Trends in
Cognitive Sciences

CellPress

Review

The Treachery of Images: How Realism Influences Brain and Behavior

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Although the cognitive sciences aim to ultimately understand behavior and brain function in the real world, for historical and practical reasons, the field has relied heavily on artificial stimuli, typically pictures. We review a growing body of evidence that both behavior and brain function differ between image proxies and real, tangible objects. We also propose a new framework for immersive neuroscience to combine two approaches: (i) the traditional build-up approach of gradually combining simplified stimuli, tasks, and processes; and (ii) a newer tear-down approach that begins with reality and compelling simulations such as virtual reality to determine which elements critically affect behavior and brain processing.

Highlights

Although commonly utilized in cognitive neuroscience, images evoke different behavior and brain processing compared with the real, tangible objects they aim to approximate. Differences have been found in perception, memory, and attention. One key factor in differences appears to be that only real objects can be acted upon.

Evolution and development are shaped by the real world. Shortfalls between proxies and reality are especially evident in other species and in young children, who have not learned to comprehend representations as human adults can.

New technologies and new experimental approaches provide the means to study cognitive neuroscience with a balance between experimental control and ecological validity.

In addition to the standard approach of building up ecologically valid stimuli from simpler components, a complementary approach is to use reality as the gold standard and tear down various components to infer their contributions to behavior and brain processes.

The Dependence on Proxies for Realism in Cognitive Sciences

In a famous painting, *The Treachery of Images*, artist René Magritte painted a pipe above the words 'Ceci n'est pas une pipe' ('This is not a pipe'). When asked about the painting, he replied, 'Could you stuff my pipe? No, it's just a representation, is it not? So if I had written on my picture 'This is a pipe', I'd have been lying!' [1]. Magritte had an insight that applies even to psychology and neuroimaging: a picture of an object is only a limited representation of the real thing.

Despite such intuitions regarding the importance of realism, researchers in the cognitive sciences often employ experimental **proxies** (see Glossary) for reality. One ubiquitous proxy is the use of artificial 2D images of stimuli that are not actually present, evoking indirect perceptions of depicted objects or scenes [2]. Images predominate over real objects in research because they are easy to create, easy to present rapidly with accurate timing on computer displays, and easy to control (e.g., for low-level attributes like brightness). Researchers will often use the phrase 'real world' to imply that some feature of the image matches some aspect of reality (such as category, image statistics, familiar properties like size, or implied depth), even though the stimuli are not real objects, which we define as physical, tangible 3D solids (Box 1).

Here, we address whether behavior and brain responses to real objects may differ from images. Although the potential theoretical importance of realism has been recognized for decades [2], there is an emerging body of empirical evidence for such differences. With the advent of human neuroimaging, our understanding has expanded from the earliest stages of visual processing (e.g., V1) to higher-level brain regions involved in recognition and actions in the real world. Correspondingly, our understanding of vision and cognition may need to progress beyond light patterns and images to encompass the tangible objects and scenes that determine everyday behavior.

Why Might Proxies Differ from the Real World?

Before reviewing empirical evidence for differences between proxies and the real world, we note that philosophically, there are reasons to posit such differences.

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Box 1. Terminology for Visual Stimuli

One of the challenges in understanding differences between stimuli is the conflicting nomenclature used by different researchers. Some of the confusion could be remedied by adopting a consistent set of terms:

2D Images

2D images are planar displays that lack consistent cues to depth. Most commonly, 2D images are presented via a computer to a monitor or projection screen; however, they can also be printed. They may differ in **iconicity,** the degree to which the picture resembles the real object [118], ranging from line drawings to photographs. Typically, 2D images provide only monocular cues to depth (e.g., shading, occlusion) but no stereoscopic, oculomotor, or **motion-parallax** cues to the depth of components within the image. 2D images often misrepresent the size of the depicted object, with unrealistic relationships between physical size, distance, and familiar size.

3D Images

3D images are generated by presenting two 2D images, one to each eye, that provide stereoscopic cues to depth. They assume a fixed head position and do not provide motion parallax if the observer moves.

Real Objects

Real Objects are tangible solids that can be interacted with. We prefer not to use the term 3D objects, which implies that the key difference from 2D images is the third dimension (versus other potential differences such as tangibility or actability). Although many researchers use the terms real or real-world for images that depict real objects, confusion could be avoided by limiting the use of real to physical objects and using other descriptors like realistic for representations that capture reality incompletely.

Simulated Reality

Simulated reality (SR) includes approaches that aim to induce a sense of immersion, presence, and **agency**. In virtual reality (VR), a computer-generated simulated environment is rendered in a head-mounted display (HMD). The display provides stereoscopic 3D depth cues and changes as the observer moves, giving the observer the illusions of presence and agency. VR may also enable interactions with objects, typically through hand-held controllers. In augmented reality (AR), computer-generated stimuli are superimposed on an observer's view of the real environment (through a transparent HMD or passed through live video from cameras attached to the HMD). Some use the term mixed reality to encompass VR and AR; however, the term is used inconsistently (sometimes being treated as synonymous with AR), so we propose the term SR. SR could also include other approaches that are technically not VR or AR, such as game engines that present stimuli on monitors or 3D projectors rather than HMDs.

