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Is Visual Perception WEIRD? The Müller-Lyer Illusion and the Cultural Byproduct Hypothesis

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A fundamental question in the psychological sciences is the degree to which culture shapes core cognitive processes—perhaps none more foundational than how we perceive the world around us. A dramatic and oft-cited "case study" of culture's power in this regard is the Müller-Lyer illusion, which depicts two lines of equal length but with arrowheads pointing either inward or outward, creating the illusion that one line is longer than the other. According to a line of research stretching back over a century, depending on the society you were raised in (and how much carpentry you were exposed to), you may not see the illusion at all—an ambitious and influential research program motivating claims that seemingly basic aspects of visual processing may actually be "culturally evolved byproducts." This *cultural byproduct hypothesis* bears on foundational issues in the science, philosophy, and sociology of psychology, and remains popular today. Yet, here we argue that it is almost certainly false. We synthesize evidence from diverse fields which demonstrate that (a) the illusion is not limited to humans, appearing in nonhuman animals from diverse ecologies; (b) the statistics of natural scenes are sufficient to capture the illusion; (c) the illusion does not require straight lines typical of carpentry (nor even any lines at all); (d) the illusion arises in sense modalities other than vision; and (e) the illusion arises even in congenitally blind subjects. Moreover, by reexamining historical data and ethnographic descriptions from the original case studies, we show that the evidence for cultural variation and its correlation with key cultural variables is in fact highly inconsistent, beset by questionable research practices, and misreported by later discussions. Together, these considerations undermine the most popular and dramatic example of cultural influence on perception. We further extend our case beyond this phenomenon, showing that many of these considerations apply to other visual illusions as well, including similarly implicated visual phenomena such as the Ebbinghaus, Ponzo, Poggendorf, and horizontal–vertical illusions. We conclude by outlining future approaches to cross-cultural research on perception, and we also point to other potential sources of cultural variation in visual processing.

Keywords: perception, cross-cultural psychology, visual illusions, modularity

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A fundamental question about human nature is the degree to which culture shapes psychological processes. Many cases of cultural influence are indisputable: The societies we are raised in, and the cultural practices embedded within them, shape our political views (Hoffman, 2015), aesthetic preferences (Masuda et al., 2008), food choices (Monterrosa et al., 2020), religious commitments (Saroglou & Cohen, 2013), and a host of other psychologically relevant variables (Berry, 2002; Heine & Ruby, 2010). Other cases remain the subject of debate: Does culture shape our personalities (Smaldino et al., 2019)? What about our moral reasoning processes (Barrett & Saxe, 2021) or cognitive styles (Nisbett, 2004)?

In these discussions, one case stands above the rest, both for the nature of the claim itself and the data marshaled in its favor: the possibility that cultural forces reach down into perceptual processing itself, literally changing how we see the world around us. This possibility is best represented by a highly influential research program exploring the perception of visual illusions—most prominently the Muller-Lyer (1889) illusion, a classic phenomenon in perceptual psychology that has been the subject of thousands of experimental studies and is a staple of introductory courses and textbooks (Fehr & Hoff, 2011; Galotti, 2017; Heine, 2020; Shiraev & Levy, 2020). The illusion is simple, but the effect is striking: When two lines end in arrowheads pointing inward or outward, the line with inward-facing arrowheads appears longer than the other, even when they are the same length. You can experience this illusion for yourself in Figure 1; anyone in the room with you will probably experience it, too.

A Cultural Byproduct?

Surprisingly, however, this seemingly obvious illusion may *not* be so obvious to everyone after all. In a landmark series of studies

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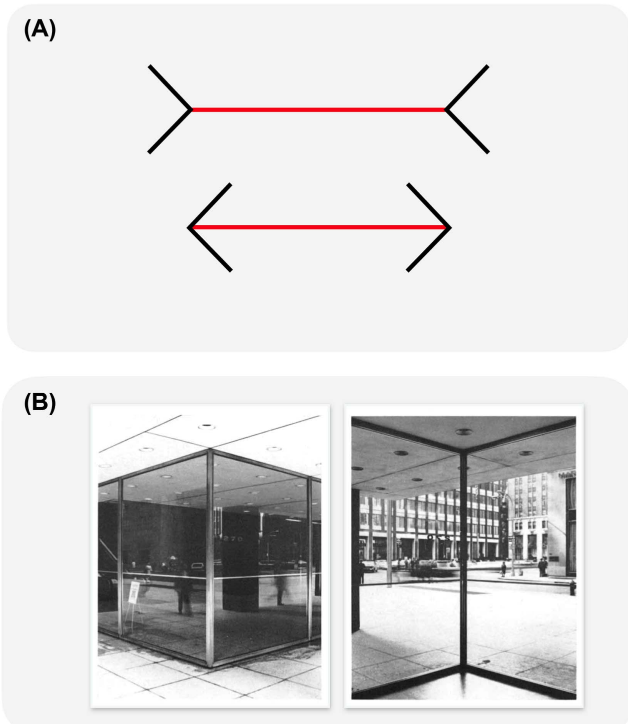
Figure 1
The Müller-Lyer Illusion



Note. (A) The Müller-Lyer illusion. The uppermost red line may appear longer than the red line below it, even though they are in fact the same length on the page. (B) An influential explanation of the illusion holds that the fins are interpreted as 2D projections of the 3D concave and convex corners one would see when standing outside or inside of a physical structure, reproduced from "Visual Illusions," by R. L. Gregory, 1968, Scientific American, *219*(5), p. 71. (https://doi.org/10.1038/scientificamerican1168-66). Copyright 1968 by the Scientific American. Adapted with permission. See the online article for the color version of this figure.

from the middle of the last century, Segall et al. (1963, 1966) showed the Müller-Lyer figure to members of over a dozen societies worldwide and reported tremendous cross-cultural variation in the magnitude of the illusion. Whereas American college students in Evanston, Illinois showed a large effect, members of many other societies were only weakly susceptible to the illusion—and in some cases (e.g., the San peoples, a hunter-gatherer society in southern Africa) seemed not to see the illusion at all. To explain this variation, Segall et al. (and many others since) suggested that the relative presence of *carpentry* in a society—including features such as rectangular dwellings, right angles, and sharp corners—determines whether or not its members see the illusion. We will return to this account in detail below, but its canonical articulation holds that the visual system interprets the illusion's inward- and outward-facing fins as projections of the concave and convex corners appearing in right-angled walls and edges typical of carpentered spaces (see Gregory, 1968). In the most provocative and consequential versions of this hypothesis, this mapping is learned over the course of one's life, as one is repeatedly exposed to carpentered features; thus, individuals raised in environments without an extensive presence of carpentry do not adapt to these regularities in the first place, and so the illusion simply never arises for them.

The Müller-Lyer illusion is just two lines on a page, but the consequences of its alleged cultural variation have been seismic. It has become perhaps the most prominent example for researchers promoting the importance of cross-cultural work (Apicella & Barrett, 2016; Bender & Beller, 2016, 2019; Goldstein, 2019; Gutchess & Rajaram, 2023; Heine, 2020; Henrich et al., 2010; Jahoda, 2011; Keith, 2019; Masuda et al., 2020; Norenzayan & Heine, 2005; Oishi, 2014; Triandis, 1964; van de Vijver et al., 2015; Vari-Lavoisier, 2021), and it has gained enormous amounts of attention in recent years in scholarly publications, popular books, and media (e.g., Alter, 2014; Eller, 2018; Feldman Barrett, 2016; Hockenbury & Hockenbury, 2010; Holmes, 2020; Keith, 2011; Kitayama & Cohen, 2010). Perhaps most prominently, it has been among the strongest pillars in the broader case that psychological research is "Western, educated, industrialized, rich, and democratic (WEIRD)," or overly reliant on samples and findings from WEIRD populations (Henrich et al., 2010). This attention is justified: The work appears to show that a seemingly basic aspect of visual processing does not reflect our genetic endowment or some other innate or universal factor but is instead a "culturally evolved byproduct" (Henrich et al., 2010); if not for certain culturally specific variables, the phenomenon would not exist at all.

