Simulation theory

Karen Shanton* and Alvin Goldman

Simulation plays a significant role in human cognition. This article reviews evidence for a simulational account of mind reading. Drawing on findings in developmental psychology and cognitive neuroscience, it shows that mind reading involves the imitation, copying, or reexperience of the mind reading target's mental processes. The article also introduces evidence for simulational accounts of episodic memory and prospection. It identifies relevant similarities between mind reading, memory, and prospection as well as independent evidence for a role for simulation in memory. © 2010 John Wiley & Sons, Ltd. *WIREs Cogn Sci*

Simulation theory (ST) is, in the first instance, an approach to the question of how people attribute mental states to others. Mental-state attribution is variously called 'folk psychology', 'theory of mind', 'mind reading', or 'mentalizing'. It is a species of 'metarepresentation', an activity in which mental states (beliefs) represent other mental states. It is generally agreed that ordinary people engage in mind reading from an early age. The controversial questions are how this task is executed, and how the ability to do it is acquired.[1]

Since the early 1980s, three principal approaches to mind reading have dominated the field. The first approach, *theory theory* (TT), holds that people somehow acquire a 'theory' of the mental realm, analogous to their theories of the physical world ('folk physics'). This theory posits causal links between environmental inputs, inner states, other inner states, and behavioral outputs.[2–5] Given information about another person's observed behavior or facial expression, etc., attributors make theoretical inferences to his mental states. Proponents of TT diverge on the story of theory acquisition. Some say that children acquire theory of mind by the same empirical, theory-testing method by which professional scientists acquire their theories.[6–8] Others say that the basic components of theory of mind are innate and emerge through triggering in the early years.[3,9]

A second approach to mind reading, *rationality theory*, holds that people use principles of rationality to attribute mental states to others. According to this theory, mind readers make a default assumption that others are rational in matters of belief, preference, and decision making. To attribute propositional attitudes, such as believing that P, desiring that Q, or deciding to do X, they conjoin information about a target's initial states with appropriate principles of rationality. On the basis of this information, they determine which further mental state it would be rational to adopt and attribute that state to the target. Such a procedure is variously called the 'intentional stance'[10] or the 'teleological stance'.[11]

ST is the third approach. Rejecting the TT emphasis on theoretical inference, ST (in its original form) says that people employ imagination, mental pretense, or perspective taking ('putting oneself in the other person's shoes') to determine others' mental states. A mentalizer simulates another person by first creating pretend states (e.g., pretend desires and beliefs) in her own mind that correspond to those of the target. She then inputs these pretend states into a suitable cognitive mechanism, which operates on the inputs and generates a new output (e.g., a decision). This new state is taken 'off line' and attributed or assigned to the target.

ST (as a theory of mind reading) was first proposed by Gordon[12] and Heal,[13] with additional defenses and elaborations by Harris[14,15] and Goldman.[16,17] Defenders of ST differ on the precise mechanisms of simulational processing. Goldman's[18] version of ST, for example, maintains that, before a mind reader can attribute a pretend mental state to the target, she must first *introspect* the state generated by her cognitive system and determine its type and content. Gordon,[19] on the other hand, rejects introspection entirely, as well as any analogical inference 'from me to you'. Theorists also differ on the scope of simulation in mind reading. In recent years, a number of writers have endorsed 'hybrid' ST–TT accounts.[18,20,21] Hybrid accounts acknowledge roles

*Correspondence to: shanton@philosophy.rutgers.edu

Department of Philosophy and Center for Cognitive Science, Rutgers University, New Brunswick, NJ 08901, USA

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for both simulation and theory in mind reading. Although we are emphasizing its simulational elements, our account is a hybrid account; we allow for the possibility of some theory-driven mind reading.

How should the concept of 'simulation' be understood? The verb *simulate* is derived from the Latin *simulare*, which means 'imitate', 'feign', or 'copy'. The Latin verb is in turn derived from *similis*, which means 'similar' or 'like'. Applying this notion to the cognitive realm, we may say that one cognitive event, state, or process 'simulates' another event, etc., just in case it imitates, copies, or reproduces the second event. In the mind reading literature, this sense is captured by other labels for simulation (e.g., 'replication'[13] or 'recreation'[22]). Another useful term, often employed in the cognitive science literature, is 'reexperience'. In cognitive scientific usage—and as we are using the term—'reexperience' does not necessarily mean *conscious* reexperience. For example, an event can be unconsciously reexperienced if there is a neural or functional resemblance (but no phenomenological resemblance) between the original experience and another experience.

