The mirror neuron system has dominated understanding of observational learning from a cognitive neuroscience perspective. Our review highlights the value of observational learning frameworks that integrate a more diverse and distributed set of cognitive and brain systems, including those implicated in sensorimotor transformations, as well as in more general processes such as executive control, reward, and social cognition. We argue that understanding how observational learning occurs in the real world will require neuroscientific frameworks that consider how visuomotor processes interface with more general aspects of cognition, as well as how learning context and action complexity shape mechanisms supporting learning from watching others.

Learning from Watching Others Is a Fundamental Human Skill

Whether learning to dance Gangnam Style, open a bottle of champagne, or tie shoelaces, humans learn a great deal by simply watching others [1,2]. Learning by observation can have many benefits over physical practice without observation. This is especially true in dangerous or novel environments where poor initial performance can be costly, such as learning to drop in on a skateboard ramp without first watching someone else do it successfully. Equally, learning by watching others is beneficial in social situations where active participation is not possible, such as watching your supervisor give critical feedback to a colleague. As such, observational learning has been of considerable interest to experts from a variety of disciplines, including social and developmental psychology, sport and exercise science, comparative biology and robotics, where researchers are examining how we learn from watching others across a range of behaviors, from simple motor movements to complex social interactions [1,3–5].

Contemporary empirical study into how we learn from watching others originated, to a large extent, in the social learning (see Glossary) research of Albert Bandura and colleagues starting in the 1960s [3,6–8]. Much of this early work focused on the role of an observer’s motivation to learn and social factors relevant to the model. Over the past several decades, however, empirical interest in examining observational learning has come increasingly from the action domain, with considerable attention from cognitive neuroscientists who have begun to explore and characterize the systems within the human brain that translate visual signals into motor output [2,9–12]. While tremendous progress has been made in identifying the neural correlates supporting observational learning of others’ actions, our understanding of how we learn from watching the actions of others remains in its infancy. The foundational structure of relevant cognitive and brain systems remains largely unknown and many key questions still need to be addressed. By synthesizing initial findings from several relevant subdisciplines of human neuroscience and placing them within a wider context of observational learning across species and agents, we aim to provide an overview of the progress that has been made towards understanding brain-based mechanisms that support observational learning. We also outline important next steps that, if taken, could generate a more complete understanding of this ubiquitous and vital capacity.
The Value of a Holistic Approach to Studying Observational Learning

Much like human neuroscience research in general, observational learning research within cognitive neuroscience has tended to focus on understanding the role of a restricted set of brain areas, such as the human mirror neuron system. This focus has undoubtedly contributed to our knowledge about how we learn from watching others, but it has also come at the expense of understanding and appreciating the roles played by a wider set of systems, as well as how such systems interact. These additional systems include the motor system more generally, as well as regions associated with semantic processing, attention, and memory. What is currently lacking, therefore, are frameworks describing how the brain enables information to be incorporated across distributed neural networks, some of which may be particularly relevant for action learning and others that may support a host of more general cognitive processes. Human social life is simply too complex to understand by focusing exclusively on the operation of subsystems in isolation. For example, if a clear understanding of motor development in children or expertise in life is simply too complex to understand by focusing exclusively on the operation of subsystems in isolation, one is likely to fall short of a holistic understanding of the processes and systems that support observational learning in the human brain, how these develop and change across the lifespan, and how these might be modeled in artificial agents.

Given the varieties of observational learning that have been studied to date (Box 1), it is important to establish the scope of this review. We focus on a specific type of observational learning — namely observational motor learning, where action observation leads to an enduring refinement to motor performance. We have organized the review into three main parts. First, owing to its

Box 1. Varieties of Observational Learning

Multiple types of observational learning exist and, like many subdomains of cognitive neuroscience, the use of vague terminology fuels confusion and hinders progress [107,108]. We define here the specific type of observational learning that we focus on to distinguish it from related, but distinct, interests. Our aim is to provide operational definitions and distinctions that are important for this article’s discussions, and we recognize that strict definitions of broad consensus may be beyond reach, given the complexity of the topic.