Here, we argue that this claim is very likely false, both as an explanation of how the illusion arises in those who experience it, and also as an explanation of its alleged cultural variation. We are in no way the first to express skepticism about such ideas; however, previous discussions have typically focused on their theoretical foundations (e.g., whether there is truly a secure trigonometric basis for Gregory's account; Deręgowski, 2013) or alternative proposals for the illusion's origin (e.g., Carrasco et al., 1986; Chiang, 1968; Coren, 1970; Zeman et al., 2013). By contrast, our discussion here has three salient features. First, we focus primarily on empirical data—that is, on results from experiments that actively contradict the hypothesis that the Müller-Lyer illusion is a cultural byproduct. In many cases, these data have come to light only in recent years, and so were not available to those initially attracted to this idea. Second, although much of our discussion will make reference to accounts that invoke carpentered environments as the driver of cross-cultural variation (if only because of the immense empirical and theoretical significance attached to them), most of our arguments will extend beyond this specific hypothesis to *any* claim that the Müller-Lyer illusion and other related phenomena are mere byproducts of culture. To this end, we introduce a new term—the *cultural by-product hypothesis*—to reflect the stronger and deeper claim that such seemingly universal aspects of visual processing are actually peculiar to certain cultural contexts. Third, we critically analyze the original cross-cultural work, reevaluating over a century of research in both qualitative and quantitative terms in light of our arguments against this hypothesis.

Roadmap

The rest of the article proceeds as follows. The History of the Müller-Lyer Illusion section describes the empirical history of the Müller-Lyer illusion and contextualizes early work on this topic within larger trends in cognitive anthropology, perceptual psychology, and the philosophy of science. The Cultural Byproduct Hypothesis section articulates the specific claims of the cultural byproduct hypothesis. A Critical Analysis of the Cultural Byproduct Hypothesis section, the most substantial section, synthesizes empirical research from diverse disciplines to give five independent refutations of the cultural byproduct hypothesis (see Figure 2 for a visual summary). Indeed, far from supporting claims that the Müller-Lyer illusion is peculiar to certain cultures and time periods, we argue that these data point to the very opposite conclusion: that susceptibility to such illusions arises from innate and evolutionarily ancient biases wired into visual processing, rather than exposure to regularities encountered in development and peculiar to certain cultural contexts (carpentered or otherwise). The Reexamining Historical, Cross-Cultural Data section then turns to the cross-cultural data themselves, reexamining historical data and records to demonstrate that the evidence for systematic cultural variation in these phenomena is far less conclusive than typically assumed, due to oft-unnoticed contradictions across studies, neglected details of site descriptions, and analytical decisions that current practice now understands to be problematic. The Other Visual Illusions section generalizes our case beyond the Müller-Lyer illusion, showing that the considerations from the earlier sections apply to many prominent visual phenomena, including others that have been subject to cross-cultural investigation. Finally, the Outstanding Questions and Future Directions section concludes by encouraging the empirical reassessment of these claims, offering suggestions for future work on this foundational issue and pointing to aspects of visual processing where cross-cultural variation may be more likely.

A History of the Müller-Lyer Illusion

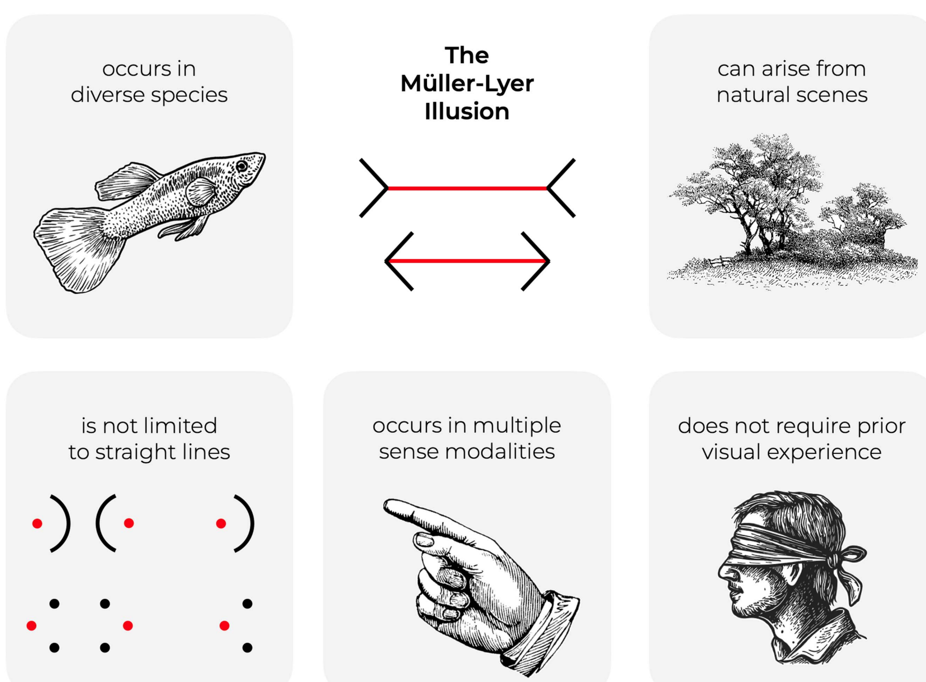
Discovery and Early Observations

In 1889, the German sociologist Franz Carl Müller-Lyer noted a curious phenomenon: A line terminating in a simple obtuse angle appeared longer than one terminating in an acute angle (see Figure 1; Day & Knuth, 1981; Muller-Lyer, 1889). Though his psychophysics career lasted only a handful of years, Müller-Lyer's contributions set into motion over a century of work dissecting what became one of the most prominent perceptual phenomena in history. His own explanation invoked the principle of *confluxion*—that length judgments were not limited to the lines themselves but also took into account surrounding visual stimuli, including the arrowheads (Day & Knuth, 1981). (As if different aspects of the stimuli *confluxed*, or flowed together, by analogy to the meeting point of two rivers.) Müller-Lyer also noted that apparent line length was related to the angle size of the arrowheads and found similar effects with line segments capped by curves rather than straight lines (a point we return to in later sections).

Shortly after its publication, the Müller-Lyer illusion attracted interest not only from perceptual psychologists but anthropologists as well. Indeed, Müller-Lyer's second article—which demonstrated that neither arrowheads nor curved lines are necessary since two equal line

Figure 2

A Visual Summary of Empirical Challenges to the Cultural Byproduct Hypothesis, Using the Müller–Lyer Illusion as a Case Study



Note. The Müller–Lyer illusion arises in species from diverse ecologies, can be captured by the statistic of natural scenes, occurs with stimuli that do not have straight lines, arises in senses other than vision, and is experienced even by congenitally blind subjects whose sight is restored. See the online article for the color version of this figure.

segments sandwiched by shorter or longer lines produce similar effects (Müller-Lyer, 1896)—was largely written to combat the flurry of alternative explanations emerging across diverse disciplines.

