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Cue Integration: A Common Framework for Social Cognition and Physical Perception

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Abstract

Scientists examining how people understand other minds have long thought that this task must be something like how people perceive the physical world. This comparison has proven to be deeply generative, as models of physical perception and social cognition have evolved in parallel. In this article, I propose extending this classic analogy in a new direction by proposing cue integration as a common feature of social cognition and physical perception. When encountering complex social cues—which happens often—perceivers use multiple processes for understanding others' minds. Like physical senses (e.g., vision or audition), social cognitive processes have often been studied as though they operate in relative isolation. In the domain of physical perception, this assumption has broken down, following evidence that perception is instead characterized by pervasive integration of multisensory information. Such integration is, in turn, elegantly described by Bayesian inferential models. By adopting a similar cue integration framework, researchers can similarly understand and formally model the ways that we perceive others' minds based on complex social information.

Keywords

social cognition, perception, cue integration, inference

Imagine encountering a person who is sobbing uncontrollably. Almost immediately, her furrowed brow and convulsive breathing render you tense and sad, and you infer that she is miserable. Now imagine learning that this person has just won an Olympic gold medal. Your inference now shifts dramatically, to a belief that she is instead thrilled.

How do we draw such rapid, flexible inferences about others' internal states based on complex social cues? Intuitively, this sounds like another task people face constantly: translating a barrage of sensory information into a coherent understanding of the physical world. As it turns out, comparisons between social and physical perception are not new. In fact, this analogy tracks the modern study of social cognition.

In this article, I will describe how this comparison can be harnessed to model inferences about complex social cues: a domain of social cognition that has often escaped programmatic research. I will suggest that such inferences resemble multimodal physical perception, in which perceivers bring together sounds, sights, and other sensory signals into unified percepts. Specifically, across both physical and social domains, understanding complex cues requires the integration of multiple information processing streams. As such, a *cue integration framework*, already established in the physical perception research, can provide new directions for the study of social cognition and, in turn, highlight Bayesian models that can fruitfully describe complex social cognition in tractable and formal terms. However, before describing the future of the classic analogy between social cognition and physical perception, it is worth thinking about its past and, in particular, about other common ideas that have shaped research and theory across physical and social domains.

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Two Parallel Shifts Across Social and Physical Domains

From objectivity to subjectivity

Until the second half of the 20th century, scientists generally believed that people processed sensory information objectively. Percepts were thought of as faithful representations of the world outside: chirping, yellow light, and heat related in lawful ways to the canaries and candles that produced them. The goal for researchers, then, was to divine the laws relating objects and events to the signals people received from them (Titchener, 1915). Within this framework, social targets (i.e., other people) were unruly objects, whose intentions, feelings, and traits were transmitted noisily through observable behaviors (Brunswik, 1947). In this view, social perception was simply a version of physical perception with two degrees of separation between targets' minds and perceivers' eyeballs (Ittleson & Slack, 1958; Tagiuri, Blake, & Bruner, 1953). Social psychologists examined how this transmission occurred (Boring & Titchener, 1923; Darwin, 1872; Heider, 1944), cataloguing the facial positions, sounds, and actions that signaled particular states. Another line of inquiry focused on how insightfully perceivers picked up on these signals—a social analogue to visual acuity (Dymond, 1949; Taft, 1955).

All of this changed in the 1950s, when the objectivist view of perception was replaced by something quite different. Much of this change occurred within a single year, spurred by the work of a few key scientists. In 1957, Jerome Bruner wrote a paper (Bruner, 1957b) that served to unite his and others' work (Bruner & Goodman, 1947; Pepitone, 1950; Postman, Bruner, & McGinnies, 1948) with earlier Gestalt theory (Koffka, 1935; Wittgenstein, 1945/1980) and make a simple, profound point. Perceivers were not the passive information receptacles for whom they had been taken. Instead, they played an active hand in constructing their impressions of the world around them. Perception, in essence, boiled down to deciding how to slot sensory signals into categories.

Bruner asked readers to consider the humble apple. How red, round, and shiny does an object have to be for perceivers to decide that it fits into the category of apples? As it turned out, this simple question has no simple answer. Instead, one's "apple perception threshold" is affected by myriad factors: A perceiver will lower their threshold if they are hungry (motivated perception), have just read a list of fruits (informational accessibility), and so forth. In making this point, Bruner brought coherence to the "new look" movement (Bruner, 1992), which rejected the objective view and rebranded perception as constructive, thus setting the stage for modern cognitive psychology (Neisser, 1967) and contemporary approaches to perception (Balcetis & Lassiter, 2010).

In the same year, Bruner—along with Renato Tagiuri—co-organized a gathering that similarly redefined social cognition (Tagiuri, 1958). At this gathering, researchers including Solomon Asch, Fritz Heider, and Lee Cronbach synthesized work they had been conducting over the previous decade (Bruner & Tagiuri, 1954; Cronbach, 1955; Gage & Cronbach, 1955; Heider, 1944) that struck a chord similar to Bruner's points about physical perception. Minds were no simpler than apples, and perceivers' judgments about others' states and traits were not fixed by the cues that the target gave off. Instead, these cues were actively interpreted by perceivers in light of their prior experiences (Asch, 1952; Higgins, Rholes, & Jones, 1977), their assumptions about a given target (Hebb, 1946), and so forth. Nathaniel Gage and Cronbach (1955) made this point directly, claiming that social cognition ". . . is a process dominated far more by what the Judge brings to it than by what he takes in during it" (p. 420). This account has guided social cognition research ever since (Epley & Waytz, 2009; Fiske, 1992; Fiske, 1993; Fiske & Taylor, 2007; Gilbert, 1998; Higgins & Bargh, 1987; Jones, 1990; Zaki & Ochsner, 2011b).

The events of 1957 bring into focus deep parallels between physical perception and social cognition research traditions. The shifts that occurred across these two domains were nearly isomorphic. In both cases, researchers labored for decades under a strong, intuitive, and incorrect assumption that perception was objective. In both cases, a small group of researchers overturned this assumption by demonstrating that biases, motivations, and the like play as much—if not more—of a role in shaping perception than the "stuff out there." And in both cases, these demonstrations were synthesized into elegant models of perception as an interpretive act. Further, this common shift from objective to subjective models marked a key moment in the history of both social and physical perception research and ushered in a central focus on cognition in both domains (Bruner, 1957a). In other words, the analogy between social and physical experience, and the crosstalk it produced between research domains, supported a central advance in 20th century experimental psychology.