Realism versus Symbolism

As Magritte highlighted best, while tangible objects satisfy needs, images are representational and often symbolic (e.g., cartoons). Images have a unique duality because they are both physical objects comprising markings on a surface, and at the same time, they are representations of something else [2–5]. Humans can easily recognize images such as line drawings; however, such representational images are a relatively new invention of humankind, with cave drawings appearing only within the past 45 000 years [6] of the 4–5 million years of hominin evolution. Moreover, pictures were highly schematic (such as outlines with no portrayal of depth) until artists learned how to render cues like perspective during the Renaissance and to use photography and film in the 19th century [7]. With increasingly compelling simulations, such as VR, there is increased awareness of the potential importance of **presence**, the sense of realism and immersion [8,9].

Actability

Animals have evolved to survive in the natural world using brain mechanisms that perform actions guided by sophisticated perceptual and cognitive systems. Modern cognitive neuroscience relies heavily on reductionism, using impoverished stimuli and tasks that neglect the importance of actions as the outcomes upon which survival has depended for millions of years [10]. Despite the importance of action outcomes for evolutionary selection, historically, psychology has neglected motor control [11], even though all cognitive processes, even those that are not explicitly motor (e.g., attention and memory), evolved in ultimate service of affecting motor behavior [12]. Increasingly, researchers are realizing that theories developed in motor control, such as

Glossary

Actability: whether a person can perform a genuine action upon a stimulus. For example, a nearby object may be reachable, and if it has an appropriate size and surface characteristics, also graspable. For example, a tennis ball within reach or being lobbed toward one is directly actable, a tennis ball lying on the other side of the court is not, and a cactus within reach may not be.

Action associations: the semantic concepts evoked by a stimulus, even an image or a word, based on long-term experiences. For example, seeing an image of a knife may evoke the idea of cutting but not be actable.

Affordance: defined by J.J. Gibson as 'an action possibility formed between an agent and the environment'. Despite its widespread use, there is little consensus on its meaning, which can include action possibilities in strict Gibsonian definition, semantic associations with objects (see Action associations), or the potential for genuine interaction (see Actability). Depending on the definition, it is unclear whether images can evoke affordances; in our view, they may evoke associations and allow inferred affordances but not enable actability or true affordances.

Agency: the feeling of control over one's environment. For example, a computer user who sees a cursor move while actively moving the mouse will experience a sense of agency.

Iconicity: the degree of visual similarity between a picture and its real-world referent.

Immersive neuroscience: a proposal for a new approach in cognitive neuroscience that places a stronger emphasis on real stimuli and tasks as well as compelling simulations such as virtual reality.

Motion parallax: differences in the speed of retinal motion from objects at different depths for a moving observer, which can be used to extract 3D relationships from retinal images, even monocularly.

Presence: the compelling feeling that a virtual stimulus or environment is real.

Proxy: a stimulus or task that is assumed to accurately represent a counterpart in the real world.

Real-object advantage: improvements in behavioral performance, such as improved memory or recognition, for real objects compared with images.

the importance of forward models and feedback loops [13], may explain many other cognitive functions from perception through social interactions [14]. As such, one must question why so many cognitive studies use stimuli – particularly static images – that do not afford motor behavior or use tasks no more sophisticated than pressing a button or uttering a verbal response.

Importantly, images do not afford actual actions. Images may evoke notions of **affordances** [15] and **action associations** [16] but they lack **actability**, the potential to interact with the represented object meaningfully. Put simply, one cannot pound a nail with a photo of a hammer.

Multisensory Processing

In addition, images are purely visual and thus lack genuine crossmodal processing. For example, when determining the ripeness of a peach, color provides some cues to ripeness but ideally this is confirmed by assessing how well it yields to a squeeze, smells fragrant, and tastes sweet and juicy. Multisensory processing not only allows more accurate interpretation of objects in the world, but it also enables hypotheses generated from one sense to be tested using another. Yet pictures are rarely touched (by adults) and haptic exploration would merely confirm the flatness conveyed by vision.

Motion and Depth

Even in terms of vision alone, images are impoverished. Most notably, images never change, although videos can be used to convey animation. In addition, images lack a veridical combination of depth cues. Whereas pictures can accurately convey relative depth relationships (e.g., the ball is in front of the block), they have limited utility in computing absolute distances (e.g., the ball is 40 cm away, within reach, and the block is 90 cm away, beyond reach). Thus images do not enable the determination of real-world size and actability. With images, depth cues may be in conflict: monocular cues (e.g., shading, occlusion) convey three-dimensionality while **stereopsis** and **oculomotor depth cues** convey flatness and implausible size–distance relationships. For example, in typical fMRI studies, stimuli may include large landmarks (e.g., the Eiffel tower) and small objects (e.g., coins) that subtend the same retinal angle at the same viewing distance even though their typical sizes differ by orders of magnitude in the real world. Compared with static images, dynamic movies have been found to evoke stronger activation in lateral (but not ventral) occipitotemporal cortex [17–19]. The addition of 3D cues from stereopsis evokes stronger brain responses and stronger inter-regional connectivity, compared with flat 2D movies [8,20]. 3D effects are stronger for stimuli that appear near (versus far) and the effects increase through the visual hierarchy [21]. Notably, previous studies have not investigated real objects, where motion and depth may be especially important for both action and perception.

