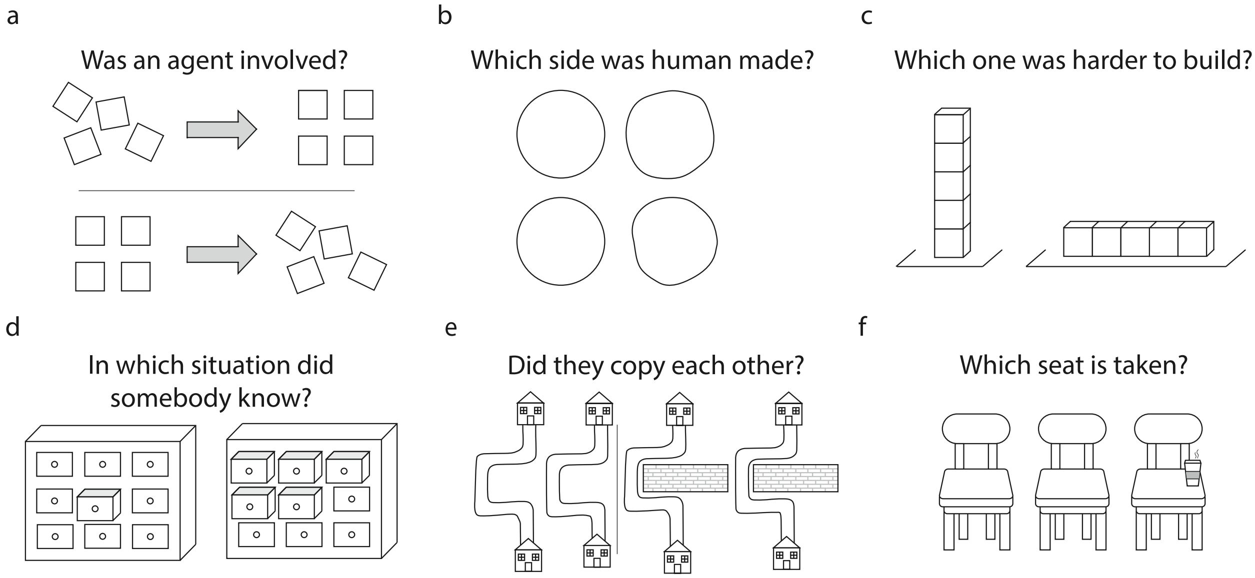

Fig. 3. Examples of social inferences we make from the physical world. (a) The creation of order is associated with agency, making the transition at the top reveal the presence of an agent more clearly compared with the transition at the bottom. (b) Imperfections, like the ones in the circles on the right side, can make objects seem handmade. (c) By inferring what actions were required to build two block towers, we can tell which one took more effort and time to build. (d) Traces of drawers left open reveal whether an agent knew where to find what they were looking for or not. (e) Inefficiencies help us detect copying and the transmission of ideas. The first pair suggests copying of track shape due to the preserved inefficiency, whereas the second pair does not because the physical constraint now makes the paths efficient. (f) Even small, easily movable objects can be used to mark spaces by communicating indirectly with others.

same inferences that people can draw from directly observable action ought to be available using the reconstructed actions. Indeed, even young children can use static images of physical displays—for example, a dresser with some drawers open and others closed (Fig. 3d)—to infer mental states, in a rational way that is well predicted by Bayesian causal inference. In this way, children use static scenes to rationally infer a person's goals (were they looking for something or just being playful?) and levels of knowledge (how certain were they of the location of the sought object—did they first not recall and then suddenly remember? Pelz et al., 2020).

Inferring the actions that shaped objects also allows people to intuit where the design ideas came from. From preschool age, people understand that artifact creation involves coming up with the design idea and physically making the object (Judge et al., 2020; Li et al., 2013). By reasoning about this causal process, children and adults can reason about where a design idea came from and whether it was original or copied (Hurwitz et al., 2019; Pesowski et al., 2020; Schachner et al., 2018). To detect copying, we do more than just look for similar appearance. Instead, we consider whether people's goals and constraints could lead them to arrive at similar designs independently. These judgments are quantitatively better predicted by a model of Bayesian causal inference than simpler processes, like similarity detection. For example, Bayesian inference explains why two identical designs provide stronger evidence of copying when they are inefficient (Fig. 3e, left pair) than when they are efficient (Fig. 3e, right pair): Since people generally prefer efficient designs, it is a more suspicious coincidence when they create the same inefficient design (Pesowski et al., 2020; Schachner et al., 2018). This capacity to detect transmission of ideas may allow us to trace sociocultural history, inferring who has had contact with whom from "suspicious similarities" in the artifacts they create or know about. In this way, children use knowledge of culturally specific artifacts, like food and musical instruments (but not general world knowledge), to infer others' social affiliations and cultural groups (Öner & Soley, 2023).