Intriguingly, cross-cultural research on the illusion began almost immediately, long before Segall et al.'s (1966) influential work. In 1901, the Müller-Lyer illusion took its first trip outside the industrialized world, when it was included in the task battery of the anthropologist W. H. R. Rivers. During field visits to the Torres Strait and Papua New Guinea, Rivers conducted experiments among indigenous populations, assessing the degree to which visual perception varied across cultures (Rivers et al., 1901). The measurement tool was interactive, presenting the illusion on a surface akin to the lid of a box, with the two line segments joined at either end; participants would move the sliding portion to the point at which they deemed the lines to be of equal length, across 10 trials. When conducted among indigenous Murray Islanders, Rivers found that all individuals were indeed susceptible to the illusion. In a comparison with English adults, however, Rivers noted that the illusion is "distinctly less marked" in Murray Islanders than in Europeans. At the same time, Rivers suggested that differences in performance were not due to differences in cultural environment per se but rather a tendency to focus differently when solving the task (Rivers et al., 1901). In follow-up work with an improved instrument, Rivers (1905) further assessed differences in susceptibility between three groups: the jungle-inhabiting Urális and Sholagas of India, the pastoralist Todas of the same country, and the English. While Toda participants showed a weaker effect than English participants, the Urális and Sholagas of tropical India showed the greatest effect of all (they "experience the illusion more strongly than any other group tested"), even compared to the English—in contrast to both Rivers' prediction and Segall et al.'s later findings (see later discussion for a more thorough assessment of the historical data). Throughout his work, however, Rivers appropriately worried about issues with interpretation and translation and sometimes attributed the differences he observed to these complicating factors (Thurston & Rivers, 1903).

A Tale of Two Research Traditions

These two foundational studies—Müller-Lyer's original discoveries and Rivers' early cross-cultural investigation—mark a striking bifurcation in the illusion's role in theorizing about the mind: a staple of vision science and even a canonical illustration of the inflexibility of visual processing, yet simultaneously a profound demonstration of the malleability of the mind in the face of cultural input.

A Classic of Visual Psychophysics and an Illustration of Modularity

The Müller-Lyer illusion is known to most students of psychology as a figure in a textbook or lecture, where it is presented as a ready example of how appearance can differ from reality, as well as an illustration of core principles of visual processing. Since its discovery, a great deal of scientific attention has focused on explaining it, with many proposals on offer beyond the theories mentioned thus far (i.e., Müller-Lyer's original "confluxion" theory and Gregory's size scaling theory).

The "conflicting cues" theory (Day, 1988), a descendent of Müller-Lyer's original account, holds that the arrowheads influence perception of length by contributing to an averaging process over all of the elements in the figure; since the figure with inward-facing fins is overall longer than the figure with outward-facing fins, the central line comes to look longer too. Relatedly, the "confusion" theory (Sekuler & Erlebacher, 1971) is similar in spirit but points to differences in the intertip distance of the fins as the explanation, and another related account proposes that the fins cause observers to misperceive the locations of the ends of the figure (rather than expand the figure as a whole; Morgan et al., 1990). A more technical instantiation of this family of views explains the illusion by appeal to low-pass spatial filtering (Ginsburg, 1971)—the thought being that attenuating or discarding high-frequency information produces similar effects, perhaps due to differences in how the two sets of arrowheads are resolved (for further evidence for this proposal, see Carrasco et al., 1986). Other explanations take quite different approaches: Efference theories, which trace their origin to Judd (1905), attribute the illusion to patterns in programmed eye movements, which may overshoot the terminating points of the central lines because of the presence of the arrowheads (see also Festinger et al., 1968). Still other theories appeal to diffraction (Chiang, 1968), lateral inhibition (Coren, 1970), and other architectural features of visual processing (Zeman et al., 2013).

A complete account of the Müller-Lyer illusion is beyond the scope of this article; such an account even eludes the field at large. Indeed, given the (at least partial) empirical success of these many theories, it is increasingly thought that the Müller-Lyer illusion may actually reflect multiple coexisting mechanisms, or even multiple parallel paths to producing the same perceptual effects.[1] Notably, however, most of these theories are given without any invocation of the cross-cultural data already known to the literature by this time. For better or for worse, they simply take the presence (and magnitude) of the illusion for granted, and propose general explanations that could account for it in any observer.

Another noteworthy development in this tradition is the *use* of the Müller-Lyer illusion to motivate deeper and more general claims about the mind, its organizing principles, and even their relation to broader societal questions. A particularly influential example is the "modularity of mind" hypothesis, articulated in the 1980s by Jerry Fodor. The modularity hypothesis holds that the mind is divided into specialized modules or systems dedicated to different mental functions. For Fodor, the "essence" of modularity is *informational encapsulation*, such that a module is restricted in terms of the information it can access and so is impervious to external influence in carrying out its function. Fodor posited visual perception (whether considered as a whole or as a collection of subsystems) as such a module, and so held that vision was encapsulated with respect to the rest of cognition (i.e., unmoved by beliefs, desires, emotions, etc.). A prominent argument for his view invokes the Müller-Lyer illusion:

> There is the widely noted persistence of many perceptual illusions … even in defiance of the subject's explicit knowledge that the percept is illusory. The very same subject who can tell you that the Müller-Lyre [sic] arrows are identical in length, who indeed has seen them measured, still finds one looking longer than the other. (Fodor, 1983 p. 66)

[1] "Researchers, therefore, might be wise to entertain the possibility that there are multiple means of producing what appears on the surface to be a single illusion, instead of continuing to pursue a Grand Unifying Theory for Müller-Lyer in all its various disguises." (Woloszyn, 2010; see also discussion in Phillips, 2016)

In other words, knowing that the lines are the same length (and indeed even measuring them to be so) does not get rid of the illusion—just as would be expected if vision were informationally encapsulated. This observation bore enormous consequences for Fodor, not only in giving an account of how the mind is organized but also in making the further case that there can be *theory-neutral observation*—a perennial issue in the philosophy of science concerned with whether we can ever observe the world in ways uncontaminated by our background beliefs and theories, or whether perception is instead hopelessly and exceptionlessly theory-*laden* (Boyd & Bogen, 2021; Kuhn, 1962). Again, Fodor invokes the Müller-Lyer:

> The Müller-Lyre [sic] is a familiar illusion; the news has pretty well gotten around by now. So, it's part of the "background theory" of anybody who lives in this culture and is at all into pop psychology that displays [of the illusion] are in fact misleading and that it always turns out, on measurement, that the center lines of the arrows are the same length. *Query: Why isn't perception penetrated by THAT piece of background theory?* Why, that is, doesn't knowing that the lines are the same length make it look as though the lines are the same length? … This sort of consideration doesn't make it seem at all as though perception is, as it's often said to be, saturated with cognition through and through. On the contrary, it suggests just the reverse: that how the world looks can be peculiarly unaffected by how one knows it to be. (Fodor, 1984 p. 34)

The illusion's persistence played a similar role in Pylyshyn's arguments for the cognitive impenetrability of visual processing ("Knowing that you measured two lines to be exactly equal does not make them look equal when arrowheads are added to them to form the Müller-Lyer illusion"; Pylyshyn, 2003), and even in Daniel Kahneman's case for *dual-process* accounts that divide the mind into two core processes (or types of processes)—those that are intuitive, fast, automatic, and effortless (System 1 processes) and those that are reflective, slow, deliberate, and effortful (System 2 processes).[2] These and still other examples (e.g., Kurzban, 2010) have attached tremendous theoretical significance to the illusion, motivating some of the deepest and most influential claims about the architecture of the mind and its relation to broader human affairs.