Development

Not only are these factors important for object processing in adults, they are also fundamental during early development. Infants learn to make sense of their environment largely through the interactions and multisensory integration provided in the tangible world. Young infants fail to understand that images are symbolic and may try to engage with them [22]. Bodily movement and interaction with objects are crucial to child development, as shown by the quantum leaps in cognitive abilities that occur once infants become mobile [23–25]. Indeed, as classic research has shown, humans [26] and other animals [27] require self-initiated active exploration of the visual environment for normal development and coordination. Realism can also have striking effects on object processing in human infants and young children, as well as in animals (Box 2).

In summary, because humans have evolved and developed in the real world, our behaviors and brain processes are likely to reflect the important features of tangible objects and environments – tangibility, actability, multisensory processing, and motion and depth.

Real-object preference: a preference to look at real objects more than images.
Stereopsis: differences in the relative positions of a visual stimulus on the two retinas (also called binocular disparity) based on differences in depth, which can be used to extract 3D relationships from the retinal images.
Vergence–accommodation conflict: two important cues to absolute distance are vergence, the degree to which the eyeballs rotate inwardly so that the fixated point lands on the foveae, and accommodation, the degree to which the lenses of the eyes flex to focus the fixated object on the retinas. On VR/AR displays, the lenses accommodate to the screen at a fixed distance, but the eyes converge at distances further away, often causing discomfort, fatigue, and feelings of sickness.

Box 2. Realness Influences Behavior in Human Infants and Animals

Similar to adults, children's object recognition is influenced by the realness of the stimuli and tasks. Object recognition in infants has traditionally been investigated using habituation tasks, which are based on infants' general preference for new stimuli over previously seen items, as reflected in looking and grasping behaviors [119]. Capitalizing on this novelty preference in habituation tasks, infants are initially exposed (or habituated) to a stimulus, such as a picture of a shape or toy, and are subsequently presented with a different stimulus, such as a real object, to see whether or not habituation transfers to the new item. Habituation studies have shown that human infants can perceive the information carried in pictures even with remarkably little pictorial experience. For example, newborn babies can discriminate between basic geometric figures that differ in shape alone [120] and between 2D versus 3D stimuli [121,122]. By 6–9 months of age, infants can distinguish pictures from real objects. Moreover, infants show generalization of habituation from real objects to the corresponding 2D pictures [122–124], and from 2D pictures to their real objects [124,125]. Although picture-to-real object transfer in recognition performance improves with age and iconicity [118], this does not mean that infants understand what pictures are. Elegant work by Judy DeLoache and colleagues, for example, has shown that when given colored photos of toys, young infants initially attempted to grasp the pictures off the page, as do children raised in environments without pictures (such as Beng infants from West Africa) [22]. As in habituation studies showing picture-to-object transfer, manual investigation of pictures of toys is influenced by how realistic the pictures look, with more realistic pictures triggering greater manual investigation [126]. In a comprehensive review of the literature on picture perception, Bovet and Vauclair [28] concluded that a diverse range of animals (from invertebrates through great apes) can show appropriate responses to depicted stimuli, particularly ecologically relevant stimuli such as predators or conspecifics. Similar to human infants, such effects in animals appear strongest when animation or three-dimensionality are present and with increased exposure to pictorial stimuli. Nevertheless, their review highlights many cases where animals, infants, and individuals from cultures without pictures fail to recognize depicted objects. Such results suggest caveats for interpreting animal neurophysiology studies of object recognition that rely on images.

Empirical Evidence for the Importance of Real Objects

Despite theoretical arguments for the importance of real objects for understanding behavior and brain function, surprisingly few empirical studies have used real-world stimuli or directly compared responses with stimuli in different formats. However, with the development of novel methods for presenting real objects under controlled conditions (Figure 1), there is growing evidence that real objects elicit different responses compared with images.

Object Recognition

Recognition performance may be better for real objects compared with pictures, an effect known as a **real-object advantage**, in both neuropsychological patients and typical individuals. Although patients with visual agnosia are typically unable to recognize 2D pictures of everyday objects, they can often recognize objects presented as real-world solids [29–36]. The real-object advantage in agnosia patients appears to be related to expectations about the typical real-world size of tangible objects – information that is not available in 2D images. Specifically, patients with visual agnosia perform better at object recognition for tangible objects than pictures but only when the physical size of the real objects is consistent with the typical real-world size [37].

A driving factor in the real-object advantage seems to be actability. An electroencephalography (EEG) study that found that, compared with matched images, real tools invoked a stronger and more sustained neural signature of motor preparation contralateral to the dominant hand of participants [38]. Moreover, a neuroimaging study found different neural representations for real, tangible objects versus similar images during hand actions, particularly when 3D cues conveyed important information for grasping [39]. Notably, not all phenomena show a real-object advantage, and this can provide clues as to the nature of processing. For example, realism does not influence tool priming, suggesting that this particular phenomenon relies on a semantic process unaffected by actability [40,68].