At its broadest, observational learning can be conceived as any instance where one observes someone and learns something new or modifies a previously learned skill or behavior. We define learning here as an enduring change in the way that an organism responds, based on its experiences [109]. In this review we focus on a subtype of observational learning that has two necessary requirements: (i) an action must be observed, and (ii) an enduring change to motor performance must occur. Several implications follow from this operational definition. First, one can study the cognitive and brain mechanisms associated with action observation without studying learning [17–19,26,110,111]. Indeed, one’s ability to perform a triple Axel jump may remain unchanged after watching figure skating in the Olympic Games. Second, learning from observing actions is not the same as imitation, although they may co-occur and do rely on partly shared cognitive and brain processes. To qualify as imitation, one must copy someone, whether intentionally or not [112–114]. By contrast, one need not immediately imitate someone to learn by observation. For example, one could watch Beyoncé dancing in a music video (without copying her actions at the time) and then be better at reproducing those dance moves the following weekend when dancing in a club. Third, we can distinguish skill learning through observation of other people’s actions from other forms of learning based on watching other people behave more generally, which are collectively referred to as social learning [4,115,116]. Although observational motor learning is one type of social learning, social learning also encompasses a much broader range of behaviors, some of which are extremely complex, such as how to resist peer pressure to partake in risky behaviors, respond to criticism, or interact appropriately with people from different cultures. Fourth, demonstration that particular cognitive and brain processes support observational learning does not imply that they are uniquely tied to observational learning per se. For example, given the links between motor imagery and action observation [117–119], it is possible that processes common to motor imagery and action observation are involved to some extent when learning by watching others.
dominance, we review research into the role of the human mirror neuron system in observational learning. Next, we review evidence implicating motor processes extending beyond the mirror system in observational learning. We outline how research on sequence learning and motor adaptation in particular informs our understanding of the neural substrates underlying observational learning. Finally, we review evidence highlighting the roles played by non-motor systems in observational learning, such as those associated with cognitive control and reward. We also detail how systems or frameworks that might seem less relevant to understanding observational learning, such as semantic and memory systems, as well as ‘real-life’ neuroscience approaches, also hold considerable potential for making progress in this endeavor.

We conclude by articulating what is known and what remains to be discovered regarding the cognitive neuroscience of learning from watching others. If the ultimate goal is to understand observational learning as it occurs in daily life, there is a need to consider a distributed and diverse set of interacting neurocognitive systems both within and beyond the human mirror neuron system. It is also imperative to combine evidence gathered from controlled laboratory conditions with work that puts observational learning to the test in complex and rich real-world contexts to better understand how to support and bolster this vital skill.

The Dominance of the Human Mirror Neuron System in Cognitive Neuroscience

Investigations of Observational Learning

Cognitive neuroscientific investigations into observational learning have focused extensively on the role played by the human mirror neuron system (Box 2). Since the discovery of mirror neurons within prefrontal and, later, inferior parietal cortices of the non-human primate brain [13–15], researchers have sought to determine whether similar neural processes exist within the human brain. To do so, researchers have used a variety of noninvasive neuroimaging and neurostimulation methods. However, some authors have argued that, instead of focusing on a core or extended mirror neuron system per se, it is more productive to think about mirroring mechanisms distributed throughout the brain, and which link visual representations of others’ behavior into one’s own visceromotor representations based on the relevant domain [110].

In this review we draw particular attention to the dominant role played by the core mirror system in observational learning research. Partly owing to the primary discovery of mirror properties within these regions, frontalparietal mirror activity has received the most attention across a variety of domains, including observational learning. However, although precedence of discovery matters on a practical level, it is important to keep in mind that such precedence can also lead the research community to artificially privilege certain brain regions above others, even if these rankings may not directly relate to the actual ways the human brain works. As we argue in this review, the key role played by extended mirror systems regions (as well as non-mirror brain regions) in observational learning illustrates the importance of considering interplay between distributed brain circuits when studying any complex form of cognition.

Box 2. Charting the Core and Extended Mirror Neuron Systems

In the human mirror neuron system literature, most studies relate to activity within inferior parietal and ventral premotor cortices in the human brain [120]. These cortices represent the human homologs of monkey brain regions where mirror neurons were first discovered [13,121]. Neurons within macaque ventral premotor and inferior parietal cortices were found to respond to the observation and execution of hand and mouth actions, and early neuroimaging work performed with human participants also found spatial overlap within ventral premotor and inferior parietal cortices when people observed or executed movements [16,122–124].