From isolationism to integration

More recent decades have witnessed another common shift across physical and social research domains: Whereas early work on the perception of isolated cues suggested that physical and social "processing streams" operated with relative independence, this view has steadily broken down over time. Newer work focusing

on the perception of complex, naturalistic cues has demonstrated that perception is better defined by the pervasive integration of multiple cues and processing streams. This framework has taken firm hold in physical perception research and is steadily gaining ground in social cognition as well. I now describe the shift toward integration in each of these domains, as well as parallelisms between them.

Unimodality to multimodality in the physical domain. Early physical perception research tended toward a "divide and conquer" strategy focusing on the workings of single senses in isolation. This approach reflected the sensible intuition that senses are dissociable. Vision, audition, olfaction, and so forth process fundamentally different inputs (photons, sound waves, and chemicals) and often operate in different contexts. You likely rely on vision to navigate through your bedroom in the morning but rely more on your tactile abilities to fumble back to bed after a midnight snack. Neuroscientific evidence provided even stronger support for sensory isolation by demonstrating that dedicated, and perhaps even modular (Fodor, 1983), physiological "processing streams" handled information from single sensory modalities (Hubel & Wiesel, 1962; Reale & Imig, 1980; Romani, Williamson, & Kaufman, 1982) and appeared to interact with each other only later in processing (Felleman & Van Essen, 1991; Mesulam, 1998). These data suggested that perception operated somewhat like a car factory: Its elements, like carburetors and transmissions, were constructed independently, and only assembled after each part was completed.

As it turned out, this car factory model may have reflected scientists' methodological choices as opposed to any deeper insight about how senses operate. Broadly, researchers' choices about how to study a phenomenon fundamentally shape their conclusions about that phenomenon's characteristics. For instance, early "isolationist" paradigms may tempt researchers to assume that because senses respond independently to unimodal cues, this independence must also characterize more complex perception. To the extent that these laboratory paradigms fail to scale up to messier, real world contexts, a divide and conquer approach can produce misleading signs about how perception works (Neisser, 1976; Rozin, 2001).

As researchers began adopting more naturalistic paradigms in which perceivers encounter multimodal, as opposed to unimodal, cues, this concern was borne out. Mounting evidence from such work suggested that interactions between senses were not late add-ons to perception but that they instead pervaded most, if not all, perceptual experience. In fact, the more that scientists looked for the operation of single senses in isolation, the less they found. This was especially striking in the domain

of neuroscience: brain regions—including the primary auditory and visual cortex—originally thought to process information from one modality were consistently caught responding to others (Calvert et al., 1997; Falchier, Clavagnier, Barone, & Kennedy, 2002; Kayser, Petkov, Augath, & Logothetis, 2005; Kayser, Petkov, & Logothetis, 2008; Macaluso, Frith, & Driver, 2000; Stein & Meredith, 1993). The car factory model could not account for this surprising sensory promiscuity, and it soon gave way to a new view of perception being multimodal from even its earliest stages (Calvert, 2001; De Gelder & Bertelson, 2003; Ghazanfar & Schroeder, 2006; Stein & Meredith, 1993).

Parallels between senses and social cognitive processes. Like multimodal perception, social cognition is relentlessly complex. Our judgments about others' minds depend on multiple, interactive cues (e.g., crying, gold medals) arising from multiple sources (e.g., a target's sensorimotor cues, contextual information about her situation). Also like physical perception, social cognition appears to rely on multiple, separable processes. For example, perceivers can stereotype social targets (Devine, 1989; Quadflieg et al., 2009), project their own beliefs and knowledge onto targets (Gilovich, Medvec, & Savitsky, 2000; Ross, Greene, & House, 1977), or explicitly take the perspective of targets (Keysar, Barr, Balin, & Brauner, 2000; Leslie, Friedman, & German, 2004; H. M. Wellman, Cross, & Watson, 2001).

Although it is tempting to nominate these processes as social analogues of the physical senses, such comparisons fail on several levels. First, the same social cue (e.g., another person's action) can serve as material for multiple social cognitive processes (e.g., stereotyping or self-projection) depending on the context (Ames, 2004). By contrast, try as we might, the vast majority of us who are nonsynesthetes (Simner et al., 2006) cannot process light through any sense other than vision. Second, physical senses operate at a "lower level" than social cognitive processes, in that social cognition often integrates over sensory information (e.g., visual or auditory cues about a social target; Gallese, 2007; Niedenthal, Barsalou, Ric, & Krauth-Gruber, 2005). Third, social cognition appears to rely, at least partially, on computations not shared with nonsocial cognition (J. P. Mitchell, 2009b; Ostrom, 1984), further muddying the relationship between these domains.

Thus, my goal is not to tighten the analogy between senses and social cognitive processes. Instead, I hope to draw out a broader parallel: an early focus on simplified paradigms across both of these domains fostered isolationist models of perception that are now untenable given evidence from naturalistic experimental approaches. This broad historical shift, like the earlier shift from

objective to subjective models of perception, hints at a common framework for studying complex physical perception and social cognition: In both of these domains, perceivers' central goal is not deciphering isolated cues, but rather integrating many cues and information processing streams.

Shifts from isolationist to integrative social cognition. Like early data on physical perception, initial evidence in the social domain suggested that social cognitive processes operated in relative isolation. Consider two such processes: experience sharing and mentalizing.[1] *Experience sharing* describes perceivers' tendency to vicariously take on social targets' internal states, facial expressions, and postures (Chartrand & Bargh, 1999; Dimberg, Thunberg, & Elmehed, 2000; Hess & Blairy, 2001; Iacoboni, 2009; Neumann & Strack, 2000; Niedenthal et al., 2005; Stel & van Knippenberg, 2008). *Mentalizing* refers to perceivers' ability to reason explicitly about targets' likely states based on goals, intentions, and behaviors (Baron-Cohen, Leslie, & Frith, 1985; Gopnik & Wellman, 1992; Leslie et al., 2004; J. P. Mitchell, 2009a; Premack & Woodruff, 1978).