Cross-Cultural Variation and the Cultural Byproduct Hypothesis

The above discussion represents only half the story of the Müller-Lyer illusion's influence. Notably, a parallel tradition sees the phenomenon in almost exactly the opposite light—that is, as a paradigm case of the mind's malleability and a testament to culture's power to shape core mental processes. In one of the most ambitious studies in the history of psychology, Segall et al. led a 6-year, worldwide investigation into the influence of culture on visual perception, the results of which were published in *Science* in 1963 and in a longer monograph in 1966. Segall et al. recruited nearly 2,000 participants from 16 diverse cultures around the globe—including large- and small-scale communities in the United States, the Philippines, Senegal, Nigeria, the Congo Basin, and the Kalahari Desert—to complete a battery of tests related to perceptual and geometric illusions.

Most prominent in Segall et al.'s battery was the Müller-Lyer stimulus—in particular, 12 drawings of the illusion with comparison lines printed in red. Each drawing varied in the length discrepancy between the comparison segments; subjects viewed these pairs one at a time and were asked to identify which segment was longer. An index score was created for each individual, reflecting the total number of illusion-supporting responses. Comparing across groups, a striking pattern emerged: Participants classified as "European" were more susceptible to the illusion than "non-Europeans"—so much so that the illusion barely existed at all for some non-European groups.

The study also included a qualitative component in which ethnographers completed inventories of the visual environment in each culture, noting visual features of the natural and built environment. (Was the terrain mostly "dense jungle," or "flat land"? Were dwellings "roughly circular," or "perfectly rectangular"?) By cross-referencing these descriptions with the illusion data, the researchers reported a relationship between the presence of rectangular features—especially those associated with carpentry—and susceptibility to the illusion. Segall et al. interpreted this relationship causally: "highly carpentered, urban European environments … could enhance, or even produce, the Müller-Lyer" (Segall et al., 1963). Their later monograph reported many additional study details and expanded upon this theoretical perspective, which became known as the *carpentered world hypothesis* (Segall et al., 1966).

Follow-up work lent additional support. Cross-cultural investigations among the Inuit of Baffin Island and the Temne of Sierra Leone further suggested a relationship between degree of carpentry and susceptibility to the Müller-Lyer illusion (Berry, 1968), as did comparisons of participants in noncarpentered versus carpentered communities in Zambia (Ahluwalia, 1978; Stewart, 1973) and Ghana (Weaver, 1974).

Contributions by vision scientists added further weight to this account and established a firmer theoretical foundation. Writing in *Nature* in 1963 and 1965, Gregory proposed that the visual system (mis)interprets the 2D fins of the Müller-Lyer illusion as 3D corners of a room or box, which appear smaller or larger, because they are interpreted as being closer or farther in depth:

> [T]he outward-going Müller-Lyer arrow figure is a typical projection of, say, the corner of a room — the fins representing the intersections of the walls with the ceiling and floor — while the in-going arrow is a typical projection of an outside corner of a house or a box, the converging lines receding into the distance. … The parts of the figures corresponding to distant objects are expanded and the parts corresponding to nearer objects are reduced. Thus in the Müller-Lyer figure the [central] line would be further away in the diverging case, and is expanded in the illusion, and vice versa. (Gregory, 1963, p. 678)

The connection to cross-cultural work was explicit. Indeed, Gregory listed two empirical studies in motivating his view. First, he observed that "in primitive races living in houses without corners the geometrical illusions are reduced," citing Segall et al.'s (1963) article and book (the monograph had been available to some researchers several years before it was published); for example, "[P]eople who

[2] Kahneman (2011): "Now that you have measured the lines, you—your System 2, the conscious being you call 'I'–have a new belief: you know that the lines are equal. … But you still see the bottom line as longer. You have chosen to believe the measurement, but you cannot prevent System 1 from doing its thing; you cannot decide to see the lines as equal, although you know they are. To resist the illusion … you must learn to mistrust your impressions of the length of lines when fins are attached to them. To implement that rule, you must be able to recognize the illusory pattern and recall what you know about it. If you can do this, you will never again be fooled by the Müller-Lyer illusion. But you will still see one line as being longer than the other."

live in environments largely free of right angular corners and parallel lines—such as the Zulus who live in a 'circular culture' of round huts—do not suffer these distortion-illusions" (Gregory, 1965). Second, Gregory referenced a patient he had studied:

> In a case of a man blind from the first few months of life, but gaining his sight after operation fifty years later, we have found that the illusions were largely absent. … In fact, it was this observation which suggested to me this kind of theory of the illusions. (Gregory, 1963)

We revisit the issue of blind subjects in a later section; for now it is sufficient to note that a weak or nonexistent Müller-Lyer illusion in observers without exposure to carpentry, corners, and/or parallel lines played a central role in both psychological and anthropological perspectives on the illusion.

A final, significant development in this tradition was the synthesis of these decades of research into a broader framework for understanding the mind and its relation to culture. In one of the most influential psychology articles of the current century, cross-cultural variation in susceptibility to the Müller-Lyer illusion became the most prominent illustration of the claim that psychological research is "WEIRD"—Western, Educated, Industrialized, Rich, and Democratic. Henrich et al. (2010) argued, generally quite compellingly, that psychology has relied too heavily on data from affluent American and European samples, and that this narrow focus often skews the field's findings and assumptions. Importantly, Henrich et al.'s leading example—and most reprinted figure—relied on Segall et al.'s investigation of the Müller-Lyer:

> These findings suggest that visual exposure during ontogeny to factors such as the "carpentered corners" of modern environments may favor certain optical calibrations and visual habits that create and perpetuate this illusion. That is, the visual system ontogenetically adapts to the presence of recurrent features in the local visual environment. Because elements such as carpentered corners are products of particular cultural evolutionary trajectories, and were not part of most environments for most of human history, *the Müller-Lyer illusion is a kind of culturally evolved byproduct*. (Henrich et al., 2010, p. 64, emphasis added)

> Even a process as apparently basic as visual perception can show substantial variation across populations. If visual perception can vary, what kind of psychological processes can we be sure will not vary? It is not merely that the strength of the illusory effect varies across populations—the effect cannot be detected in two populations. (Henrich et al., 2010, p. 64)

McCauley and Henrich (2006) further highlighted the reach of this picture, emphasizing its connection to Fodor's arguments for both modularity and theory-neutrality:

> What Fodor has consistently taken, then, as the single most uncontroversial piece of empirical evidence for the informational encapsulation of the visual input system (and, therefore, for the possibility of theory-neutral observation) is suspect. … What the research of Segall et al. (1966) shows, even with respect to Fodor and Pylyshyn's favorite example, is that informational encapsulation is not comprehensively specified in the human genome, that it is not pervasive, and that there is no consensus about the pertinent stimuli among human observers. (McCauley & Henrich, 2006, p. 98)[3]

These arguments and conclusions have now been widely adopted, echoed by many other researchers in contemporary articles, textbooks, and media (Bender & Beller, 2016; Heine, 2020; Henrich et al., 2023; Lawrence & Low, 1990; Mather, 2006; Matsumoto & Yoo, 2006; Mesoudi, 2007; Norenzayan & Heine, 2005; Oishi, 2014; Oishi & Graham, 2010; Talhelm & Oishi, 2019)—cementing the Müller-Lyer illusion's place as a cornerstone of cultural psychology.