We are interested in a particular category of simulation, namely, *mental* simulation. Of course, other types of simulation, such as weather simulation and flight simulation, exist. But we are not concerned with these types of simulation. Of interest to us are cases in which one *mental* event, state, or process is the reexperience of another mental event, state, or process. We allow for some looseness, however. X can be a simulation of Y even if it isn't an *exact* duplicate of Y. Moreover, X can be a simulation of Y even if it only *aims* to duplicate, copy, or replicate Y, or if its *function* is to duplicate or replicate Y. Simulation does not require successful duplication. The simulated event or process (Y) may also be a merely *possible* event, not an actual one (e.g., as when we simulate hypothetical events).

In the cognitive domain, we can speak of either *inter*personal or *intra*personal types of simulation. Interpersonal simulation involves *other*-directed simulation (e.g., empathy or third-person mind reading). Intrapersonal simulation involves *self*-directed simulation. One example of intrapersonal simulation is the construction of visual imagery. When visualizing, one attempts to reproduce or 'reexperience' episodes of genuine vision. In other words, visualization is an attempt to generate a mental state that occurs, or might occur, in one's own mind. The method of attempted generation in this case is endogenous rather than exogenous (it omits stimulation of the receptors). Nonetheless, visualization uses many brain areas that also used by genuine vision.[23] This suggests substantial similarity between visualization and genuine vision. The first half of this article shows how *inter*personal simulation is used in mind reading. The second half largely focuses on a pair of tasks involving *intra*personal simulation, namely, episodic memory and prospection. We argue that episodic memory and prospection consist in the (attempted) reexperience of events in one's past and (attempted) preexperience of events in one's future, respectively.

LOW-LEVEL SIMULATION-BASED MIND READING

In light of recent discoveries, it is helpful to distinguish two types of mind reading and two associated types of simulation processes. There seems to be a fairly simple or 'primitive' way of assigning mental states to others that involves comparatively little computation or inference. Among other things, mental states 'read' in this fashion do not have associated propositional contents, which inevitably introduce greater complexity. We refer to this ostensibly 'simple' mode of mind reading as 'low-level' mind reading. It is to be contrasted with a more complex mode of mind reading, which we refer to as 'high-level' mind reading. We treat low-level mind reading in this section and high-level mind reading in the next.

Consider the assignment of emotion states to another person on the basis of his facial expression. Each of the six basic emotions (fear, anger, disgust, sadness, happiness, and surprise) has a fairly characteristic form of facial expression, and normal people can discriminate them based on these distinctive expressions. As will be explained below, there is also excellent evidence (for at least some of the basic emotions) that there is an automatic mechanism by which observation of facial features for an emotion E produces an *experience* of emotion E in the observer. Thus, there is a process reaching from a first subject of E (X) to a second subject of E (Y). Since the E-experience in Y is an (interpersonal) *reexperience* of E, the process that generates it is a simulational process.

The bases for such a process are 'mirror neurons' or 'mirror processes', which were discovered in the laboratory of Rizzolatti in Parma, Italy.[24–26] Mirror neurons are a class of neurons, initially found in the premotor cortex of macaque monkeys, that are activated both when a monkey performs a specific goal-oriented action and when it simply observes another monkey (or human) performing the same action. Premotor activation can be considered the neural basis of an *intention* to perform a motor act, for example, grasping an object. Since the same intention is experienced by both the performer and the observer of the action, neurons with this execution–observation matching property are called 'mirror neurons'. The process by which mirroring is effected may be called a 'mirror process' or a 'resonance process'. Since the observer *reexperiences* the same motor intention as the performer, a mirror process is an interpersonal simulation process (a 'low-level' one).

Humans have also been found to possess motor mirror systems.[27,28] In humans, the (motoric) mirror neuron system is composed of regions in the posterior inferior frontal gyrus (IFG), the ventral premotor cortex, and the rostral inferior parietal lobule (IPL). The ventral visual stream feeds into the posterior IFG and rostral IPL, providing them with motion-specific information (e.g., hand grasping, eye gaze, and so on). This information prompts (motor) mirroring activity in neurons in these regions.

The terms 'mirror system' and 'mirror neuron' are primarily applied to motoric systems and motoric neurons. However, motoric areas are not the only portions of the brain that house mirroring, or resonance, systems. Analogous systems are also found for experiences of (1) pain,[29,30] (2) touch,[31] (3) happiness,[32] and (4) disgust.[33] In each of these cases, under appropriate observational conditions, an experience in one person is mirrored, or reexperienced, in an observer. Although we use the terms 'experience' and 'reexperience' here, they do not refer to *conscious* experiences. Most mirroring events (at the observer's end) occur below the threshold of consciousness, and can be detected only by brain-oriented techniques, commonly, functional magnetic resonance imaging (fMRI). An interesting departure from this rule occurs in a patient who suffers from a hyperactive mirror system for touch; when she observes another person being touched, she consciously experiences touch in herself, as if she were being touched.[34] No such experience happens in ordinary people. Despite the nonconscious nature of ordinary observation-based mirroring, we still deem this to be a simulational phenomenon. Gallese stresses that mirror simulation is 'automatic, unconscious, and prereflexive'[35] [p. 521].