Early work suggested that mentalizing and experience sharing were anatomically and functionally distinct. Anatomically, the systems of brain regions engaged by each process are almost totally nonoverlapping (Fig. 1; van Overwalle & Baetens, 2009; Zaki & Ochsner, 2012): Whereas experience sharing causes perceivers to engage structures associated with targets' sensorimotor, visceral, and affective states (Iacoboni, 2005; Keysers & Gazzola, 2009; Lamm & Singer, 2010; Rizzolatti & Sinigaglia, 2010; Zaki, Davis, & Ochsner, 2012), mentalizing engages cortical regions associated with various forms of self-projection, including prospection, autobiographical memory, and

counterfactual reasoning (Buckner & Carroll, 2007; J. P. Mitchell, 2009b; Saxe, 2006; Saxe, Carey, & Kanwisher, 2004; Spreng, Mar, & Kim, 2009). Further, damage to each system produces specific deficits in either experience sharing or mentalizing (Fernandez-Duque, Hodges, Baird, & Black, 2010; Shamay-Tsoory, Aharon-Peretz, & Perry, 2009; Shamay-Tsoory, Tomer, Goldsher, Berger, & Aharon-Peretz, 2004).

These neuroscientific data suggest a second, functional dissociation: Mentalizing and experience sharing appear "tuned" toward different types of cues. Whereas brain regions associated with experience sharing respond to cues about targets' sensorimotor states (such as facial expressions or actions), regions involved in mentalizing are preferentially engaged by contextual cues describing the sources of those states (Gobbini, Koralek, Bryan, Montgomery, & Haxby, 2007; Spunt, Falk, & Lieberman, 2010; Spunt & Lieberman, 2012; Wheatley, Milleville, & Martin, 2007). For example, upon seeing a target crying, perceivers may engage in experience sharing, allowing them to access the targets' sensory and visceral experience. By contrast, learning that the target won a medal might cause perceivers to mentalize about the target's states vis-à-vis knowledge about that context (e.g., winning gold medals typically makes people happy).

These data supported the idea that mentalizing and experience sharing make relatively independent contributions to perceivers' social inferences. This "isolationist" view is highlighted, for instance, by a longstanding debate as to whether experience sharing or mentalizing primarily supports perceivers' social cognitive abilities (Apperly, 2008; Gallese, 2007; Gallese, Keysers, & Rizzolatti, 2004; Goldman, 2006; Gopnik & Wellman, 1992; Heal, 1996; Saxe, 2005). However, like the car factory models in the physical domain, isolationist
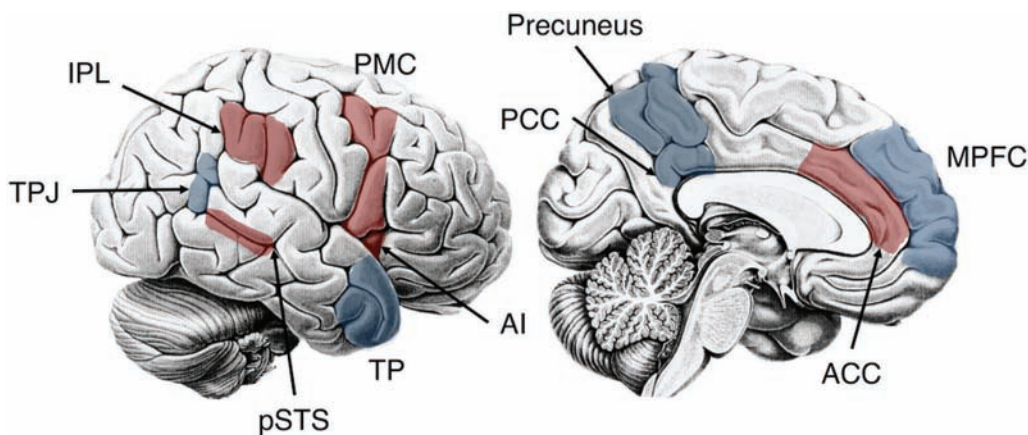

Fig. 1. Brain regions involved in experience sharing (red) and mentalizing (blue). IPL = inferior parietal lobule, TPJ = temporoparietal junction, pSTS = posterior superior temporal sulcus, TP = temporal pole, AI = anterior insula, PMC = premotor cortex, PCC = posterior cingulate cortex, ACC = anterior cingulate cortex, and MPFC = medial prefrontal cortex. Image adapted from *The Human Central Nervous System: A Synopsis and Atlas*, by R. Nieuwenhuys, J. Voogd, and C. van Huijzen. (2007, New York, NY: Springer)

models of social cognition might reflect quirks in how social cognition has been studied as opposed to how it actually operates (McArthur & Baron, 1983; Mook, 1983; Neisser, 1980; Rozin, 2001). This is because early research on social cognitive processes tended to employ highly controlled, nonnaturalistic cues and paradigms.[2] For example, studies of experience sharing typically exposed perceivers to simplified, context-free sensorimotor cues (e.g., pictures of actors posing emotional facial expressions or hands being pierced by syringes) and rarely involved any explicit inference about targets' internal states. By contrast, studies of mentalizing typically required perceivers to draw such inferences based on contextual stimuli (e.g., vignettes describing the sources of targets' false beliefs). In other words, researchers often employ paradigms that are optimized to each process, and it should come as no surprise that perceivers respond by deploying only the process called on by the experimental setting.

Although powerful (Epley & Waytz, 2009; Gilbert, 1998; Zaki & Ochsner, 2012), this approach—like paradigms employing only unimodal physical cues—ignores situations in which social cognitive processes might interact. Life is full of such situations. Like the crying gold medalist, social targets often produce noisy (subtle or ambiguous) and bundled (concurrent) social cues. As such, a perceiver's interpretation of one social cue is often constrained or altered by other cues in the environment (Barrett, Mesquita, & Gendron, 2011; Carroll & Russell, 1996; Ethofer, Pourtois, & Wildgruber, 2006; Gendron, Lindquist, Barsalou, & Barrett, 2012; Russell, Bachorowski, & Fernandez-Dols, 2003). This complexity renders an isolationist view of social cognition unappealing—a perceiver's best chance of understanding complex social cues derives not from processing single cues but rather through integrating all available information, likely using a combination of experience sharing, mentalizing, and other processes (Zaki & Ochsner, 2009, 2012).