Since the initial discoveries of mirror neurons in monkeys, and follow-up work with humans, several other human brain regions have been reported to show similar mirror-like properties, including the insula and anterior mesial frontal cortex (together referred to as the limbic mirror system, thought to be involved in the recognition of affective behavior [125]), primary motor cortex [126], dorsal premotor cortex, superior parietal lobule, cerebellum [18], supplementary motor area, and the medial temporal lobe [127]. Concurrent with a growing number of brain areas reported to respond during the perception and production of certain behaviors came a proliferation of proposals for the behaviors and psychological tasks that such an extended mirror neuron system might drive [37]. These span diverse topics including language, general learning, autism, mind reading, and imitation, among others. In an attempt to incorporate this expanding cartography of neural tissue demonstrating mirror-like properties into our understanding of mirror neurons based on the original discovery, some authors have argued that, instead of focusing on a core or extended mirror neuron systems per se, it is more productive to think about mirroring mechanisms distributed throughout the brain, and which link visual representations of others’ behavior into one’s own visceromotor representations based on the relevant domain [110].

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measures to probe links between action and perception [16–22]. This work revealed compelling evidence that the human mirror neuron system is engaged not only during action perception and performance but is also sensitive to learning and experience, with more familiar actions leading to more robust engagement [23–26]. Furthermore, research examining learning guitar chords [27–29], dance movements [9,30], and assembling or using novel objects [10,31–33] reported converging evidence that frontoparietal brain regions are modulated when observation of others’ actions resulted in subsequent learning. This evidence has led to a general understanding within cognitive neuroscience that action learning by observation relies, at least in part, on functions performed by the mirror neuron system.

A role for the human mirror neuron system in observational learning makes intuitive sense, given that the neurons found in these cortical regions have well-documented sensory and motor properties. At the same time, we argue that an outsized focus on the human mirror neuron system has produced an oversimplified account of the neural underpinnings of observational learning. Indeed, as already foreshadowed in an early meta-analysis [16], as well as more recent empirical work (e.g., [28,34–36]), several lines of evidence document brain regions and systems extending beyond the mirror neuron system that contribute to this fundamental capacity. In the following sections we examine the role(s) played by some of these systems. Our starting point is that the mirror neuron system is unlikely to be the ‘center’ of any complex cognitive process. Instead, we argue that the mirror neuron system is likely to perform a range of different subprocesses that contribute to many broader cognitive functions [37]. Consequently, we offer a deflationary account of the mirror neuron system in observational learning, which assigns a more limited role to this system than is typically proposed. Instead of the mirror system being the star (or even solo) performer in observational learning, we emphasize how this type of learning is far more likely to rely on coordinated interplay between the mirror neuron system and other brain networks.

The Role of an Extended Motor Network in Observational Learning

In this section we review recent work on observational motor learning highlighting roles for cognitive and brain systems extending beyond the core brain regions traditionally associated with the mirror neuron system. We focus on two broad types of task: sequencing learning and motor adaptation [38] (Box 3). Studying sequence learning holds value because, in real life, much of skilled human behavior follows a sequential structure (e.g., learning to speak, dance, play the piano, ride a bike, and drive a car). Moreover, like many other kinds of human behavior, sequence learning can be achieved via physical practice or by observing others [2]. Observational motor sequence learning is often studied via the serial reaction time (SRT) task (Box 3), and shares two important behavioral characteristics with motor learning achieved primarily through physical practice. First, increasing the number of observation trials improves learning in much the same manner as increasing the number of physical practice trials does [39]. Second, contextual interference effects occur in observational settings [40] exactly as they do in physical practice settings [41–43]. Therefore, learning via physical and observational practice appears to rely on partially shared cognitive foundations [1,2,44–46].