The Cultural Byproduct Hypothesis

The Müller-Lyer illusion may well be the most studied visual stimulus in the history of psychology, and rightly so: On either of the traditions associated with it, it is the basis for deep and wide-reaching claims about the nature of the mind and its relationship to the physical and social environment. The claim that this illusion is a "cultural byproduct" thus bears tremendous significance. In this short section, we precisely characterize what we call the *cultural byproduct hypothesis*, so that it is clear exactly which claims we are evaluating.

The cultural byproduct hypothesis makes two central claims as well as one auxiliary claim.

Central Claim 1: The Müller-Lyer illusion arises from experience with the environment—in particular, through a process of adaptation or calibration to certain visual regularities encountered during one's life.

This is the claim made by researchers who invoke "visual exposure during ontogeny" to variables that "create and perpetuate this illusion" (Henrich et al., 2010).[4] It is also the claim made by Segall et al. (1966), who point to regularities in the visual environment that "enhance, *or even produce*, the Müller-Lyer" (emphasis added). Correspondingly, this aspect of the hypothesis posits that the illusion would not exist if not for exposure to these variables—hence Henrich et al.'s emphasis that "It is not merely that the strength of the illusory effect varies across populations—the effect cannot be detected in two populations," and that "the San foragers of the Kalahari were unaffected by the so-called illusion (it is not an illusion for them)" (Henrich et al., 2010). The same perspective animates Gregory in his invocation of "the Zulus who … do not suffer these distortion-illusions" (Gregory, 1965), as well as his blind patient: "A man of middle-age, who recovered his sight by corneal graft after being blind since infancy, was not subject to the illusions" (Gregory, 1963).[5]

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[3] To be sure, and as McCauley and Henrich (2006) noted, such an influence (if it exists) would at best amount only to "diachronic" penetration of visual perception (which accounts of modularity typically allow) rather than "synchronic" penetration. However, even then it would need to further be shown that other requirements for penetrability are met, and is it unclear whether cultural influences of this sort in fact meet those criteria.

[4] Similarly, Henrich (2008): "Illusions such as this probably came into existence through an interaction between a particular line of cultural-technological evolution and the ontogenetic processes of brain development. Cultural evolution has likely generated changes in brains without any changes in genetics."

[5] In some discussions of the cultural byproduct hypothesis (including Segall et al.'s quotation used here and perhaps Henrich et al., 2023), one occasionally finds the weaker claim that the environment enhances (or attenuates) preexisting biases, causing *variability* in the illusion rather than creating (or eliminating) it. As we shall see in later sections, many of our arguments apply even to these weaker formulations. Still, we focus here on the claim that encounters with certain types of visual information during one's life "create" (Henrich et al., 2010) and/or "produce" (Segall et al., 1966) the Müller-Lyer illusion, both because this perspective is well-attested in the literature, and also because it is simply the more interesting and consequential claim.

Central Claim 2: Observers who experience the Müller-Lyer illusion are the exception, not the rule.

That a seemingly basic aspect of our minds arises from experience with the environment is consequential on its own, but it will not be quite so ground-shaking if the relevant experiences or variables turn out to be universally shared, or nearly so.[6] The cultural byproduct hypothesis goes a step further, then: It also proposes that susceptibility to the Müller-Lyer illusion is the *exception*, both in time and location. This perspective is captured by claims that the relevant environmental variables "are products of particular cultural evolutionary trajectories, and were not part of most environments for most of human history" (Henrich et al., 2010), as well as vivid statements concerning the visual experience of past (and future) humans:

> A plausible argument can be made that through most of our species' history *most* human beings were probably *not* susceptible to the illusion. … For most of human history, people were raised in visual environments closer to those inhabited by people like the Suku and the San than to those characteristic of Evanston, Illinois. In addition, we have no guarantees about the predominant visual environments of human beings in the distant future. (McCauley & Henrich, 2006, p. 99)

Auxiliary Claim: The environmental variables responsible for producing the Müller-Lyer illusion are those associated with carpentered spaces (such as corners, sharp angles, and rectilinear structures).

Although the first two claims above form the core of the cultural byproduct hypothesis, those claims are silent on *which* environmental variables are responsible for creating the Müller-Lyer illusion in those who experience it. However, the most popular, influential, and empirically investigated candidate is the role of "carpentry." This is the explanation put forth by Segall et al. (1966), who invoke "highly carpentered, urban European environments," as well as Henrich et al. (2010, "'carpentered corners' of modern environments may favor certain optical calibrations and visual habits that create and perpetuate this illusion"), Gregory (1965, "angular corners and parallel lines"), Feldman Barrett (2016, "the illusion results as your visual system gets 'tuned' by rectilinear objects like buildings and streets") and others. This account also dovetails with Gregory's size scaling theory, on which the arrowheads are interpreted as projections of the concave and convex corners appearing in right-angled walls and edges typical of carpentered spaces.

Though our primary target here is the first two claims, any assessment of the cultural byproduct hypothesis will inevitably discuss the factor most prominently proposed to explain the illusion's emergence. Our treatment does so as well, though in ways that often go beyond carpentered corners per se—thereby challenging any account that appeals to unique or unusual factors of so-called "urban European environments."

Importantly, characterizing the cultural byproduct hypothesis in this way distinguishes it from other related hypotheses and so motivates this new piece of terminology.

On one hand, as noted earlier, Segall et al. used a different phrase, the *carpentered world hypothesis*, as a label for their view. However, that view is articulated too narrowly for present purposes. For example, if it turned out that exposure to linear perspective in Western art, rather than to carpentered buildings and structures, was responsible for creating the Müller-Lyer illusion, then this would refute the carpentered world hypothesis as literally stated but would do little to undermine most of the implications of Segall et al.'s data. Similarly, given skepticism around Gregory's size scaling account, some of the theoretical grounding for the carpentered world hypothesis is now lacking. For our purposes, however, this does not matter: Our chief interest is in claims that the Müller-Lyer illusion emerges from exposure to visual regularities peculiar to certain cultures, regardless of what those variables might be.

On the other hand, another view sometimes associated with this work is known as the *ecological hypothesis*, which is simply the view that the Müller-Lyer illusion arises from experience with the environment. Though this view is also consequential, it is not quite strong enough to carry the implications discussed here, since it essentially embraces only Claim 1 above (and even then in a weaker form; see Footnote 5).

The cultural byproduct hypothesis, then, is just right: It carries immense empirical, theoretical, and sociological importance, and in ways that are in genuine conversation with key data and arguments. We now turn to assessing this hypothesis.

A Critical Analysis of the Cultural Byproduct Hypothesis

Having characterized the cultural byproduct hypothesis, its implications, and the evidence in its favor, our aim is now to evaluate it. In this section, we synthesize research from diverse fields to offer five refutations of its claims. To preview our case, we present evidence that (a) the illusion is experienced by nonhuman animals from diverse ecologies, suggesting an evolutionarily ancient origin that is not peculiar to humans exposed to Western, urban, or constructed environments; (b) modeling approaches show that the statistics of natural scenes are sufficient to capture the illusion, without an additional role for the built environment; (c) there exist many variations of the illusion that do not require straight lines—nor even any lines at all—calling into question any account that locates the illusion's origin in the presence of lines and corners in one's environment (whether from carpentry, art, or other sources); (d) the illusion arises in sense modalities other than vision, challenging claims that visual exposure is the source of the illusion; and (e) the illusion arises even in congenitally blind subjects whose sight is restored, suggesting that visual experience is not necessary to produce the illusion in the first place.