The most popular interpretation of motor mirroring is the *direct-matching hypothesis*. According to this hypothesis, 'an action is understood when its observation causes the motor system of the observer to 'resonate'[36] [p. 661]. In other words, action mirroring is the automatic and mandatory duplication of an observed action in the observer's own motor system. This automatic mirroring, or resonance, leads to an understanding of the target's action in terms of a motor code. Though popular, this interpretation of mirroring is not universally accepted. In particular, Csibra[37] offers an alternative account according to which action mirroring in the observer is not direct or automatic, but results from goal-related reconstruction. Observed actions receive high-level interpretation (i.e., understanding) within the visual system *before* becoming transformed and represented in a motor code. Evidence that mirroring may not be entirely automatic comes from studies that show that mirroring, or resonance, can be modulated by information the observer possesses. Singer et al.[38] had male and female volunteers play an economic game in which confederates played either fairly or unfairly. Subjects of both sexes exhibited mirroring activation in pain-related brain areas. However, these mirroring responses were reduced in males when they observed an unfair person receiving pain.

However mirroring processes operate, do they serve as the basis of *mind reading* on the part of observers? This was first conjectured for motor intentions by Gallese and Goldman.[39] More specific experimental evidence for mirror-based mind reading has been adduced in several domains. Perhaps the clearest case concerns the (face-based) mind reading of disgust (Figure 1). Mirroring of disgust was established via the use of fMRI. Wicker et al.[33] scanned participants while they inhaled foul, pleasant, and neutral odors through a mask. The regions selectively activated in the foul odor condition were the left anterior insula and the right anterior cingulate cortex. When the same participants were scanned again while merely *observing* other people inhale foul odors (and make facial expressions of disgust), the same brain areas were selectively activated. These brain areas, especially the anterior insula, are known from animal studies to be associated with disgust.[40]

The above study demonstrates mirroring—and hence simulation—for disgust. However, it doesn't show that subjects *impute* a mental state of disgust to the people whose faces are observed. Therefore, it doesn't show that the observers base an *attribution* of the mental state disgust on their mirrored (re)experience of disgust. However, evidence from neuropsychology strongly points in this direction. Calder et al.[41] described a patient, NK, who suffered insula and basal ganglia damage. On a questionnaire about the experience of various emotions, NK scored significantly lower than controls for disgust but not for anger or fear. Interestingly, NK was also significantly and selectively impaired at recognizing and attributing disgust, through both visual cues (using faces) and auditory cues. Similarly, Adolphs et al.[42] reported a patient, B, who had extensive anterior insula damage and was selectively impaired

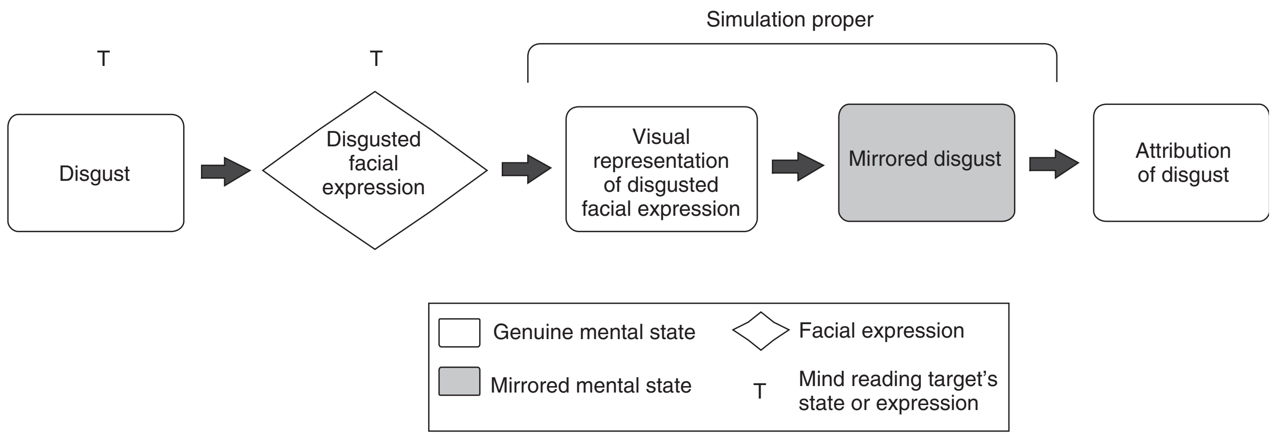

FIGURE 1 | Low-level mind reading.

at recognizing disgust in dynamic displays of facial expressions. The straightforward explanation of NK's and B's selective inability to mind read disgust is that they lacked the ability to *mirror* disgust in virtue of their anterior insula damage. This implies that normal mind reading of disgust—at least through facial and other perceptual cues—is causally based on a mirrored (re)experience of disgust, just as ST predicts. A similar story seems feasible for fear. No comparable predictions are made by TT[18,43] [chapter 6].