With this sociophysical interface in place, people can not only extract rich social information from the environment; we expect others to do the same and exploit this to create more complex forms of social behavior. If you expect other people to read social information from the physical world, then you can purposefully embed social information in the objects around you and expect that others will extract it. This allows people to use objects as social signals. We display objects in our homes or offices to show our identity (Gosling et al., 2002; Wheeler & Bechler, 2021) and engage in conspicuous consumption, for example, of luxury goods, in order to send targeted messages (Wang &

Griskevicius, 2014). Our expectation that others will read social information from objects also provides a foundation for communicative behaviors, like placing a small, easily movable item to assert that a seat is taken (Fig. 3f; Sommer & Becker, 1969); to mark ownership (e.g., Gelman et al., 2012); or to prevent people from taking a certain path (Lopez-Brau et al., 2023). In all of these cases, the objects placed do not physically block people. Instead, they work because they lead people to make an inference through event reconstruction—that the object has been placed there intentionally to communicate that the seat or path is unavailable. Critically, this inference does not always involve slow, complex reasoning. After inferring the implication of an object via Bayesian inference, people can store the result as a simple object-meaning association, allowing people to bypass complex, high-level reasoning in subsequent encounters with that inanimate cue (Lopez-Brau et al., 2023). Overall, this ability powerfully expands the bounds of the social domain, allowing the physical world to serve as a rich source of social information that humans intuitively both write and read.

Looking Forward

What are the implications of this capacity? Cognitive scientists often conceptualize physical and social reasoning as distinct systems of knowledge that are informationally encapsulated: one for processing physical events, forces, and inanimate objects and one for processing actions, mental states, and animate agents (Spelke, 2022). In contrast, the studies reviewed here suggest that the two systems are deeply integrated—much more than previously thought (see also Liu et al., 2024). From physical traces alone, people infer the involvement of agents, reconstruct their behavior, and infer their mental states and traits. This means that social cognition is deployed to reason about not only agents' faces, voices, bodies, and actions but also inanimate things, like tools, toys, and technology. Although we have focused primarily on visual input, this reasoning may extend to other modalities as well, for example, to explain the activation of social areas by instrumental music (Steinbeis & Koelsch, 2009). Overall, this provides a new framework for understanding the nature of human social intelligence. Our ability to quickly and seamlessly read social information from the physical environment allows us to refine our social expectations of others even before direct personal interaction begins.

Here we focused on how integrating naive physics and naive psychology helps us extract social information from the physical world and how this reasoning is further supported by simpler associations. One open question is the extent to which this should all be thought of as a unified system or as multiple independent (but interconnected) processes. Given the literature we reviewed, it might be tempting to think of the lower-level processes as cue-based implementations of high-level reasoning (e.g., detecting small errors perceptually is, in most cases, a fast way to accomplish the same conclusions we would draw through high-level causal reasoning). However, such an account fails to explain why people also attach social significance to the physical world in ways that are not captured entirely by our naive physics and our naive psychology. For example, people believe objects become tainted by emotional and moral qualities of previous owners (Gelman & Echelbarger, 2019; Marchak et al., 2020).

A related open question is how the interaction between naive physics and naive psychology is instantiated at an algorithmic level. The simplest possibility would be that the two systems act independently and interface only through representations of action. This would be a natural way for the two naive theories to communicate, because both naive theories seem to already have representations of action (in naive psychology as the output of mental states and in naive physics as an input to generate forces with causal power). In this view, naive physics would reconstruct the actions—or a collection of hypotheses about events—and transfer them to naive psychology to infer which movements were intentional and other underlying mental states. However, this initial view would also predict that people have some latent action representation any and every time the two systems interact. This is unlikely to be the case, given that people can directly associate observable physical outcomes with abstract social attributions in ways that do not appear to require representing the exact actions someone took (e.g., attributing the trait of "disorganized" to someone upon seeing their messy room; Gosling et al., 2002). Understanding the particular (and perhaps multiple) ways in which these systems interact to create the sociophysical interface is an important question for future work.

To what extent is the capacity to read social information from the physical world shared with other animals? On the one hand, insects coordinate through traces on the physical world (e.g., ant pheromone trails), a capacity known as stigmery. Predators can track prey through visual and olfactory traces left behind (although many rely on direct detection of smell traces; Lima, 2002), and bowerbirds attract mates through ornate physical structures (Madden, 2008). However, it is unclear whether these capacities involve a flexible system of reasoning similar to the one established in humans or whether they constitute only narrow and specialized forms of reasoning that do not require high-level cognition (for a related discussion with nonhuman primates, see Cheney & Seyfarth, 2019, pp. 128–129). This comparative domain opens an exciting area of research for future work, characterizing the multiple kinds of cognitive systems that allow different species to read social information from the physical world not only through vision but through other senses such as olfaction (Yong, 2022).

What is clear is that the ability to infer social information from the physical world comes naturally to humans. The social and physical worlds are deeply intertwined, and our mental representations of the world reflect this reality. The human physical world is brimming with information about others' actions, goals, ideas, and social identities. The ability to read this social information may serve as important glue in social interaction, allowing individuals to smoothly navigate the social environment by identifying social partners, inferring past actions of others as context for social interactions, and appropriately responding to communicative signals. Understanding this reasoning provides a key to understanding the complex, nuanced, and real-time social reasoning characteristic of human interaction and social intelligence.

Recommended Reading

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Transparency

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