The Illusion Is Not Limited to Humans, Arising in Diverse Species

A central insight motivating the cultural byproduct hypothesis is that studying broader and more diverse populations can reveal surprising variation—especially cultural variation—in phenomena that were otherwise assumed to be universal (perhaps due to overly narrow sampling in previous work). In the case of the Müller-Lyer, the claim is that the illusion arises in Western observers because of

[6] By analogy: Tooth decay arises from experience with the environment, but it is found to at least some degree in all known societies (because everybody eats). At best, there are simply societies with more or less tooth decay than others. Here too, then, the cultural byproduct hypothesis acquires its import not only because it argues for an ontogenetic origin of the Müller-Lyer illusion, but also because it holds that the illusion arises peculiarly for certain humans in certain unusual times and locations in our history.

some factor peculiar to *them* and their cultural context, rather than a more basic aspect of our shared nature. However, a first strike against this hypothesis comes from broadening the subject pool even further. Specifically, a large and impressive body of work in comparative psychology shows that the illusion arises not only in certain humans at certain times and locations in our history but also in many nonhuman animal species from diverse ecologies, including birds, fish, reptiles, insects, and other mammals (Feng et al., 2017). This observation seems nearly impossible to attribute to cultural forces of the sort invoked to explain the Müller-Lyer illusion in humans and instead points to a deeper and more evolutionarily ancient origin.

Consider a study by Santacà and Agrillo (2020a), which explored susceptibility to the Müller-Lyer illusion in the teleost fish *Poecilia reticulata* (the guppy; see Figure 3). During a training phase, each fish was given a food reward for swimming to the longer of two horizontal lines. After demonstrating proficiency in training, a test phase displayed the Müller-Lyer stimulus, whose two central lines are equal in length. Remarkably, the fish who had learned that approaching a longer line yields a food reward chose to approach the line with inward-facing arrows attached to it, as if it appeared longer to them. Multiple control conditions ruled out confounding factors, including the role of the arrowheads themselves, a preference for whichever stimulus simply took up more space, and other related variables. In other words, the fish perceived the illusion too.

This pattern is not limited to guppies. Susceptibility to the Müller-Lyer illusion has been observed in other fish species (Sovrano et al., 2016), as well as parakeets (Watanabe, 2022), pigeons (Nakamura et al., 2006), horses (Cappellato et al., 2020), capuchins (Suganuma et al., 2007), and bearded dragons (*Pogona vitticeps*, a species of lizard; Santacà et al., 2020). The illusion can even emerge in the foraging patterns of ants (Sakiyama & Gunji, 2013) and the gaze patterns of flies (Geiger & Poggio, 1975). Moreover, the illusion's behavioral effects are apparent not only at the group level but also at the "subject level": In studies that broke down performance by individual animals, a tendency to see the Müller-Lyer illusion was observed in every parakeet, every pigeon, every capuchin, and all but one bearded dragon and guppy.

It is worth being explicit about the significance of this evidence. The cultural byproduct view holds that the Müller-Lyer illusion is an artifact of Western culture, arising in certain populations because of the particular environmental regularities they are exposed to. On this view, the illusion would not exist at all if not for exposure to those regularities, which have been present only at certain times and locations in human history. The comparative work directly challenges this assumption: Observing the Müller-Lyer illusion in diverse animal species that differ from us along many dimensions suggests that the illusion is not specific to some humans at some peculiar times and locations, but rather is quite pervasive and likely reflects a deeper and more enduring aspect of perceptual processing.[7]

A potential objection to this interpretation is that the animals studied above may themselves have been exposed to the same regularities as the Western observers who exhibit the Müller-Lyer illusion. For example, the horses in Cappellato et al.'s (2020) study were reared in a barn, which of course contains carpentered corners of the sort alleged to produce the illusion in humans. Could this explain the animals' performance? First, this account seems rather unlikely in the case of insects such as flies, who seemingly do not interact with human carpentry at the right scale to trigger the kind of learning hypothesized to explain the illusion. But second, other cases above involve carpentry in only a very minimal sense, or in ways that would not be sufficient to teach the animals the required regularities. Consider again the study of guppies (Santacà & Agrillo, 2020a). Here, the fish were reared in a large tank containing only gravel and natural vegetation; and the walls of the tank, though carpentered, were transparent. Moreover, the fish were of course located *inside* the large tank, and so even if they occasionally visited a corner and were able to perceive its geometry (despite the transparent walls), they would only ever have seen concave corners and never convex corners. This last observation is crucial, because Santacà and Agrillo's study included conditions in which one line had no arrowheads and the other line had either outward-facing or inward-facing arrowheads; in *all* such conditions, line choices were consistent with the direction of the Müller-Lyer illusion. Exposure only to concave corners and never to convex corners should predict success in only some of these conditions but not others, such that even if the minimal exposure to carpentry managed to shape the guppies' visual processing, it would still be insufficient to explain their overall pattern of behavior.

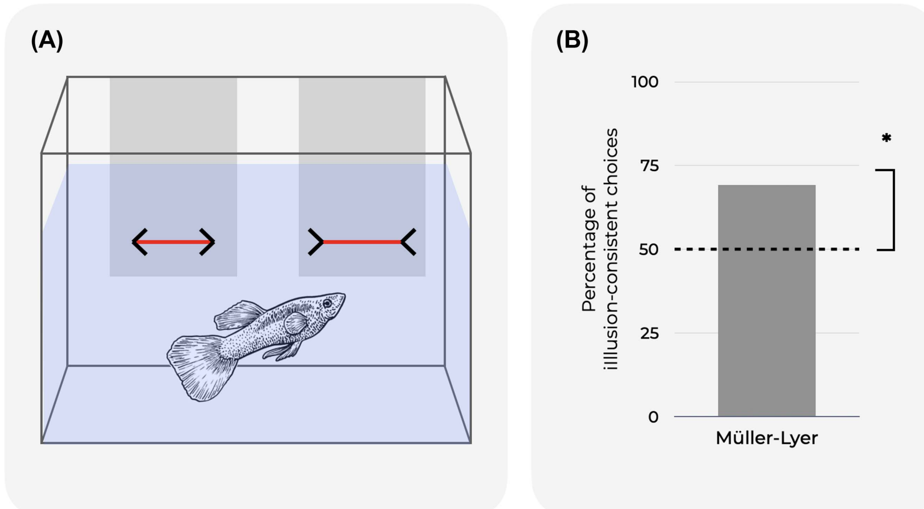
The presence of the Müller-Lyer illusion in these many species thus constitutes a direct and compelling challenge to the cultural byproduct hypothesis and shows how considering diverse populations actually *strengthens*, rather than diminishes, the case for an innate and evolutionarily ancient origin of the illusion.