The studies by Singer et al.[29] and Jackson et al.[30] provide evidence for mirror-based attribution of pain and its properties. Even better evidence has been obtained by Avenanti et al.[44,45] The experience of pain is accompanied by a *decrease* in the amplitudes of motor-evoked potentials (MEPs) specific to the muscle that receives the painful stimulation (this is associated with motor inhibition). Using transcranial magnetic stimulation, Avenanti et al.[45] found a corresponding decrease in MEPs during the mere observation of needles penetrating body parts of a human model. This decrease did not depend on the instructions given to observers. It occurred whether observers were asked to deliberately adopt a first-person perspective, i.e., to 'imagine feeling the same pain as the model, in the same body part', or simply to 'watch the movie clips attentively' (passive observation). This suggests that the observed stimuli induced fairly automatic mirroring, or resonance, of pain. In a second experiment, subjects were presented with similar videos and asked to judge the level of pain supposedly felt by the model in different conditions. Subjects were asked to rate the intensity and unpleasantness of the model's pain on a scale from 0 to 10, where 0 represented 'no effect' and 10 represented 'maximal effect imaginable'. Avenanti et al. found that the largest MEP inhibition (i.e., mirrored experience of pain) occurred in subjects who rated the model's pain as most intense. Presumably, the intensity judgments, or attributions, were based on the observers' mirrored experiences of the pain.

An inventive study by Iacoboni et al.[46] provides evidence that people use mirror processes to predictively assign intentions to people's future actions. Subjects in this study were presented with three types of videos: (1) *intention clips*, (2) *context clips*, and (3) *action clips*. The intention clips depicted a grasping hand action in a context scene (e.g., whole-hand prehension on a teacup in an array of objects set for tea), the context clips depicted just the context scene (e.g., an array of objects set for tea), and the action clips depicted just the grasping hand action (e.g., whole-hand prehension on a teacup). In contrast to the other two types of clips, intention clips elicited significant increases in activation in subjects' premotor mirror systems. Iacoboni et al. take this to show that subjects use mirroring processes in the attribution of intentions.

Now, given just the imaging data, this conclusion is open to dispute; there are at least two interpretations of the imaging findings that don't implicate mirroring processes in intention attribution: (1) the activations could reflect predictions of *actions* rather than attributions of intentions, or (2) they could reflect *mere mimicry*—rather than actual attribution—of intentions.[47] However, Iacoboni et al.[46] also collected verbal report data. These data indicate that, even when they had not been explicitly instructed to do so, subjects associated the hand actions in the intention clips with intentions. For example, subjects associated the whole-hand prehension in the array of objects set for tea with the intention to drink the tea. This seems to confirm Iacoboni et al.'s conclusion that subjects were not merely predicting actions or mimicking intentions; they were actually *attributing* intentions and using their mirror systems to do so.[47]

SIMULATION AND HIGH-LEVEL MIND READING

In contrast to low-level mind reading, high-level mind reading is more complex and tends to involve propositional attitudes. It typically requires guidance by information stored in long-term memory. This kind of simulation process also involves the use of *imagination*. Imagination is here understood as a constructive process that attempts to produce a prespecified mental state in the self by endogenous means (not, e.g., by scanning the environment). As remarked earlier, visualization is a species of imagination in which one attempts to produce a visual state akin to seeing a specified object or scenario. For me to visualize Barack Obama taking the oath of office is to construct in my mind a state akin to seeing this event. (I can visualize it either beforehand, before actually seeing it, or afterwards, based on recall.) Imagination need not involve a sensory modality. One can imagine *believing* something one does not actually believe, and *hoping* for something one does not actually hope for; neither the belief nor the hope has to involve any modality-specific cognition.