To date, a small but growing number of functional magnetic resonance imaging (fMRI) studies have investigated the neural substrates underpinning observational motor sequence learning. Some researchers have used tasks involving learning the correct sequence of movements to assemble an object [31]. When watching the sequence of actions with the intention to learn compared with a perceptual control task, widespread engagement emerged across inferior and superior frontal and parietal cortices, presupplementary motor area (pre-SMA), the cerebellum, basal ganglia, and the hippocampus. Likewise, others have used dance and complex knotting paradigms to study observational sequence learning [9,10]. These studies show that
when people watch dance sequences they learned via observation, or view pictures of knots that they observed another person learn to tie, dorsal premotor cortex shows stronger engagement compared with observing untrained stimuli. In addition, several fMRI studies have used the SRT task to probe the neural correlates of observational learning [11,28,36,47]. Across these studies, researchers consistently report sensitivity within dorsal premotor cortex and superior parietal lobule, as well as ventral premotor cortex, when learning SRT tasks via observation. These results show that observational motor sequence learning is not restricted to engagement of inferior frontal and parietal brain regions but extends to a broader motor network that includes dorsal premotor, superior parietal, and cerebellar regions (Figure 1).
Brain imaging research on the motor system also highlights how responses can increase or decrease following learning, depending on a range of factors, which can complicate the interpretation of learning-related neural activity changes. Activation decreases following both physical and observational sequence learning have been reported in inferior and superior portions of the anterior parietal lobe, as well as in ventral and dorsal premotor cortex [11,28,36,48]. This is consistent with a general pattern reported in the literature of activity decreases across a number of areas, including primary motor cortex (M1), pre-SMA, and dorsolateral prefrontal cortex (DLPFC), during the initial fast stages of learning a sequential motor task (reviewed in [49]). Importantly, later stages of learning are associated with activation increases in M1, SMA, ventral premotor cortex (PMv), and primary somatosensory cortex (S1) ([50,51], reviewed in [49]; cf [52] for a contrasting view). Whether observational motor sequence learning occurring over even longer time-periods (months and years rather than weeks and days) results in similar increases in activation in areas that exhibited short-term learning-related decreases remains unexplored.

Figure 1. Human Brain Regions Implicated in Observational Motor Learning. Many studies to date that have examined observational motor learning have focused on the core mirror neuron system, but emerging evidence suggests vital contributions are also made by several other motor areas, as well as by brain systems implicated in reward, executive control, and memory. Further discussion of the relationship between the core and extended mirror neuron system is given in Box 2. Abbreviations: aIPS, anterior intraparietal sulcus; BA44, Brodmann area 44; DLPFC, dorsolateral prefrontal cortex; IFG, inferior frontal gyrus; IPL, inferior parietal lobule; M1, primary motor cortex; PMd, dorsal premotor cortex; PMv, ventral premotor cortex; S1, primary somatosensory cortex; SPL, superior parietal lobule; V5/MT+, middle temporal visual area. Brain schematics accessed from Needpix.com.
Whereas motor sequence learning supports the acquisition of complex motor skills, motor adaptation supports the maintenance of consistent performance in response to changes in the body or external environment (Box 3). According to the dominant theoretical framework, this type of learning involves the recalibration of internal models (i.e., representations of body–environment interactions) used to support feedforward and feedback motor control [53–56]. Observational motor adaptation describes how individuals can learn to respond to novel sensorimotor perturbations by observing someone else adapt their movements to those same perturbations. Observation has been shown to facilitate visuomotor adaptation [46–48], force-field adaptation [46,57,58], and force estimation [59,60]. For example, in experiments probing the effects of observation on subsequent visuomotor adaptation [61–63], participants observe someone else learning to reach using rotated visual feedback. When observers are subsequently exposed to the same visuomotor rotation, their reaches become more accurate during initial exposure compared with those who had no previous observational experience.

Despite their similarities, some important differences have also been noted between observational and first-hand, physical visuomotor learning. First, although passive observers exhibit improved learning when they encounter the same visuomotor perturbation they previously observed, they do not show after-effects (reaching errors in the normal unperturbed environment following exposure to perturbed conditions) – a hallmark of implicit motor adaptation [61,62]. Second, observers do not suffer interference costs when consecutively learning two opposing visuomotor perturbations, another defining characteristic of implicit motor adaptation [64,65]. These results imply that the benefits of observation may reflect learning explicit aiming strategies [66] as opposed to using motor errors on a trial-by-trial basis to incrementally update an internal model [67–69]. More work is needed in this area to identify the underlying mechanisms.