Although we have focused on visual objects, realism may also be important for sensory processing and recognition in domains other than vision. For example, audition researchers are coming to

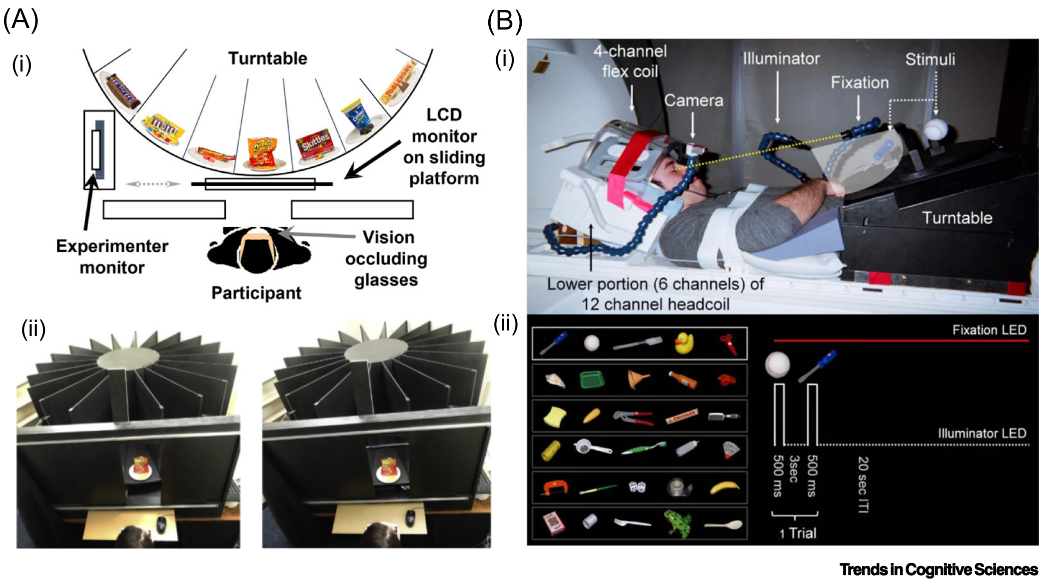


Figure 1. Methods Used to Study Behavior and Brain Responses to Real Objects. Innovative methods used to compare responses to real objects and representations. (A) Example from behavior. (i) In a recent study of decision-making, Romero *et al.* [56] used a custom-built turntable device to display a large set of real objects and closely matched 2D computerized images of everyday snack foods. Schematic shows the experimental setup from above. On real object trials the stimuli were visible on one sector of the turntable; on image trials the stimuli were displayed on a retractable monitor mounted on a sliding platform. Stimulus viewing on all trials was controlled using liquid-crystal glasses that alternated from transparent (closed) to opaque (open) states. (ii) Real object trial (left); image trial (right). Although stimuli are shown from above here, from the participants' viewpoint, displays appeared similar except for differences in depth. Adapted with permission from Romero *et al.* [56]. (B) Presenting observers with real objects is especially challenging within fMRI environments. (i) Snow *et al.* [52] used fMRI to compare brain responses to everyday real-world objects versus photos. Using a repetition-suppression design, pairs of real/picture stimuli were presented from trial to trial on a turntable mounted over the participant's waist. Following from Culham *et al.* [129], the head coil was tilted forwards to enable participants to view the stimuli directly, without the use of mirrors. (ii) On each trial, two objects (lower left), each mounted on opposite sides of a central partition, were presented in rapid succession. Stimulus viewing on each trial was controlled using time-locked light emitting diode (LED) illumination; gaze was controlled using a red fixation light (lower right). Abbreviation: ITI, intertrial interval.

realize that a large body of research using simple tones may not generalize to natural sounds [41–44].

Memory

Real objects are more memorable than 2D photographs of the same objects. When asked to remember everyday objects, free recall and recognition were both superior for participants who viewed real objects compared with those who viewed colored photographs or line drawings [45]. Realism may be particularly important for the study of episodic memory, which is heavily framed by the context [46].

In an EEG study, a neural correlate of familiarity for previously seen stimuli (the old–new effect) was stronger when objects were first seen in real format then picture format compared with the converse [38]. These results suggest that stimuli that were first encountered as real-world objects were more memorable than their pictures [45].

Attention and Gaze Preferences

Real objects also capture attention more so than 2D or 3D images. When participants were asked to discriminate the orientation of tools (spoons), their reaction times were more affected by the orientation of irrelevant distractor objects when the stimuli were real objects compared with pictures or stereoscopic 3D images [47]. Critically, the stronger attentional capture for real stimuli depended on actability. When the stimuli were positioned out of reach of the observer, or behind a transparent barrier that prevented in-the-moment interaction with the stimuli, the real objects elicited comparable interference effects as did the 2D images. The use of a transparent barrier is a particularly elegant manipulation because it removes immediate actability while keeping the visual stimulus (including 3D visual cues) nearly identical.

Studies of eye gaze also suggest that real objects capture attention more effectively than pictures, an effect we term the **real-object preference**. For example, when infants as young as 7 months see a real object beside a matched photo, they spend more time gazing at the real object, even if they have already habituated to it [48]. Moreover, the preference for real objects is correlated with the frequency with which individual infants use touch to explore objects, suggesting that actability and multisensory interactions are key factors [49]. Macaque monkeys also spontaneously look at real objects longer than pictorial stimuli [50].