How is imagination useful for third-person mind reading? If you seek to predict someone's decision—for example, the choice of a main dish by your dinner companion at a restaurant—how could you use imagination to make this prediction? The first step is to put yourself in your target's shoes, or take her 'perspective'. Taking someone's perspective here means adopting, as far as feasible and in light of what you know about her, the mental states she starts with. This includes her preferences about food in general, what she liked at this restaurant on previous occasions, how hungry she is on the present occasion (did she have a light lunch, no lunch, or a heavy lunch today?), and so forth. Using the imagination, you can simulate being in her various dinner-relevant states. Such pretend states can then be fed into your decision-making mechanism, which generates a decision to order a particular main dish. Having used this simulation process to generate a (pretend) choice, you don't order this dish yourself but attribute the choice to your companion. Thus, the attribution is based on imagination-driven simulation (Figure 2). Note that the simulation process does not rely on the mind reader's appeal to psychological generalizations (e.g., a generalization about human decision making), which is a crucial part of TT. You don't need such generalizations under ST; you just need the cognitive ability to simulate decision making via pretend rather than genuine inputs.

Simulation-based mind reading could be inaccurate for a variety of reasons. A mind reader might lack pertinent information about his target's initial states (preferences, beliefs, and so on) or he might fail to 'quarantine' or inhibit his own genuine states when doing a simulation. At the restaurant, one might do a bad job of quarantine by allowing one's own preference for pasta, say, to intrude into the simulation of the companion. That simulation is apt to generate this kind of error does not undercut the theory, however. On the contrary, if it were found that mind readers are prone to such errors, it would constitute positive support for it.

In fact, empirical evidence of precisely this sort has been found in abundance (for review, see Ref 18, chapter 7). ST predicts that failure to quarantine one's own states when constructing pretend input states will lead to egocentric biases in attribution. Such biases are evident in at least three categories of mind reading: attribution of (1) knowledge states, (2) valuation states, and (3) feeling states. Studies by Krauss and Glucksberg,[48] Camerer et al.,[49] Birch and Bloom,[50] and Keysar et al.[51] show that subjects tend to project their own knowledge states onto a target and hence (in many cases) to make incorrect mental-state ascriptions. Van Boven et al.[52] found that subjects have difficulty predicting another person's valuation of a coffee mug because of 'egocentric empathy gaps',

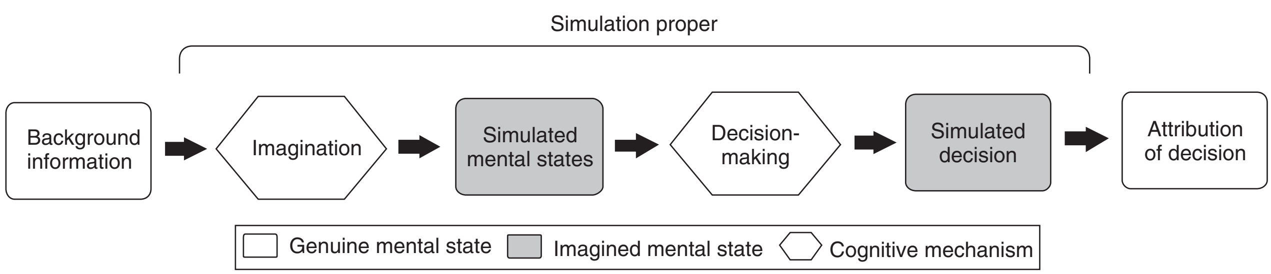

FIGURE 2 | High-level mind reading.

their expression for what we call failures to quarantine one's own valuations. Van Boven and Loewenstein[53] found a significant difference in predictions of a target's relative preferences for food and water when the predictors themselves were in a thirsty condition versus a nonthirsty condition.

The standard tool of TT in explaining attribution errors is an appeal to some sort of theorizing deficit. But it is unclear what theorizing deficit would explain the foregoing cases, especially Van Boven and Loewenstein's[53] thirst condition case. In addition, studies of neurological problems with inhibition of self-perspective appear to support the ST story. A neurological patient who suffered from an inability to inhibit his self-perspective, WBA, systematically failed many third-person attribution tasks involving visual experiences, desires, emotions, and false beliefs. In one task, four colored circles were placed in the middle of a table, WBA was seated at one side of the table and other people were seated at the other sides. When asked to describe how the color display looked to the other people at the table, WBA tended to respond according to his own visual experiences; 70% of his responses involved egocentric errors.[54] This seems to favor an ST explanation of egocentric error over a TT explanation.