Examining the neural mechanisms underlying observational learning using motor adaptation tasks is a growing area of research, and novel insights are coming from studies employing neurostimulation and neuroimaging methods. In one study, repetitive transcranial magnetic stimulation (rTMS) was applied over M1 after participants observed someone learning to reach in a force field [70]. Even though observation improved subsequent learning in a control group, participants in the rTMS group showed degraded adaptation to the same force field they observed at levels comparable with another group of controls who received no observational experience at all. Similarly, single-pulse TMS over M1 has been shown to induce larger increases in corticospinal excitability when observing motor learning compared with observing similar movements that involved no learning [71]. In addition to M1, emerging evidence supports a tight interplay between sensory and motor areas during motor learning by observing [72,73]. For example, a role for S1 in observational learning in motor adaptation tasks has been demonstrated using median nerve stimulation to disrupt the function of S1 [35]. Stimulation delivered to the same arm used in the observed action impaired subsequent learning, whereas stimulation of the opposite arm did not. Together, results from neurostimulation studies indicate a crucial role for M1 and S1 in learning by observation.

Neural reorganization following observational learning has also been studied using fMRI combined with motor adaptation tasks. For example, in a study where participants observed movement errors performed when adapting to novel force fields [57], the authors found activation of portions of the posterior parietal cortex, dorsal premotor cortex, and cerebellum. In another fMRI study [58] the authors investigated changes in resting-state functional connectivity after participants observed others complete a force-field learning task and identified a network consisting
of the middle temporal visual area (V5/MT), S1, M1, and cerebellum. Importantly, connectivity changes correlated with the amount of learning gained through observation. Subsequent work showed that individual differences in pretraining resting-state functional connectivity in sensorimotor brain areas could predict the amount of learning by observation [74]. The studies reviewed in this section demonstrate that, even if one only considers standard motor learning paradigms, a widespread and distributed neural network is involved when learning from watching other people’s actions. Accordingly, even simple, pared-down tasks involving relatively simple actions (e.g., planar reaching, button pressing, etc.) recruit a complex network of brain areas that extends beyond the mirror neuron system (Figure 1). These considerations underscore the value to be gained from broadening the focus of observational learning research.

The Role of Non-motor Systems and Frameworks

Brain circuits beyond the motor system have received less attention in the context of observational motor learning. This makes sense, given that the motor system is the obvious place to start when attempting to understand the brain mechanisms that underpin motor skill learning (observational or otherwise). However, as outlined earlier, to scientifically understand complex processes or systems, one must consider how the component subprocesses or subsystems operate both in isolation and in combination [75,76]. In addition, one of the earliest and arguably most influential psychological theories of observational learning to date emphasized that a wide range of non-motor factors, such as an individual’s motivation to learn, also make important contributions to observational learning [3]. In this section we review research implicating a role for non-motor systems in observational learning, including those associated with cognitive control and reward. We also outline how considerable value should be gained from exploring observational learning from different perspectives, such as those associated with semantic or memory systems and so-called ‘real-life’ neuroscience approaches. Finally, we suggest that observational learning is a prime case where ‘neuroscience needs behavior’ [77]. In other words, our understanding of how brain systems support observational learning will be fundamentally limited until neuroscientific methods can be connected to real-world behavior in meaningful ways.

The first two perspectives that we consider have already been studied in observational learning contexts, albeit to a relatively small degree. The first concerns general cognitive control processes, which are reliably associated with bilateral DLPFC [78,79]. Cognitive control processes regulate other mental processes and guide attention onto relevant features of the environment through processes such as alerting, orienting, filtering, and inhibition [80]. The versatility of this frontoparietal brain network to operate across a range of tasks and contexts has led to it being labeled the ‘multiple demand network’ [79]. In the context of observational learning, depending on the type of learning task or aims of the individual, cognitive control is necessary to direct attention to features that are most relevant in a given context. The efficiency and effectiveness of such control processes also likely contributes to the observational learning rate. Indeed, evidence has shown that DLPFC correlates with performance gains following with observational practice of a guitar chord learning task [28]. Furthermore, transcranial magnetic stimulation to DLPFC makes behavior more error-prone when performing motor sequences previously learned via observation, but not through physical practice [81]. As such, visual and motor processes do not appear to operate in isolation, but are instead modulated by other task demands, which are likely to reflect a range of other supervisory and control processes.