Newer paradigms combining sensorimotor and contextual cues consistently favor this integrative view. For instance, systems of brain regions associated with mentalizing and experience sharing are coactivated by complex social cues, such as videos of targets initiating joint attention (e.g., by making eye contact with perceivers; Redcay et al., 2010), expressing emotions (Spunt & Lieberman, 2012; Zaki, Weber, Bolger, & Ochsner, 2009), or executing motor actions (de Lange, Spronk, Willems, Toni, & Bekkering, 2008; Spunt, Falk, et al., 2010; Spunt, Satpute, & Lieberman, 2010), contradicting prior data suggesting that these neural systems were independent. These data, along with other work (see below), suggest that isolationist models fail to describe the lion's share of "real-world" social cognition.

Cue Integration as a Common Framework

A growing focus on complexity and realism suggests a new direction for the analogy between physical perception and social cognition: Both represent difficult, noisy tasks that require flexibly employing multiple processes. In this section, I propose that *cue integration*—the interaction between multiple environmental signals and information processing streams—is a key feature of both multimodal physical perception and complex social cognition. Cue integration has already been adopted as a central principle in physical perception research (Ernst & Bulthoff, 2004). As such, insights from this domain can provide a new roadmap for social cognition research and suggest avenues for formally modeling complex social cognition by plugging into parallel traditions in physical perception research.

Cue integration in the physical domain

I've described two major, counterintuitive realizations that shaped the science of perception: There are neither clean connections between our minds and the world outside nor any bright lines dividing senses from one another. These insights may appear to boil perception down into an undifferentiated multisensory goulash. However, physical perception research has avoided confusion in the face of complexity, by adopting elegant formal models to characterize interactions between the senses.

Often, these models adopt a Bayesian approach (Adelson & Pentland, 1996; Ernst & Bulthoff, 2004; Green & Swets, 1966; Kersten, Mamassian, & Yuille, 2004; Knill & Richards, 1996), which posits that objects and events produce perceptual cues with *conditional probabilities*. For example, a fire engine will produce the perception of the color red and a siren sounding, each with a given probability—for example, the probability of seeing red given a fire engine or P(red|engine). In the Bayesian view, perceivers integrate these probabilities with their prior knowledge—for example, how generally likely it is to see a fire engine, or P(engine)—to infer how likely it is that a fire engine is indeed nearby given what they have perceived, P(engine|red,siren). Perceivers' likelihood of drawing this inference is proportional to the probabilities connecting the thing out there (in this case, a fire engine) to the sights and sounds they have encountered:

$$P(engine|red,siren) \propto P(red|engine) * P(siren|engine) * P(engine)$$

Such models offer an impressive fit for data on multimodal perceptual judgments and an impressive view of perceivers, whose judgments often integrate multiple cues in a near-optimal fashion (Alais & Burr, 2004; Ernst & Banks, 2002).

Social cue integration

A similar framework can easily be applied to the social domain. Much like physical cues, social cues arise from targets' internal states with certain conditional probabilities: If the target is happy, it is improbable that she will cry—thus, P(crying|happy) is low. The causal direction connecting internal states to social cues can also be reversed, especially in the case of contextual cues; for example, whereas happiness alone does not cause people to win gold medals, winning gold medals often produces happiness such that P(happy|medal) is high. Thus, a perceiver's likelihood of inferring that the our crying medalist is happy is proportional to these probabilities, along with the overall likelihood that people are happy—P(happy):

$$P(happy|crying, medal) \propto P(crying|happy) * P(happy|medal) * P(happy)$$

As the high probability of happiness given a medal overwhelms the low probability of crying given happiness, the perceiver would likely infer that the target in fact feels positively. Critically, a cue integration approach posits that, like a perceiver integrating over vision and audition when encountering multimodal cues, perceivers might employ multiple cognitive processes to infer conditional probabilities in the social domain. For example, experience sharing could support inferences over sensorimotor cues—here, P(crying|happy)—whereas mentalizing could support inferences over contextual cues—here, P(happy|medal) (Fig. 2).

Over the decades, social psychologists have proposed Bayesian models of trait attribution (Ajzen & Fishbein, 1975; Griffiths, 2001), stereotyping (McCauley, Stitt, & Segal, 1980), and action understanding (Baker, Saxe, & Tenenbaum, 2009; Goodman et al., 2006; Ullman et al., 2009), along with allied approaches to capture other aspects of social inference (Bahrami et al., 2010; Behrens, Hunt, & Rushworth, 2009; Freeman & Ambady, 2011; Kunda & Thagard, 1996; Shafto, Goodman, & Frank, 2012).[3] In fact, several classic theories of attribution (Heider, 1958; Jones, 1990; Kelley, 1973) exemplify this approach, suggesting that perceivers form beliefs about targets' traits based on their behaviors (e.g., a person cowering in the corner of a crowded room might be dispositionally anxious), but only to the extent that these behaviors imply such traits with a high conditional probability (e.g., this person is at a cocktail party, not at a bank that is being robbed).

Given that Bayesian logic has inhabited social psychology's research landscape for so long, it is surprising
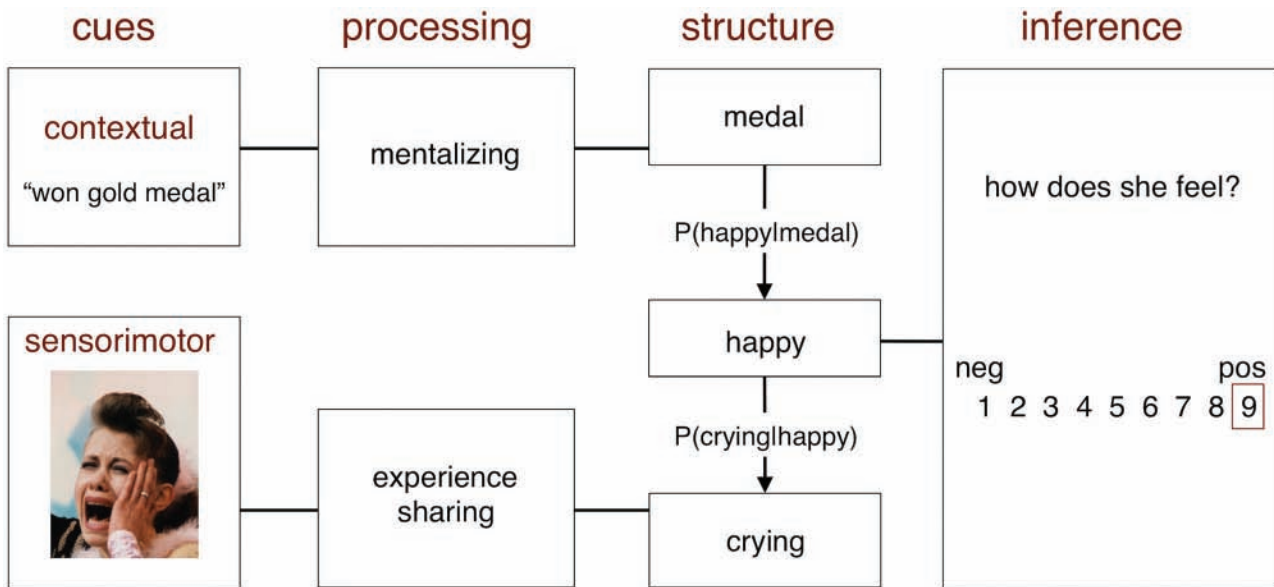