A long-standing focus of theory of mind research has been the well-documented change in the ability of children between 3 and 4 years of age to pass verbal false belief tasks. Theory theorists (at least of the 'child–scientist' variant) explain this change in terms of a 'conceptual deficit' in 3-year-olds (i.e., a deficit in their folk-psychological theory) that allegedly prevents them from making sense of false belief.[6–8] Simulation theorists offer a different explanation: an increase in executive function ability between 3 and 4 years, which enables older children to exhibit better perspective-taking skills. The putative conceptual deficit of 3-year-olds has been dealt a serious blow by Onishi and Baillargeon's[55] finding of false belief understanding in 15-month-olds. Therefore, the developmental record favors ST over at least the child–scientist version of TT. Arguments against the other, modularist form of the TT approach are presented in Nichols and Stich[20] and Goldman.[18]

INTRAPERSONAL INTERTEMPORAL SIMULATION: MENTAL TIME TRAVEL

The orthodox literature on ST centers on mind reading. However, there is increasing evidence that the kind of simulation mechanism involved in (high-level) mind reading is also deployed in a wide variety of other areas of human cognition. Whether this mechanism is merely *similar* to the mechanism involved in mind reading or the *very same* mechanism is open to debate. But we shall survey evidence that at least similar *types* of mechanisms—simulational mechanisms—operate in several areas outside interpersonal mind reading. We refer specifically to uses of simulation to project the self into the past and the future. Projection into the past is standardly referred to as *episodic memory* and projection into the future is sometimes called *prospection*.[56,57] The general idea is that humans are capable of *mental time travel*,[58,59] or mentally transporting themselves into the personal past or future.

This mental time travel is similar to high-level simulational mind reading in at least two respects. First, the mental time traveler *detaches* herself from the present environment or the present moment and endeavors to *reexperience* her past or *preexperience* her future. This is analogous to the simulational mind reader, who tries to detach herself from her own genuine mental states and project herself into the mental states of another. Second, in all of these cases, there is an attempt to flexibly recombine details from past events into a 'construction' of either the personal past, the personal future, or the states of another. For a review of these relationships, see Refs 60, 61.

We proceed in this section by first presenting evidence for a simulational account of memory. Then we explore parallels between episodic memory and prospection. Finally, we describe evidence that these two processes—along, perhaps, with mind reading—utilize the same brain network, or at least substantially overlapping brain areas.

Episodic memory is memory for personally experienced events, for example, marrying your spouse, celebrating your 30th birthday or eating lunch. When you recall any such event, you retrieve an episodic memory. Memory research has produced numerous findings that are consistent with a simulational account of memory.[62] (Hereafter, all mention of 'memory' refers to episodic memory retrieval, unless otherwise indicated).

First, there are at least three dimensions of resemblance between processes involved in remembering previously experienced events (*retrieval processes*) and processes involved in the original experiences of the events (*remembered processes*): (1) phenomenological resemblances, (2) neural resemblances, and (3) functional resemblances. According to memory theorists, an essential feature of episodic memory retrieval is that it is accompanied by *autonoetic consciousness*.[63] Autonoetic consciousness is a conscious feeling of reexperiencing or reenacting a previously experienced event. Memory processes are, therefore, largely *characterized* in terms of their *phenomenological resemblance* to remembered processes.

A recent single-cell recording study suggests that neurons activated during perceptual experiences are selectively reactivated during recall of those experiences. Gelbard-Sagiv et al.[64] implanted epileptic patients with depth electrodes and then presented them with a series of 5–10-s video clips. Subjects viewed each clip 5–10 times and then performed a 1–5-min distractor task. After the distractor task, they were asked to verbally report their recollections of the previously viewed clips. While they were performing these tasks, researchers recorded the activity in 857 units in their medial temporal lobes and medial frontal cortices.

Gelbard-Sagiv et al.[64] found that particular units in each patient's brain exhibited consistent responses to presentation of particular clips. For example, in one patient, a single unit in the right entorhinal cortex consistently responded to a clip from an episode of *The Simpsons*. The same units also exhibited consistent responses to free recall of the clips. For example, the previously described patient's *Simpsons*-responsive neuron displayed activity not only when he watched the *Simpsons* clip but also when he remembered it. This suggests that the same neural units that are activated when subjects watch a video clip are reactivated (in the same patterns) when they remember watching the clip. In other words, memory processes seem to bear *neural resemblances* to remembered processes. This finding dramatically confirms a series of earlier studies of nonpatient populations, which found that remembering emotional experiences activates emotion-processing regions of the brain and remembering perceptual experiences activates perception-processing regions.[65–67]

When the circumstances in which remembering occurs are congruent with the circumstances of the remembered experience, memory retrieval is faster than when the circumstances are incongruent. Dijkstra et al.[68] instructed subjects to remember specific past occasions on which they had experienced each of eight common events (e.g., going to the dentist). Subjects were asked to assume congruent body postures (e.g., lying in a reclined position for the dentist memory) while remembering some of the experiences and incongruent postures (e.g., standing with hands on hips for the dentist memory) while remembering others. Dijkstra et al. found that subjects remembered the experiences faster when posed in congruent postures than incongruent postures. Similar findings were obtained for congruent and incongruent eye movement patterns; the more overlap there is between eye movement patterns during perception of a stimulus and eye movement patterns at retrieval, the more accurate memories of the stimulus tend to be.[69]

An explanation of these facilitation effects is that retrieval processes *functionally resemble* remembered processes. Particular body postures perform a function in the experience of going to the dentist and particular eye movement patterns perform a function in perception of a visual scene. The fact that reenacting these postures and eye movement patterns at retrieval increases retrieval speed and accuracy suggests that they play a similar function in *remembering* such experiences and perceptions.