The second system concerns reward and value-based learning [34,134,135]. For example, some authors have made the case that basic principles of learning, such as those grounded in Pavlovian and instrumental learning, must be considered together with advances in social cognition to
better understand observational learning [34]. Across a range of non-human species, they show that social learning is partly indexed by similar reward centers in the brain that coordinate learning by direct experience. Similarly, in humans, single-neuron recordings have identified neurons in the amygdala that track the expected value of any given trial in a gambling task based on one’s own experience, as well as knowledge gained from watching others [82]. Accordingly, it has been suggested that learning from others is partly mediated by a general-purpose value system in combination with more socially specific processes such as mental state reasoning [34]. Future research building on these value processes and extending them more deeply into the domain of human neuroscience would be particularly valuable, especially given that a strong foundation exists in the non-human literature to guide predictions.

In addition to cognitive control and reward processes, it is also important to consider perspectives that have not yet been widely considered in cognitive neuroscience models of observational learning. Consider semantic cognition research, for instance, which investigates how meaning is extracted from interactions with the environment (e.g., [83,84]). This perspective has recently been applied to social cognition more generally, under the view that observing other people is nothing special and is merely one more way to learn about the world and people in it [85]. Another example is research on memory systems. Recent theoretical work makes the case for how research on impression formation, which is a form of learning about people and their trait characteristics, could benefit from a much greater consideration of developments in the neuroscience of memory [86]. The proposal outlines how distinct types of memory, such as episodic, associative, and instrumental, are associated with distinct but interacting brain circuits, and such knowledge is likely to inform how social aspects of knowledge are stored and retrieved. We would argue that the same lessons apply to research on observational learning. Specifically, important questions to explore include which types of memory systems are involved when we learn from watching others, how the learning or social context shapes their engagement, and how they interface with social information processing systems more generally. One major advantage of considering semantic and memory frameworks in more depth is that they are based on decades of research across multiple species, thus providing a rich foundation to build upon.

Finally, we offer two further proposals. First, to accelerate progress toward understanding how we learn from others in daily life, it will be important to consider the fast-changing developments that are emerging in ‘real-life’ neuroscience [87–89,136]. For instance, how do individuals learn from other people when interacting in groups? How do complex contextual signals, such as person identity, type of action, and setting (e.g., exam conditions, combat, surgery, or leisure time) interfere with or facilitate observational motor learning? Although some laboratory work has taken steps toward understanding action learning among dyads present in a laboratory (as opposed to watching video-based representations of to-be-learned actions; e.g., [10]), current understanding of how learning unfolds in complex real-world contexts where multiple models and environmental pressures and opportunities are present remains limited at the behavioral (let alone neural) level. This progress will require the development of approaches that work both within and beyond the confines of the research laboratory. Portable neuroscience technologies, such as functional near-infrared spectroscopy (fNIRS), may offer a suitable methodological approach to bridge this gap between the research laboratory and the real world [90–92]. Embracing more ‘real-life’ neuroscience approaches will likely further reinforce the need to take an expanded view of the cognitive and brain systems involved in observational learning. A fuller understanding of how we learn from others in daily life stands to further advance several related areas of inquiry, including motor development and learning across the lifespan, how expertise is established, and how best to program robots to accomplish joint actions with human users.
Second, much like neuroscience research more generally, the role of behavior in revealing principles of observational learning should not be undervalued [77]. For instance, in a laboratory sequence-learning task, behavioral research has shown that individual differences in dimensions of personality, working memory, and intelligence play a minimal role in observational learning [93]. Such findings may help to constrain expectations about the underlying brain mechanisms, especially those that may be more or less variable across individuals. That said, while behavioral experiments are certainly crucial for understanding the phenomenon of observational learning, we advocate a pluralistic approach in which investigations across multiple levels of description can play complementary roles in elucidating the links between brain and behavior [77,94–96]. It is becoming increasingly clear that both behavioral and neural data can help to adjudicate between competing mechanistic models and place useful constraints on mechanism discovery in the human brain [97,98].

Overall, our central argument in this section is that, for more substantial progress to be made, we encourage the field to fully embrace research perspectives from separate but related domains. Progress will be facilitated by a greater focus on generalized processes and other general frameworks, which are not necessarily or strictly tied to visual or motor processing per se [99–102].