Fig. 2. Schematic representation of complex social cognition as cue integration. Multiple social cues (sensorimotor and contextual) present conflicting information about the target's likely internal state. These cues are processed through experience sharing and mentalizing, respectively. Perceivers then apply Bayesian inference to estimate the likelihood that a target would cry given that she is happy and that a target would be happy given that she won a gold medal. These probabilities feed into a final inference about the target's internal state. In this example, contextual information is more reliably tied to the internal state of interest than sensorimotor information (that is, medaling is less ambiguous than crying in its relationship to happiness); as such, the perceiver's final percept is biased toward the contextual cue.

how little attention it garners; mainline social cognition and social neuroscience research rarely adopts this approach. Why might this be? One intuition is that social cues are simply too unruly to fit into such a framework. In the physical domain, researchers can tractably manipulate the extent to which a cue (e.g., a pattern of light) implies the presence of a stimulus (e.g., an object with a particular texture), because phenomena like light and texture can be easily quantified. In other words, the things "out there" can be controlled, allowing researchers to characterize perceivers' decision processes. By contrast, internal states are much more slippery: Emotional experiences, for example, are complex and contextually constructed (Barrett, 2009; Barrett, Mesquita, Ochsner, & Gross, 2007), and the cues we might use to isolate emotions (e.g., self-report, facial expressions, levels of physiological arousal, and so forth) often fail to cohere (Barrett, 2006; Mauss, Levenson, McCarter, Wilhelm, & Gross, 2005; Mauss & Robinson, 2009). Without knowing for sure how to quantify the thing out there (in this case, a target's internal state), researchers' ability to formally model perceivers' judgments about that thing appears necessarily dubious.

However, as we saw above, Bayesian models do not require any *a priori* definition of the things out there; instead, this approach rests on quantifying two phenomena: a stimulus and a perceiver's judgment. Bayesian modeling of social cognition in no way requires researchers to know whether a target's crying actually means that she feels happy; they merely need to track the conditional probability with which perceivers believe that a target's state (e.g., happiness) produces a particular social cue (e.g., crying). Thus, the "fuzziness" of these cues need not be a barrier to modeling social inference.

In fact, this type of modeling will be especially vital to understanding naturalistic social cognition, which—like multimodal perception—relies on the integration of multiple cues and processes. Although researchers have described interactions between processes such as experience sharing and mentalizing in qualitative terms (Decety, 2011; C. D. Frith & Frith, 2012; Keysers & Gazzola, 2007; Shamay-Tsoory, 2010; Singer, 2006; Uddin, Iacoboni, Lange, & Keenan, 2007; Waytz & Mitchell, 2011; Zaki & Ochsner, 2012), systematizing our understanding of complex social cognition requires tractable, quantitative theoretical models of perceivers' inferences in this domain. Cue integration can serve as a plausible framework under which to develop such models.

Examples of social cue integration

I will now focus on two situations in which physical and social perceivers encounter complex cues. In both cases, I will describe parallels between perceivers' engagement of senses in the physical domain and cognitive processes in the social domain, and discuss the meaning of such parallels for building Bayesian models of social cognition.

Conflicts between cues. In the physical domain, cues from different modalities often conflict in ways that alter perceivers' judgments (McGurk & MacDonald, 1976; Stein & Meredith, 1993). For example, a slew of "ventriloquist effects" demonstrate that inferences about where a sound originates are affected by simultaneous but conflicting visual cues (Howard & Templeton, 1966; Rock & Victor, 1964) and that visual inferences are similarly affected by auditory and tactile cues (Graybiel, 1952; McGurk & MacDonald, 1976; Sekuler, Sekuler, & Lau, 1997; Stein, Meredith, Huneycutt, & McDade, 1989). Neurally, these effects are supported by feedback loops that alter processing in low-level sensory cortex based on a perceiver's expectations (Beauchamp, Nath, & Pasalar, 2010; Bushara et al., 2003; Driver & Spence, 2000; Skipper, van Wassenhove, Nusbaum, & Small, 2007), and they likely drive the top-down influences on perception Bruner described half a century ago.

Bayesian cue integration offers strong predictions about how perceivers should handle such conflicts. For example, consider a situation in which you see one thing but hear another—which cue should you trust? This depends on how reliable you believe each cue to be at that moment. If you are in the dark, vision will be less reliable than hearing, but if you are in a noisy room, hearing will be less reliable than vision. In Bayesian terms, reliability reflects the conditional probability with which a given sensory experience (e.g., a sight or sound) predicts the presence of a stimulus. Critically, perceivers are "lay Bayesians," in that they tightly follow these principles when making judgments. In the presence of conflicting multimodal cues, inferences are highly tuned to each cue's likely reliability (Alais & Burr, 2004; De Gelder & Bertelson, 2003; Rock & Victor, 1964; Shams, Kamitani, & Shimojo, 2000; Welch & Warren, 1980). Moreover, the reliability of a given cue (e.g., a visual signal) tracks activity in neural structures involved in processing that cue type (e.g., visual cortex; Ernst & Bulthoff, 2004). In other words, perceivers engage a given sense to the extent that information from that modality is likely to be useful in their current context.