According to our conception of simulation, simulational processes resemble—or aim to resemble—the processes they simulate. The above evidence of phenomenological, neural, and functional resemblances between retrieval processes and remembered processes is, therefore, fairly direct evidence for a simulational account of memory. It suggests that retrieval processes (aim to) resemble remembered processes and, consequently, count as cases of simulation.

Second, much like high-level mind reading, memory is susceptible to egocentric biases. Evidence for this comes from studies of emotion memory. Immediately after Ross Perot withdrew from the US presidential race in July of 1992, Levine[70] asked a group of Perot supporters to rate how sad, angry, and hopeful they felt. Later, after Perot reentered the race in October and had a relatively strong showing against Bill Clinton and George HW Bush in the November election, she asked them to remember their earlier emotions.

Levine[70] reported that subjects' emotion memories tended to covary with their current appraisals of Perot's withdrawal from the race. For example, subjects who started out as fervent Perot supporters and then switched allegiances to one of the other candidates rated themselves as highly sad, angry, and hopeless in July but, in November, they remembered experiencing much lower levels of emotion (in July). This suggests that subjects' memories of their *past* emotions were biased, or inappropriately influenced, by their *current* appraisals. Similar egocentric biases have been observed in memory for many other mental states, including pains, attitudes, and perceptions.[71–73]

As noted in the previous section, evidence that a process is susceptible to egocentric biases is evidence that it involves simulation. If we use current mental mechanisms to reenact past experiences and (sometimes) fail fully to quarantine our current mental states, we would expect our memories (sometimes) to be biased by our current states. Egocentric biases in memory are readily explainable—and even predictable—on the assumption that memory is a simulational process.

Third, there are surprising similarities between memory and mind reading. Not only are both memory and mind reading particularly susceptible to egocentric biases but they are also selectively impaired in the same patient population. Individuals with autism consistently fail the false belief task, which is considered to be a core measure of mind reading ability.[74] They also seem to have impaired episodic memory.[75] Memory theorists draw a distinction between 'knowing' and 'remembering'. 'Knowing' that an event occurred indicates use of the semantic memory system while 'remembering' that it occurred signals use of episodic memory. Although individuals with Asperger Syndrome accurately recognize previously experienced events at roughly the same overall rates as IQ-matched adults, they are significantly more likely than IQ-matched adults to describe their memories as *known*. This suggests that they have episodic memory impairments for which they compensate by relying more heavily on semantic memory.[76]

The best explanation of these similarities is that memory and mind reading employ the same basic type of mechanism. Consistent deficits and biases are typically the result of weaknesses or impairments in the operation of a cognitive mechanism. If memory and mind reading consistently display the same deficits and biases (e.g., paired deficits in individuals with autism and susceptibility to egocentric biases), then, the straightforward explanation is that they employ the same type of cognitive mechanism. As argued above, mind reading often employs a simulation mechanism. Importantly, it is this mechanism that is responsible for its susceptibility to egocentric biases and its impairment in individuals with autism.[18] The above cited similarities are, therefore, indirect evidence that memory also involves simulation.

Similar support for a role for simulation in prospection comes from evidence of similarities between memory and prospection. Recent research has uncovered a number of parallels between memory and prospection (for review, see Refs 58, 61). First, the phenomenological richness of the outputs of both memory and prospection varies with the distance between the remembered or imagined event and the present; normal subjects' memories of events in the distant past and imaginings of events in the distant future are less phenomenologically rich than their memories and imaginings of events in the near past and future.[77] Second, impairments in memory and prospection seem to travel together. Amnesic patients who can't remember yesterday's events also have trouble predicting what might happen tomorrow.[78,79] Similarly, children under the age of 4 have difficulty answering questions about both the personal past and the personal future.[80] Third, memory and prospection activate similar neural regions. In a positron emission tomography (PET) study, Okuda et al.[81] asked subjects to talk about events in either the past or the future. Subjects in both past and future conditions displayed selective activations in specific regions in the prefrontal cortex and parts of the medial temporal lobe, including right hippocampus and bilateral parahippocampal gyrus. Interestingly, Hassabis et al.[82] pinpointed the function of some of these regions as imagination related. They asked normal control subjects and subjects with bilateral hippocampal amnesia to imagine everyday experiences like lying on a white sandy beach. The scenarios constructed by the amnesic subjects were significantly less rich and detailed than those of control subjects. This suggests that hippocampal regions are implicated in imagination.