Natural Scenes Are Sufficient to Capture the Illusion

The cultural byproduct hypothesis holds that the Müller-Lyer illusion arises in the cultures it does because of exposure to environmental variables present in those cultures, whatever those variables might be. A corollary of this claim is that the key environmental variables that produce the Müller-Lyer illusion where it does appear must therefore be absent (or severely attenuated, inaccessible, etc.) in cultures whose members allegedly *do not* experience it; or, put the other way around, whatever environmental variables *are* present in those cultures must be insufficient to produce the illusion, so as to explain why members of those cultures fail to see

[7] While the evidence that the Müller-Lyer illusion is not limited to humans is overwhelming, not every nonhuman species that has been tested has shown susceptibility to the illusion. Notably, one study of domestic dogs (*Canis familiaris*) failed to find evidence of the illusion (Keep et al., 2018). However, this finding does not in any way detract from our argument; if anything, it is more problematic for the cultural byproduct view. First, a compelling comparative challenge to the cultural byproduct account need not require that *every* sighted creature perceive the Müller-Lyer illusion; simply discovering the illusion in a diverse cohort of species is already enough to support the argument that the illusion is not peculiar to some unusual population of humans. But second, on the cultural byproduct view, *Canis familiaris* is perhaps the nonhuman animal that should be *most* likely of any species to show the illusion. The subjects in Keep et al.'s (2018) experiments came from British dog owners who volunteered their pets for a study, so the dogs would have been exposed to the very same urban, carpentered environments as their Western owners. The failure to find Müller-Lyer susceptibility in these dogs, then, underscores our broader point that the key factor in this illusion is the visual system a creature is endowed with, rather than the regularities they are exposed to. Finally, we note further that Keep et al. (2018) themselves included an extensive discussion (and follow-up experiments) interpreted this failure, a point we return to below when discussing the key Segall et al.'s (1966) results.

Figure 3
The Illusion Arises in Diverse Species



Note. Experimental studies with nonhuman animals, such as guppies (shown in A), birds and lizards, have yielded evidence for susceptibility to the Müller-Lyer illusion (shown in B, data from Santacà & Agrillo, 2020a). * = statistically significant. See the online article for the color version of this figure.

it whereas members of other cultures do. This assumption has been the subject of speculation since the very beginning of cross-cultural work on the Müller-Lyer illusion, but without any crucial test to independently confirm or disconfirm it. Recently, however, the emergence of powerful optical and statistical tools to quantify information in naturalistic images has enabled precisely such a test. Its results directly challenge this long-standing assumption by demonstrating that natural scenes can produce the Müller-Lyer illusion all on their own.

Howe and Purves (2005b) created a database of "fully natural" images containing few if any human artifacts and used a LiDAR scanner to acquire distance information for every pixel in every image of the database (see Figure 4). These images featured ordinary, unremarkable scenes of outdoor areas, containing grasses, trees, and gentle slopes (which are, of course, not unique to Western societies).[8] The researchers applied to these scenes geometric "templates" corresponding to the lines and arrowheads of the Müller-Lyer stimulus, and then queried the size of whatever physical source in the image produced the projection that matched the template. Remarkably, this approach revealed that the probability distributions of those physical sources was perfectly in line with the percepts of the Müller-Lyer illusion: When the retinal image contained lines terminating in inward-facing arrowheads, the source of that image was more likely to have been a physically longer object in the world than it was for lines terminating in outward-facing arrowheads. In other words, the connection between inward-facing arrowheads and larger objects is already present in the natural world, even without human artifacts or structures.

This work went further still. Even if information in natural scenes is biased in the direction of the Müller-Lyer illusion, one could still imagine that built environments are even more (perhaps *much* more) biased, in ways that might still predict a stronger illusion in Western observers than in observers from other cultures. To address this, Howe and Purves added to their database another sample of images that included human artifacts and structures and ran the same analyses as above. While the distributions of these images were also biased in the direction of the illusion, they were no different in this respect than the natural images were—that is, they were no more (or less) likely to contain regularities consistent with the Müller-Lyer illusion. Thus, not only is the natural environment sufficient to capture the illusion, but it is *just as good* at doing so as the built environment.[9]

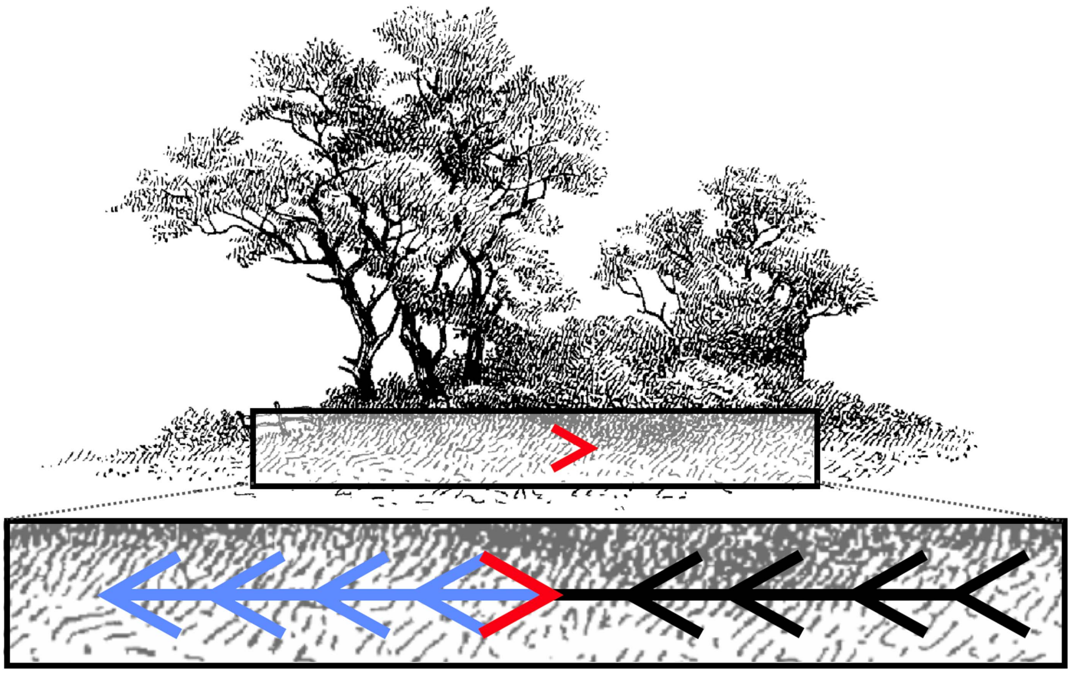
An important upshot of this work was that, in establishing an independent connection between natural scenes and the Müller-Lyer illusion, it opposes the cultural byproduct hypothesis in ways that go beyond the proposed role of "carpentry." As McCauley and Henrich (2006) were careful to note, while the prevalence of carpentered corners has certainly been the most prominent variable proposed to account for cultural variation in the illusion, there are also hypotheses that invoke other environmental variables, such as exposure to visual perspective in art. Thus, for McCauley and

[8] Of course, grasses and slopes are not present in all human societies, some of which are or have been located on ice sheets, sand dunes, and other diverse landscapes. For our purposes, however, what matters only is that the environments studied by Howe and Purves are relevantly similar to at least some of the environments where humans allegedly do not experience the Müller–Lyer illusion.

[9] Note that we are not ourselves committed to the claim that the Müller-Lyer illusion *in fact* emerges from the statistics of natural scenes. Instead, our aim here is only to meet the cultural byproduct hypothesis on its own terms. The cultural byproduct hypothesis holds that features of the visual environment are responsible for the illusion, and that the relevant features are present in Western societies but not elsewhere (or not to the same degree), so as to explain the (alleged) cultural variation. The role of Howe and Purves's (2005b) work was to challenge that assumption by demonstrating that the statistics of natural scenes are, all on their own, (a) biased in the direction of the Müller-Lyer illusion and (b) no more or less biased in that direction than the statistics of the built environment. However, there are reasons to think that a complete explanation for the Müller-Lyer illusion is ultimately broader than this, as we explore in later sections.

Figure 4

Natural Scenes are Sufficient to Capture the Illusion



Note. The Müller-Lyer illusion can be captured by the statistics of image–source relationships in natural scenes, such as those of hills and natural vegetation, without any additional role for the built environment (Image modeled after Howe & Purves, 2005b). See the online article for the color version of this figure.