Neural evidence suggests that real objects are processed differently than matched pictures, consistent with behavioral preferences and mnemonic advantages for real objects. While repeated presentations of object images lead to reduced fMRI activation levels, a phenomenon called repetition suppression [51], surprisingly, such repetition effects were weak, if not absent, when real objects were repeated [52].

Neural evidence from humans and non-human primates suggests that brain responses in action-selective regions are driven by actability, with stronger responses in action-selective brain regions to real objects that are within reach [53], especially of the dominant hand [54]. Indeed, the responses in some neurons is reduced or eliminated when a real object is placed beyond reach or blocked by a transparent barrier [55]. In studies of human decision-making, real food is considered more valuable [56,57] and more irresistible [58] than images of food [59], particularly when it is seen within reach [57,60].

Attention also appears to be modulated by the cognitive knowledge that an object is real, including the recognition that real interactions would have real consequences. That is, actability may include not just the ability to grasp and manipulate stimuli but for those stimuli to have real ecological consequences. As one example, participants who believed a real tarantula [61] or snake [62] was approaching showed robust activation in emotion-related regions, apparently stronger than for images [63].

Quantitative versus Qualitative Differences between Real Objects and Images

Accumulating evidence certainly suggests that, compared with artificial stimuli, realistic stimuli lead to quantitative changes in responses, including improvements in memory [45,46], object recognition [37], attention and gaze capture [47,48,50], or valuation [56,57]. These findings signal that realistic stimuli can amplify or strengthen behavioral and brain responses that might otherwise be difficult to observe when relying on proxies.

Although it may be tempting to dismiss quantitative changes as trivial, large changes can nevertheless be meaningful. Some quantitative differences in responses between real objects versus images may stem from low-level attributes (such as the absence of stereopsis and oculomotor depth cues), and may thus seem uninteresting; however, these cues provide a gateway to higher-level stimulus characteristics, such as egocentric distance and real-world size, which are important for actability. Moreover, when research statistics have limited power, especially in neuroimaging studies where costs limit sample sizes, boosts to effect sizes can affect the detectability of meaningful effects. However, given that artificial stimuli are easier to generate and present in the laboratory than real ones, an alternative approach to tackling quantitative differences would be to rely on proxies but compensate for attenuated effects, for example, by designing experiments to maximize power (e.g., with larger sample sizes).

Although quantitative differences are of theoretical and practical interest, a vital question for ongoing and future research is whether stimulus realism leads to qualitative differences. Qualitative differences would be reflected, for example, by different patterns of behavior, or by activation in different brain areas or networks, for real objects versus artificial stimuli. This question is vital because qualitative differences suggest that the conclusions about behavior and brain processing generated from studies using images may not generalize to real stimuli. Finding qualitative differences associated with realism could enrich our understanding of naturalistic behavior and brain function, and critically inform theoretical frameworks of vision and action.

New methodological approaches that address the similarity of behavioral [64] or neural [65] representations (based on the similarity of ratings, or patterns of fMRI activation within a brain region, respectively) can assess qualitative differences in the way real versus artificial stimuli are processed, over and above differences in response magnitude. Using these approaches, recent studies have begun to reveal qualitative differences arising from realism.

Real and simulated objects appear to be represented differently in typical adult participants. When observers are tasked with manually arranging a set of graspable objects by their similarities, their groupings differ between pictures, real objects, and virtual 3D objects presented using augmented reality (AR) [66]. Using a computer mouse, observers group pictures of objects by a conceptual factor, the objects' typical location. By contrast, using the hands to move virtual 3D projections of objects using AR, observers arrange the items not by their typical location but rather according to their physical characteristics of real-world size, elongation, and weight (rather surprisingly as virtual objects have no actual mass). Observers who lift and move real objects incorporate both conceptual and physical object properties into their arrangements. Thus, changes in the format of an object can lead to striking shifts in responses. Objects that can be manipulated using the hands, either directly in reality, or indirectly via AR, evoke richer processing of physical properties, such as real-world size and weight. Such results suggest that experimental approaches that rely solely on images may overestimate the role of cognitive factors and underestimate physical ones.

We propose a testable hypothesis: the factors that contribute to behavioral and neural differences (both qualitative and quantitative) will depend upon the processes being studied and the brain regions and networks that subserve them. For example, images may be a perfectly good, arguably preferable [67], stimulus for studying low-level visual processes at the earliest stages of the visual system (e.g., primary visual cortex). Even at higher levels of visual processing concerned with perception and semantics (the ventral visual stream), images may effectively evoke concepts to a comparable degree as real objects [40,68]. However, higher levels of visual processing for representing space and actions (the dorsal visual stream) [69,70] are likely to be strongly affected by depth [71–74], and actability [53].

From Stimulus Realism to Task Realism

In addition to enhancing the realness of stimuli, cognitive neuroscience will also benefit from approaches that allow more natural unfolding of cognitive processes. Growing evidence suggests that real actions affect behavior and brain processes differently than simulations. For example, real actions differ from pantomimed or delayed actions, both behaviorally and neurally [75–78].