On the basis of these types of evidence, several researchers[56,60] have proposed that there is a 'core network' that critically underlies both episodic memory and prospection. Schacter and Addis[60] specify that this core network consists of medial prefrontal and frontopolar cortex, medial temporal lobe, lateral temporal and temporopolar cortex, medial parietal cortex including posterior cingulate and retrosplenial cortex, and lateral cortex (see also Ref 83). Buckner and Carroll[56] suggest that this core network also makes contributions to theory of mind or mind reading. This claim is much more controversial than the previous claim but there does seem to be some empirical support for it. For example, there's evidence that the frontopolar cortex contributes to theory of mind tasks; the paracingulate cortex—the anterior-most portion of the frontal midline—is recruited in executive components of simulating others' perspectives.[84] Saxe and Kanwisher[85] provide further evidence of a role for the core network in mind reading. They asked subjects to answer questions about stories that required them to conceive a reality different from the current state of the world. In one condition, the conceived state was a belief held by a person; in the other, the conceived state was an image held by an inanimate object (e.g., a camera). Conceiving the beliefs of another person strongly activated the network shared by prospection and remembering; conceiving the inanimate object's image did not.

OTHER APPLICATIONS OF SIMULATIONIST IDEAS

Simulationist ideas have influenced several areas of inquiry in addition to mind reading, memory, and prospection. In cognitive science, for example, there is emerging evidence of a connection between psychological well-being and the simulation of future events. In philosophical areas such as esthetics, metaphysics, philosophy of language, and epistemology, applications of simulationist ideas are multiplying. We conclude this article with a brief sampling of simulationist approaches to these topics.

Schacter et al.[61] review considerable evidence that simulations play an important role in psychological well-being. The ability to generate detailed simulations of possible future events is correlated with the ability to cope effectively. Subjects who are good at simulating future events tend to consider positive outcomes more likely than negative ones and not to worry much about future events. Poor simulators, on the other hand, are less likely to anticipate positive outcomes and more prone to worry. The link between difficulty with simulation and decreased well-being is illustrated by work with patient populations. For example, Williams et al.[86] found that suicidally depressed patients tend to have difficulty with simulating both past and future events. A possible explanation of the link between simulation and well-being is that detailed simulation enables simulators to more effectively regulate their emotions and more successfully solve problems.[87,88]

Simulation has frequently been invoked in discussions of esthetics. Walton[89,90] has long discussed esthetic appreciation in terms of games of pretense or 'make believe', where these may be construed in terms of imaginative simulation. Simulational accounts may help solve the 'paradox of fiction': why fiction has the power to move us emotionally despite our knowing that the situations are not real.[91] Currie[22,92] has developed a simulationist view according to which readers of fiction make believe that they are reading true accounts of events. Interaction of their simulated beliefs with their simulated desires accounts for their emotional reactions. While this approach invokes high-level simulation, Freedberg and Gallese[93] offer a low-level—or mirroring—account of esthetic responses to painting and sculpture. They cite ways in which viewers of certain artistic works engage in bodily empathy, e.g., feeling activation in the same muscles that are activated in the figures of Michelangelo's *Prisoners*, who are depicted as struggling to free themselves from their material matrix.

Turning to metaphysics, philosophy of language, and epistemology, a number of theorists suggest that the language of ontological commitment often reflects *simulation* of a belief in the existence of certain entities (e.g., numbers) rather than *actual* belief in them.[94] Egan[95] tells a similar story about pretense and the interpretation of idioms. He suggests that, although parts of an idiom-containing sentence retain their usual semantic values and are composed in the usual way, the sentence is assigned a nonstandard truth value by processing its literal content through a pretense or simulation. Another philosophical application of simulationist ideas is in the epistemology of counterfactuals. It is plausible that we evaluate the truth values of counterfactual propositions by feigning or simulating belief in the antecedent and working out in imagination what would hold under this scenario.[96] Williamson[97] adopts this approach to the epistemology of counterfactuals and contends that simulational appraisals of counterfactuals lie at the heart of philosophical methodology.

As evidenced by even this brief sampling, there is growing appreciation, among both cognitive scientists and philosophers, of the importance of simulation to human cognition. Although simulation initially appeared primarily in accounts of mind reading, there is increasing evidence that it is also involved in many other aspects of human life. Not only is it essential to episodic memory and imagination of the future but it also explains puzzles in numerous philosophical areas, from esthetics to metaphysics to philosophy of language. We anticipate that further investigations will only expand the scope of application of simulationist ideas.

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