Similar conflicts often arise in the social domain: A perceiver faced with incongruent social cues, such as a happy face paired with a sad voice, might draw inferences about a target's state (perhaps deciding that the target is embarrassed) that are not consistent with any one cue in isolation (De Gelder & Vroomen, 2000; R. L. Mitchell, 2006; Wittfoth et al., 2009). It is interesting to note that when sensorimotor cues that typically engage

experience sharing (most often emotional facial expressions) conflict with contextual cues that typically engage mentalizing, perceivers often vastly alter their interpretation of one cue or the other (Aviezer et al., 2008; Carroll & Russell, 1996) (Fig. 3).

Recent evidence suggests that such interpretations might reflect Bayesian inferences about the reliability of particular cues and social cognitive processes. For example, when faced with our crying gold medal winner, a perceiver could infer that sensorimotor cues are highly reliable ("I don't care if she's won, she seems miserable"), or—more likely—he or she may deem contextual information to be more reliable ("She may look upset, but this is clearly the most thrilling moment of her life"). As it turns out, reliance on sensorimotor and contextual cues tracks activity in brain areas related to experience sharing and mentalizing, respectively (Zaki, Hennigan, Weber, & Ochsner, 2010), suggesting that perceivers may deploy social cognitive processes to the extent that each process is likely to provide reliable information about a target's state (Fig. 2).

Convergence between cues. Although cues from multiple sensory modalities sometimes conflict, they most often do not. This is helpful to perceivers, because convergence between cues increases sensory acuity: The sound of someone speaking at a noisy party may be difficult to parse on its own, but it becomes much easier to understand when paired with the sight of that person's lips moving (Stein & Meredith, 1993; Sumby & Pollack, 1954). Such "sharpening" of perception by converging cues reflects shifts in the activity of early sensory cortex, as well as engagement of multimodal "convergence zones" (Beauchamp, Argall, Bodurka, Duyn, & Martin, 2004; Kayser, Logothetis, & Panzeri, 2010). Further, inferences about converging multimodal cues appear to follow Bayesian logic (Ernst & Bulthoff, 2004; Ma, Zhou, Ross, Foxe, & Parra, 2009). For instance, perceivers will use sound or vision to decide what someone is saying—and engage brain regions used to process that modality—only to the extent that each converging sensory channel provides reliable information (Narain et al., 2003; Nath & Beauchamp, 2011; Olman, Ugurbil, Schrater, & Kersten, 2004).

Social cues similarly cohere more than they diverge; the vast majority of individuals who are now crying are not responding to gold medals but to much less positive events. Like multimodal convergence, consistent
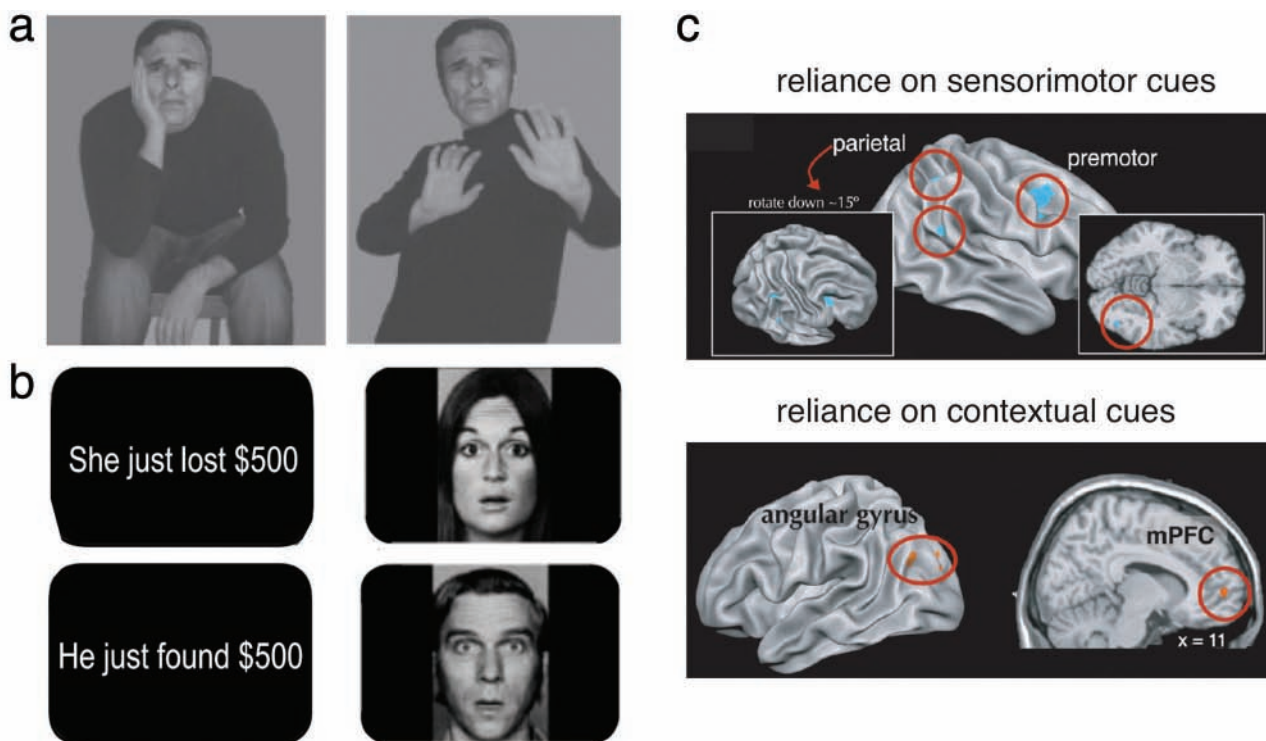

Fig. 3. Conflicts between social cues can produce "illusions" in which percepts of social targets do not faithfully represent any single cue. (a) Example of conflict between multiple sensorimotor cues—in this case, postural and facial (reprinted from Aviezer et al., 2008). (b) Example of conflict between contextual and sensorimotor cues (reprinted from Kim et al., 2004). (c) Inferences about such conflicting cues are accompanied by modulation of activity in related neural systems. For example, in a recent study, perceivers' reliance on sensorimotor cues in drawing inferences about targets' internal states tracked with engagement of brain areas associated with experience sharing, whereas their reliance on contextual cues tracked engagement in the medial prefrontal cortex, a region associated with mentalizing (reprinted from Zaki, Hennigan, Weber, & Ochsner, 2010).

information across sensorimotor and contextual channels sharpens perceivers' accuracy about targets (Dolan, Morris, & de Gelder, 2001; Gesn & Ickes, 1999; Hall & Schmid Mast, 2007; Zaki, Bolger, & Ochsner, 2008, 2009) and increases interpersonal rapport (Butler et al., 2003; Butler, Lee, & Gross, 2007). Neurally, such effects produce coactivation of, and functional coupling between, neural systems involved in experience sharing and mentalizing (Lombardo et al., 2010; Stephens, Silbert, & Hasson, 2010; Zaki & Ochsner, 2011b; Zaki, Ochsner, Hanelin, Wager, & Mackey, 2007; Zaki, Weber, et al., 2009). In other words, convergence between cues likely improves social inference through interactions between multiple social cognitive processes.