Cognitive neuroscience uses a reductionist taxonomy of siloed cognitive functions – perception, action, attention, memory, emotion – studied largely in isolation [79] and by structured experimental paradigms with experimenter-defined trials and blocks [80]. Yet, in everyday life, a multitude of cognitive functions and the brain networks that subserve them are seamlessly and dynamically integrated. New naturalistic approaches examine correlated brain activation across participants watching the same naturalistic movie segments [81,82]; the results corroborate findings from conventional approaches [83,84], providing a balance between rigor and realism [85]. Nevertheless, movie viewing is a passive act and may neglect active, top-down cognitive or motor processes.

Many experimental approaches in cognitive neuroscience map stimuli to responses without closing the feedback loop, such that the consequences of one response become the stimulus for the next response [13]. This issue has long been recognized [86] but has had limited impact on mainstream experimental approaches. Alternative approaches advocate for the study of the freely behaving brain [87]. For example, studies of taxi drivers' neuroanatomy [88] and spontaneous cognitions during virtual driving tasks [89,90] have unveiled the neural basis of dynamic real-world navigation. Emerging technologies may enable recording of human neural activity in real-world scenarios [91–95]. Emerging data-driven analysis strategies enable the study of brain processes during broad-ranging stimuli or behaviors [94,96,97], even under natural situations. Rather than trying to isolate stimulus or task features, users of these approaches realize that features that co-occur in the real world are likely jointly represented in brain organizational principles [98,99].

Immersive Neuroscience

Based on the theoretical and empirical differences between reality and proxies, we propose a potential new direction in the cognitive sciences, an approach we call **immersive neuroscience**. The goal of immersive neuroscience is to push the field of experimental cognitive sciences closer to the real world using a combination of realism and, where realism is challenging or impossible, compelling simulations such as virtual reality (VR)/AR. The approach resonates with historical advocacy for an ecological approach [15,100], which is reviewed in depth elsewhere [46,101]. However, the development of new technologies for studying brain and behavior in realistic contexts has dramatically improved in recent decades (Box 3).

We conceptualize the move toward realism as a continuum, with highly reduced stimuli (and tasks) on one end, fully real stimuli (and tasks) on the other, and gradations in between (Figure 2). A typical assumption is that reduced stimuli provide high experimental control and

Box 3. The Potential of Simulated Reality in Research

Thus far, we have presented empirical evidence that the realness of stimuli and tasks affects behavior and brain activation; one key question for moving forward is to determine which aspects of realness matter. Studies that use fully real stimuli are providing important new insights into perception, cognition, and action. Nevertheless, studies that use real stimuli and tasks also present practical challenges that are not typically encountered when using images, such as the need to control or factor out potential confounds. Yet, there are powerful arguments for moving away from approaches in which cognitive and neural processes are studied as if they are discrete decontextualized events, but rather, as a continuous stream of sensory–cognitive–motor loops, reminiscent of how they unfold in naturalistic environments [80].

One emerging tool for both enhancing realism and testing the importance of components of realism is virtual reality (VR) and augmented reality (AR). There is growing enthusiasm for simulated reality (SR) in cognitive sciences because the technology enables a more compelling experience for a user or research participant than conventional (typically computer-screen based) stimuli. VR/AR has the potential to optimize the trade-off between realism and control, though how well they evoke natural behavior and brain responses remains an open question and one that must be actively addressed (Figure I). That is, researchers should not take for granted that VR/AR is a perfect proxy for reality, particularly in light of current technical limitations. Some contend that, because VR and AR can compellingly place the observer egocentrically and actively in a scene, especially through self-generated motion parallax, they evoke a sense of presence and recruit the dorsal visual stream more than much more reduced simulations like 2D images [127]. Others contend that present-day technology is limited in verisimilitude because it may not fully engage action systems without genuine interactions directly with the body (versus handheld controllers without haptic feedback) and displays are limited (e.g., low spatiotemporal resolution, small field of view) [128]. Many of these limitations are under active development by technology firms and will likely improve dramatically in the near future. However, some features are hard to improve, particularly the **vergence–accommodation conflict** and the need for compelling, affordable haptics that do not require cumbersome cybergloves. Moreover, issues such as motion sickness may limit the utility of simulation and no matter how good the technology becomes, people may remain aware that even compelling environments are not real and thus lack complete presence.