**Key Figure**

Towards an Expanded Framework of Studying Observational Motor Learning

The mapping between brain systems and cognitive processes is likely complex and ‘many-to-many’ in structure

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**Figure 2.** An updated account of observational motor learning requires concurrent consideration of the role played by distributed brain systems, heterogeneous cognitive processes, and the complexity and context of any given action to be learned. Illustrated in the figure are some possible brain systems (in green) and cognitive processes (in yellow) that are likely to be involved to a greater or lesser extent when we learn from watching others’ actions, depending on the complexity, expertise of the performer and observer, learning context, learner’s motivation, and the model’s identity (in blue). This heuristic is not intended to be exhaustive or prescriptive, and instead suggests some of the contextual, neural, and cognitive features that are likely to shape observational motor learning. We stress that this is a call towards a general approach or framework for studying observational learning, which currently lacks specificity. Indeed, at this point in the development of the framework, we are simply trying to put together a broader set of processes and brain networks than has previously been considered in the context of observational learning. For reasons outlined in the main text, this is an important first step towards firmer progress. However, we acknowledge no hierarchy or prioritization in the proposal – that is, we expect all aspects to be involved to some degree because observational learning is likely to reflect complex, interacting cognitive and brain processes (like all forms of complex cognition). Image sources of the five photographs in middle panel: respectively the authors, Alex Green from Pexels, Ketut Subiyanto from Pexels, Kohinoor Darda, and Olga Guryanova (@designer4u) from Unsplash. Abbreviations: M1, primary motor cortex; PMd, dorsal premotor cortex; SPL, superior parietal lobule.
Concluding Remarks

Our review of the current state of knowledge on the cognitive neuroscience of observational learning raises several considerations for future research (see Outstanding Questions). Studying component processes in isolation and under controlled laboratory conditions has made valuable contributions to understanding cognitive and brain mechanisms of observational learning and will continue to do so. At the same time, an overemphasis on one system or process can give the illusion that complex and multifaceted processes can be reduced to the workings of a few solitary cognitive and brain subsystems [103, 137].

Future observational learning research may benefit from taking a different starting point, which is predicated on an updated and richer set of assumptions (Figure 2, Key Figure). We suggest that it will be valuable to start from a position that expects a large number of ‘many-to-many’ mappings between cognitive processes and brain circuits. To better understand how we learn from others in the real world, the contributions of a multitude of factors (social, semantic, motivational, contextual) that may up- or downregulate basic observational learning processes must be considered. A consequence is that, to understand basic motor processes, one must understand how they operate in tandem with a diverse set of social goals that those actions sometimes serve. This is not to say that all research in this domain should change tack to focus exclusively on interactions between and integration across networks. Instead, going forward, a combination of functional segregation and integration perspectives will be necessary. One particular promising approach for accelerating progress toward a deeper understanding of observational motor learning is the type of neural network modeling that is gaining momentum in human motor learning research (e.g., [104–106]).

A combination of methodological and theoretical expertise from a wider range of cognitive neuroscience subdisciplines should bring this field closer to characterizing how the human brain can translate information about other people’s actions from observation into sound tooth-brushing technique, the intricate hand and foot moves of Bharatanatyam dance, or the ability to successfully perform minimally invasive surgery.

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Declaration of Interests

The authors declare no competing interests in relation to this work.

References


Outstanding Questions

How, when, and between which cognitive and brain systems does functional integration occur during observational learning?

How can laboratory-based research best connect to and inform real-life observational learning processes?

How best can we accommodate contributions made by the mirror neuron system to observational learning, while also remaining open and sensitive to the influence of non-mirror neuron structures and systems whose influence might be more subtle and context-specific?

Especially during the current time of pandemic-related social isolation and the consequent shift to online instruction for millions of students of all ages, to what extent can people learn complex new motor behaviors from video-based instruction alone, and what do live, embodied models contribute to learning above and beyond screen-based instruction?

How are observational learning-related increases and decreases in neural engagement related to performance and efficiency gains across time, and how do these fluctuations in engagement relate to those seen during physical practice/learning?

To what extent do the performance gains reported in existing observational motor learning studies reflect the learning of explicit cognitive strategies and heuristics versus learning that is largely implicit and automatic?

How might the contributions of different neurocognitive systems to observational learning be up- or downregulated to improve observational learning in laboratory as well as real-world contexts?

How dynamic is the interplay between different cognitive and brain systems during observational learning, and how does this interplay change throughout the lifespan? How might factors such as motor development, skill, semantic knowledge, and memory shape how we learn from others in motor and non-motor contexts, from early life through to advanced age?