Do judgments about converging social cues reflect Bayesian inferences about each cue's reliability? Research has yet to directly address this question. However, at least some evidence suggests that perceivers employ social cognitive processes only to the extent that they are likely to be informative. Consider a perceiver who observes an anesthetized target receiving what looks like a painful injection. In this case, the perceiver's own response to the painful-seeming sensorimotor cue is irrelevant to understanding how this target feels, rendering experience sharing a relatively uninformative process. It is interesting to note that brain activity in such situations shifts away from systems involved in experience sharing and toward regions involved in mentalizing (Aziz-Zadeh, Sheng, Liew, & Damasio, 2012; Calvo-Merino, Glaser, Grezes, Passingham, & Haggard, 2005; Lamm, Meltzoff, & Decety, 2010), suggesting that the perceivers' information processing is sensitive to these conditional probabilities.

Applications of a social cue integration framework

Parallels between multimodal perception and complex social cognition are provocative, but the data supporting these parallels are preliminary. A cue integration framework offers hints about how to flesh out models of social cognition by adopting the tools used to build similar models of physical perception. Such models can foster powerful advances in scientists' understanding of complex social cognition. In the following sections, we detail three examples of such applications.

Conditional probabilities change over time. Beliefs in the reliability of different cues are not created *de novo* each time we encounter a stimulus. Instead, perceivers build longstanding lay theories of how strongly cues predict a state of the world based on their learning history (Knowlton, Mangels, & Squire, 1996; Tenenbaum, Kemp, Griffiths, & Goodman, 2011; Weisswange, Rothkopf, Rodemann, & Triesch, 2011).

Social inference likely reflects similar patterns of learning. Some social cues predict targets' internal states with stable probabilities across time and space: A target who stubs her toe will likely feel less positively than she had the moment before, regardless of where she is. However, many probabilities shift across situations: A Red Sox home run predicts a high probability of positive affect among targets at a sports bar in Boston but not in Brooklyn. Moreover, perceivers learn to "tune" their beliefs about these probabilities over time.

Interpersonal familiarity exemplifies such learning. Upon first encountering a social target, a perceiver may have a template that describes how happiness is predicted by sensorimotor cues such as laughing (positively) and contextual cues such as being kicked in the jaw (negatively). However, some probabilities are idiosyncratic to particular targets: A socially anxious martial artist, for example, might laugh when she is nervous and not mind getting kicked as much as most people. Perceivers learn the "signatures" of particular targets' cue-state probabilities as they get to know them (Stinson & Ickes, 1992), but there is little information as to how this learning operates at the level of information processing. A cue integration framework offers tools for formally modeling this phenomenon. Consider a perceiver who repeatedly learns that his socially anxious friend fails to communicate affect through sensorimotor cues such as facial expressions (as, indeed, some targets do; see Ansfield, 2007; Gross, John, & Richards, 2000; Gross & Levenson, 1993, Zaki, Weber, & Ochsner, 2012). In this case, the conditional probability that this target's smile indicates positive affect—P(happy|laughing)—will decrease, and the perceiver might tend to deploy experience sharing less in the presence of that particular target. Testing such models can produce first steps toward a more formal understanding of learning and familiarity in social contexts (Behrens, Hunt, Woolrich, & Rushworth, 2008).

Rational use of probabilities can produce "irrational" judgment errors. Cue integration also brings new perspective to classic issues in social cognition. Consider illusions: As mentioned above, conflicting sensory cues often produce "illusions" such as the ventriloquist effect. These quirks in processing do not imply that the perceiver is doing anything wrong; instead, they reflect rational inferential rules applied to unusual inputs (Knill & Pouget, 2004; Weiss, Simoncelli, & Adelson, 2002).

Social perceivers also produce an array of famous inferential "errors" or demonstrably misguided social judgments (Epley, Keysar, Van Boven, & Gilovich, 2004; Gilbert & Malone, 1995; Gilovich et al., 2000; Jones & Harris, 1967; Ross & Nisbett, 1991). These errors could signal inadequacies of social cognition, but they more

likely parallel physical illusions as logical responses to unusual circumstances (Funder, 1987; Trope, 1986). A Bayesian approach can help to quantify the rational sources of classic social cognitive biases (see also Griffiths, 2001).

Consider the false consensus effect, a classic bias in which perceivers assume that others share their opinions, beliefs, and knowledge (e.g., a voter who opposes a foreign war assuming that the majority of other voters do as well; see Ross et al., 1977). As anyone who has mistakenly brought up politics at Thanksgiving can attest, assumed similarity can mislead perceivers. Does it typically do so? Let's imagine a perceiver who holds a liberal political opinion (or *LPO*) encountering a target. For the perceiver to use her own opinion as a basis for inferring the target's opinion, she must aggregate over a few pieces of information:

$$P(\text{target } LPO \mid \text{perceiver } LPO) \propto$$
$$P(\text{perceiver } LPO \mid \text{target } LPO) * P(\text{target } LPO)$$

The opinions of a randomly drawn target will not necessarily predict the perceiver's own—P(perceiver *LPO*|target *LPO*)—or be liberal—P(target *LPO*). If both of these probabilities approach chance levels, the perceiver's opinion says little about the target's likely view and it is a mistake to assume consensus. However, targets are rarely drawn randomly; instead, perceivers typically cluster with like-minded targets (Luo & Klohnen, 2005; McPherson, Smith-Lovin, & Cook, 2001; Sunstein, 2009). If a perceiver is liberal, this increases the base rate with which he or she can assume targets in his or her environment are also liberal—P(target *LPO*). In fact, assumed consensus in such contexts increases perceivers' accuracy about others' minds (Hoch, 1987; Neyer, Banse, & Asendorpf, 1999) and is not "false" after all.