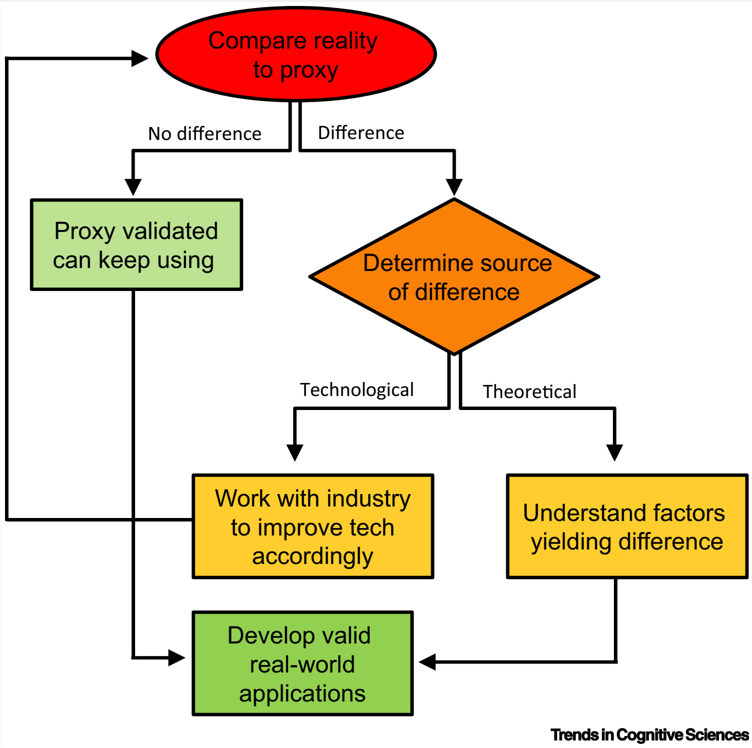
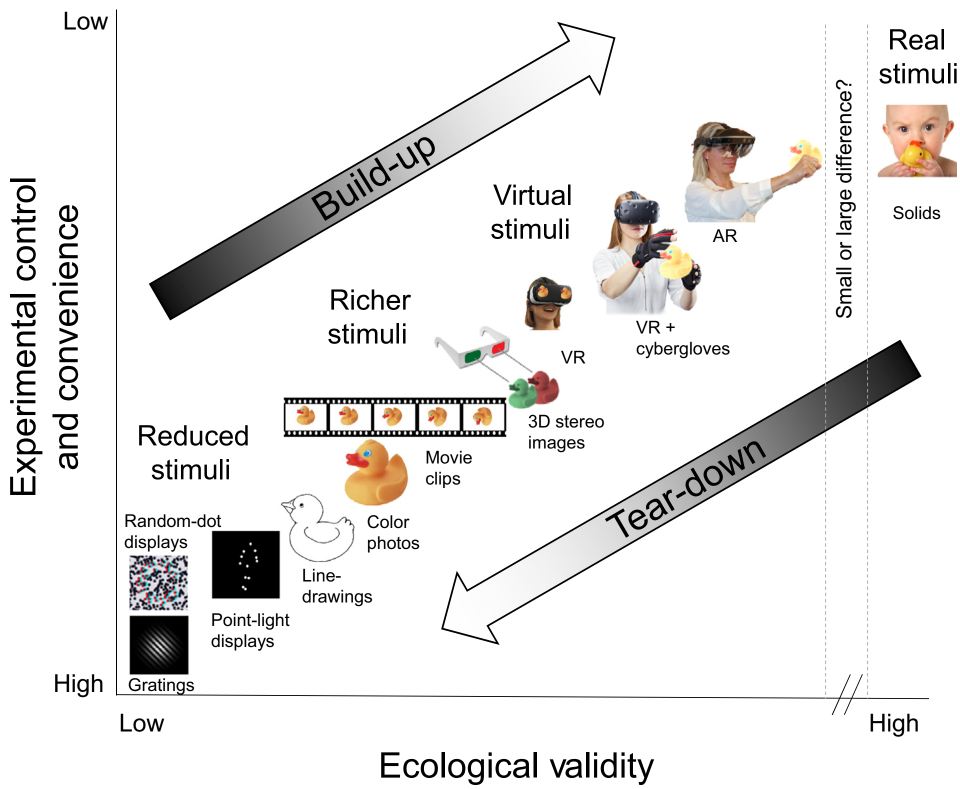


Figure I. Which Aspects of Reality Matter? The flowchart illustrates a sequence to determine and optimize the validity of a proxy for reality.

convenience while sacrificing ecological validity; whereas, real-world stimuli provide the converse (but note that concepts like ecological validity and real world have been criticized as ill-defined and context dependent [102]). However, there are ways of optimizing both control/convenience and ecological validity through well-designed apparatus and protocols [103]. Although we have depicted ecological validity (and control/convenience) as a continuum, effects of stimulus richness may be monotonic but not necessarily gradual. That is, although gradual increases in stimulus realism could lead to gradual changes in behavior and brain responses, it is also plausible that there could be abrupt qualitative changes, for example, between tangible solids and all simulations. Thus, although we are advocating for increasing realism, including better simulations like AR/VR, we view full reality as the empirical gold standard against which simulations should be assessed. Moreover, although we have depicted a continuum of realness according to visual richness, the relevant stimulus dimensions may turn out to be highly multidimensional and the dimensions may not be straightforward to define [99].

The immersive neuroscience approach is not intended to suggest that centuries of research using reductionist approaches are invalid, nor that all research necessitates realism. Reductionism is one essential approach in science and starting simple is especially important in the early years of new fields (such as neuroscience, little over a century old, and cognitive neuroscience, mere de-cades old). Moreover, research in the full-blown real world involves many technical challenges that can limit rapid progress [104]. That said, we promote an alternative to the reductionist or build-up approach of only using minimalist stimuli that become gradually combined to add complexity. The alternative is a tear-down approach in which we start with reality and remove components to see