More broadly, such models refine scientists' understanding of social inferential accuracy and biases. The acuity of social inferences is typically described in broad, qualitative terms: Perceivers diverge from perfectly rational judgment, but also from perfect ignorance about targets (Epley & Eyal, 2011; Zaki & Ochsner, 2011a, 2011b). Nevertheless, accurate and inaccurate social judgments alike necessarily rest on specific information processing components, including baseline assumptions about targets, assumed similarity, and so forth (Cronbach, 1955; Funder, 1995; Gage, Leavitt, & Cronbach, 1956; Gilbert & Malone, 1995; Kenny & Albright, 1987; Trope, 1986). How strong is each of these components in social judgment? How rational is the use of each one? These questions are only now being addressed, and only regarding some forms of social inference (Jussim, Stevens, & Salib, in press; West & Kenny, 2011). A cue integration framework can broaden and systematize our models of these mechanisms, and when they produce biased or accurate inferences.

Social impairments might reflect disordered cue integration. Finally, cue integration opens new vistas for understanding impaired social functioning—a central diagnostic feature of many conditions including autism spectrum disorders, psychopathy, borderline personality disorder, and schizophrenia (Blair, 2005; Flury, Ickes, & Schweinle, 2008; Harvey, Zaki, Lee, Ochsner, & Green, 2012)—using tractable, quantitative models. Consider a perceiver who meets a stranger in an unbearably hot New York City subway car. In attempting to understand whether this stranger feels contempt toward him, the perceiver must integrate over both the scowl on the target's face and the situation in which they met:

$$P(\text{contempt} \mid \text{scowl,heat}) \propto \frac{P(\text{scowl} \mid \text{contempt,heat}) * P(\text{contempt})}{P(\text{scowl} \mid \text{heat})}$$

City dwellers likely understand that crowded, sweltering public transportation offers many scowl-worthy experiences. If this is the case, then the target's facial expression may say less about their evaluation of the perceiver and more about their ability to sense temperature, pressure, and smell. In informational terms, this represents a "noisy-OR gate" (Pearl, 1988; Srinivas, 1993), in which a sensorimotor cue (scowling) could be produced by one of multiple sources (here, heat or contempt). Thus, knowledge that hot subway cars produce scowls—P(scowl|heat)—and that the target is experiencing heat explain away the likelihood of contempt by reducing the need for contempt to explain the scowl (M. P. Wellman & Henrion, 1993).

The modal perceiver can integrate this information (e.g., by engaging in mentalizing) in deciding that the target's scowl is uninformative in this context. However, a perceiver suffering from social anxiety may not fare as well. This perceiver might instead (a) overestimate the meaningfulness of the target's expression by inflating P(scowl|contempt,heat), (b) discount contextual cues that this facial expression is uninformative by deflating P(scowl|heat), or (c) overestimate the base rate with which targets feel contempt overall, P(contempt). Any of these integration failures could in turn worsen the perceiver's inference and impair their ability to engage with the target.

In fact, social anxiety is characterized by both inflated expectations concerning the base rates of negative social events (Foa, Franklin, Perry, & Herbert, 1996) and negatively biased processing of social cues (Bar-Haim,

Lamy, Pergamin, Bakermans-Kranenburg, & Van IJzendoorn, 2007; Hirsch & Mathews, 1997; Voncken, Bogels, & De Vries, 2003). More broadly, a focus on information processing bias forms the cornerstone of cognitive models of psychiatric disorders (Eysenck, 1992; Rachman, 1997) and cognitive therapies aimed at overwriting such biases (Beck, 1976; Clark, 1999). A cue integration framework can complement these foundational clinical models in at least two ways.

First, although processing biases are well described in a number of disorders, the empirical work describing such biases often examines abnormalities in processing isolated social cues. Such disorders likely also involve difficulties integrating over more complex social cues. If this is the case, isolationist approaches could constrain scientists' ability to relate cognitive abnormalities to social impairments as they are measured clinically (Fombonne, Siddons, Achard, Frith, & Happe, 1994; U. Frith, Happe, & Siddons, 1994) or to design interventions that ameliorate these impairments (Golan & Baron-Cohen, 2006; Hadwin, Baron-Cohen, Howlin, & Hill, 1996). A cue integration approach offers novel methods for addressing information processing biases in more realistic settings.

Second, this approach can offer quantitative measures of processing bias—for instance, the amount that an individual overestimates the conditional probability connecting a particular cue, such as a scowl, to a given internal state. Such indices could prove deeply useful as both diagnostic tools (e.g., to assess the severity of information processing biases in a given individual) and as markers of treatment efficacy in adaptively remapping perceivers' conditional probabilities in the social world (Maia & McClelland, 2011; Montague, Dolan, Friston, & Dayan, 2011).

Conclusion

For the better part of a century, scientists have compared our perceptions of the physical world and of other minds. This comparison is apt: Social cognition and physical perception are both challenging tasks surmounted through the use of multiple information processing streams. Research in both of these domains began by examining these processing streams in isolation, but it has steadily shifted toward the study of interactions between processes in response to naturalistic stimuli. By recognizing the common information processing demands placed on perceivers across physical and social domains, a cue integration framework offers novel ways to conceptualize complex social cognition. This framework suggests that social cognitive processes are fundamentally interactive and that social perceivers are "lay Bayesians," who rely on conditional probabilities when deciding how reliably cues predict targets' internal states.

Such insights can provide early steps toward more deeply understanding humans' profound ability to translate barrages of social signals into an understanding of each other's minds.

Notes

1. I choose to describe these two processes instead of a number of others (e.g., stereotyping) because mentalizing and experience sharing have garnered an outsize amount of attention across both behavioral and neuroscientific approaches, making them ideal for describing isolationist and integrative models at multiple levels of analysis.
2. This process-oriented work stands in contrast to more holistic paradigms used, for example, in research on nonverbal behavior and interpersonal sensitivity (Ambady & Rosenthal, 1992; Hall & Bernieri, 2001).
3. Formalizations of social cognition have often drawn on types of modeling, such as parallel constraint satisfaction or connectionist approaches, that complement Bayesian cue integration, by demonstrating how Bayesian inference could be implemented within a distributed (e.g., neural) network (McClelland, 1998, for details of the relationships between these modeling approaches).

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