Trends in Cognitive Sciences

Figure 2. Tearing Down versus Building up Approaches. Different stimuli can be conceptualized as falling along a continuum of realness, from reduced or artificial (low in ecological validity, as shown in the lower left), to fully real (high in ecological validity, as shown in the upper right). Although ecological validity and control/convenience are thought to trade off, immersive neuroscience approaches can optimize both through well-designed apparatus and protocols. Answering questions about the importance of realness requires a fundamental shift to incorporate not just the traditional build-up approach, in which cognition is studied by making reduced stimuli gradually more complex, but also a complementary tear-down approach, in which we start by studying responses to fully real stimuli and then gradually remove components. Although tear-down and build-up approaches may not always yield the same results, combining the two methods will permit a fuller understanding of the cognitive and brain mechanisms that support naturalistic vision and action. For example, the importance of stereopsis as a depth cue may differ between a build-up approach using random-dot stereograms [130] and a tear-down approach in which other depth cues (especially motion parallax) are available. A tear-down approach can reveal whether solids are processed qualitatively differently than artificial stimuli (represented by the distance between vertical broken gray lines), in which case responses to real-world solids cannot be predicted by those to pictures or virtual stimuli. We postulate that the gap between artificial stimuli versus real objects may be more quantitative or qualitative depending on the participants' task and the brain area under study. Abbreviations: AR, augmented reality; VR, virtual reality.

which matter (Figure 2). Importantly, the tear-down approach is a complement, not a replacement, to the build-up approach. A third alternative is to relinquish the notion of experimentally dissecting behavior and brain processing at all, instead embracing the complexity of the natural environment in its own right [100,101]. The challenge remains that many current neuroscience techniques are not entirely reality compatible. For example, bringing the real world into the MRI scanner [52] introduces elaborate technical challenges. In such cases, the tear-down approach can determine whether heroic efforts to enhance realism are worthwhile or whether easier proxies (e.g., VR/AR) may suffice.

A comprehensive understanding of the cognitive sciences will likely benefit from the combination of approaches: building up, tearing down, and studying fully natural situations and environments.

While controlled experiments are useful for testing hypotheses about the contributions of components (e.g., whether a component is necessary or sufficient), ecological experiments are useful for testing whether those hypotheses generalize to natural settings, and for generating new hypotheses that consider the complexities of the organism in its environment.

The use of reality and validated proxies also informs cutting-edge computational techniques, such as artificial neural networks [105], which can handle the messy complexities of the natural world, as does the brain itself [106]. As some have recently argued [101], a key factor in the success of modern neural networks is the utilization of large data sets sampled from the real world, including its inherent nonlinearities, redundancies, and interactions. This approach has proven far more successful than earlier approaches in artificial intelligence that have sought sterilized and comprehendible algorithms based on limited input data. Nevertheless, artificial neural networks are often trained on data sets that lack potentially crucial aspects of realism. In vision science, for example, giant databases of static images [107] are used to train artificial neural networks and compare the representations with those in the brain [108–110]. While this approach has been enlightening, especially for ventral-stream perceptual processes, next-generation endeavors could benefit from incorporating 3D depth structure [111], self-generated motion [112], embodiment [106], and active manipulation [113,114]. Such approaches could lead to artificial intelligence that learns in a manner akin to how human infants learn to comprehend and act within the real world through a series of transitions in their active experiences [25,115].

Concluding Remarks

We have reviewed a growing body of literature that emphasizes: (i) the theoretical arguments for why stimulus realism might matter for perception, cognition, and action; (ii) the feasibility of developing approaches, both real and virtual, for enhancing naturalism in research paradigms; (iii) the evidence that realism affects multiple domains of cognition; (iv) the factors that influence the real-object advantage, with actability seeming the most prevalent; and (v) a proposal for how an immersive neuroscience approach could operate and could benefit the field (see Outstanding Questions). In experimental psychology and neuroscience, restricting the stimuli, the tasks and the processes that we investigate may limit our understanding of the integrated workings of sensory–cognitive–motor loops and our theoretical framework of human and animal cognition. Such limitations may hamper the development of real-world applications such as robotics [116] and brain–computer interfaces [117]. We argue that the importance of various components of realism is an empirical question, not merely a philosophical one. Reductionist and virtual proxies may prove appropriate for investigating cognition, but greater validation of these approaches in natural contexts would serve the community well.

Outstanding Questions

How well do common stimuli (e.g., pictures) and tasks developed for cognitive neuroscience research evoke the same behaviors and neural processes as real-world situations? Are differences qualitative or merely quantitative?

When differences between proxies and reality are found, what drives those differences (e.g., three-dimensionality, multisensory attributes, tangibility, actability, ability to fulfill goals, presence)?

Given the long-history of the build-up approach (reductionism) in cognitive neuroscience, how can the tear-down approach be used to ask interesting new questions?

How can simulated realities (VR/AR/game engines) be used to bring cognitive neuroscience closer to realism? How do these technologies need to improve to better simulate reality? How can we optimize the balance between experimental control and convenience versus ecological validity in research? How can simulated realities be optimized for commercial, practical, and clinical applications (e.g., image-guided surgery, VR training, rehabilitation)?

How can cognitive neuroscience study not just natural stimuli and tasks but also the natural cognitive processes of the freely behaving brain?

As the real-world comes to include more technology with simulated stimuli and interactions (e.g., smartphones, computers, VR), how does this affect behavior and brain processing?

As artificial neural network approaches improve, how can they take advantage of the complexities of the natural world and the means by which organisms learn in the natural world?

How can emerging technologies (e.g., functional near-infrared spectroscopy) measure brain activation in humans with fewer constraints and enable real-world neuroscience?

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Declaration of Interests

There are no interests to declare.

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