Henrich (and perhaps other proponents of the cultural byproduct view), what is important is only that there be *some* environmental factor present in Western cultures as opposed to non-Western cultures that could explain why the illusion emerges in the former but not the latter. What is powerful about Howe and Purves's (2005b) work, then, is that it challenges even this more general articulation of the cultural byproduct view. If natural scenes contain the information necessary to capture the illusion, and that information is present in most if not all of the cultures studied by Segall et al. (which they indeed seem to be; see site descriptions by Segall et al. 1966[10]), then the ingredients necessary for the illusion are not exclusive to Western cultures after all. In other words, it does not matter whether one supposes that carpentry, or visual art, or some other as-yet-unarticulated variable is responsible; all such hypotheses are equally targeted by this demonstration.[11,12]

The Illusion Is Not Limited to Straight Lines or Arrowheads

The canonical formulation of the cultural byproduct hypothesis points to carpentered environments as the source of the Müller-Lyer illusion. As noted earlier, however, our discussion is more general than this; we are concerned with the broader set of accounts of the Müller-Lyer illusion as a cultural byproduct, regardless of whether any one of those accounts points to carpentry per se as the illusion's source. Nevertheless, a common thread running through every version of this hypothesis that we are aware of—including discussions of the potential role of exposure to visual perspective in art (see discussion in McCauley & Henrich, 2006)—is some emphasis on the Müller-Lyer figure's straight lines and sharp angles in generating the illusion. In that case, another strike against this hypothesis is simply that straight lines of this sort are not necessary to produce the

[10] Some examples: The Ankole site contains "slopes of rolling hills … and occasional flat, grassy plains"; the Toro site contains "broad, hilly, grassy areas, some extended plains, and many papyrus swamps"; the Suku site is "open savanna, rather hilly, with only occasional strips of forest visible on the crest of hills." Many other descriptions contain similar details (Segall et al., 1966).

[11] In a more recent treatment of cultural variation in visual illusions, Henrich et al. (2023) discussed Howe and Purves (2005b) study, citing it as showing that "illusions are influenced by how our minds calibrate to the statistical patterns found in our visual environments," and interpreting it as further evidence for the malleability of perception in light of regularities in our environment. However, it is not obvious that this work demonstrates the malleability of perception, at least in ontogenetic terms. It seems just as plausible, if not more plausible, to assume that these regularities were so pervasive in our history that they became embedded in visual processing over the course of evolution and are now "hard-coded" into the minds of humans born today (rather than learned anew by each person when they look out at their environment). Indeed, Howe and Purves seem to favor this view themselves, when they note that they used artifact-less scenes, because those scenes were "presumably the most important visual environment in the evolution of human perception." Moreover, and in line with our central point in the main text, even if malleability and/or online adaptation were the right interpretation of these results, they would still challenge the cultural byproduct hypothesis, because they would still show that all the information required to produce the illusion is and would have been available to those populations that (allegedly) do not see it.

[12] A more recent study pushing this line of work even further suggests that the Müller-Lyer illusion may emerge from the architecture of the visual system itself, by showing that a biologically plausible model of the ventral visual stream "perceives" the illusion too (Zeman et al., 2013).

illusion—not only in terms of the visual regularities that the observer is exposed to (as discussed in the previous section) but also in terms of the illusory stimulus itself. Indeed, while typically referred to as *the* Müller-Lyer illusion, as if it were only a single figure or demonstration, there are in fact many Müller-Lyer illusions, including variants of the original figure that involve only curves, or even no lines at all.

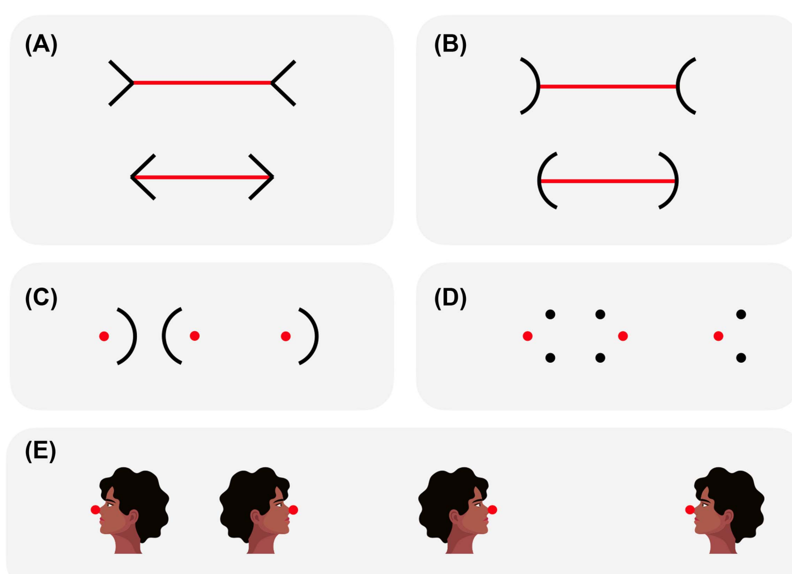
A collection of these variants appears in Figure 5. Consider Panel B; here, the arrowheads have simply been replaced by semicircles, yet the illusion remains all the same. But lines terminating in curves do not correspond to planes meeting at right angles (e.g., walls, floors, and ceilings), whereas such patterns would likely arise in many natural environments (i.e., environments shared across many times and locations in human history). And so they continue to challenge theories that point to sharp angles (Feldman Barrett, 2016) and other similar features as the drivers of the illusion and the cultural variation associated with it.

There are even more challenging variants still, including stimuli that do not even contain the central horizontal lines nor indeed any other straight lines. In Figure 5C, the central dot looks closer to the leftmost dot than to the rightmost dot, owing to the orientation of the semicircles between them. There are no straight lines of any kind in this stimulus, and yet the illusion remains. Figure 5D goes even further: Here, there are no lines at all—just nine dots arranged in three groups—and yet the illusion persists even under these impoverished conditions. Finally, Figure 5E shows that the illusion can arise even when the inducers are rich and independently recognizable objects. This variant using faces (adapted from Bunce et al., 2021) not only is visually striking but also shows that the illusion does not depend on the stimulus being a 2D collection of lines and/or dots. (Indeed, an adventurous reader could recruit three friends to recreate this configuration in real life!)

Note that, unlike the two previous sections, which targeted nearly any version of the cultural byproduct hypothesis beyond formulations appealing to carpentry, our argument here is less than maximally general. While nearly all extant cultural byproduct views do *in fact* invoke some kind of relationship between cultural variation in the Müller-Lyer illusion and the presence of straight lines or sharp angles—including Segall et al.'s (1966) carpentered world hypothesis (further promoted by Henrich et al., 2010), Feldman Barrett's (2016) reference to "objects with sharp angles", McCauley and Henrich's (2006) invocation of "exposure to perspective in art", and more—there could in principle be an alternative, entirely unrelated, but still perfectly sufficient explanation for cultural variation in the Müller-Lyer illusion. If this explanation does not rely on the prevalence of straight lines and sharp angles, then the variants that we have displayed here may not address it.

Still, these data are valuable both because (a) as just noted, nearly all cultural byproduct views do in fact invoke carpentry, art, or other explanations premised on straight lines and sharp angles in the environment, and (b) they place key constraints on future theorizing. If a new theory emerges to explain cultural variation in the Müller-Lyer illusion, it will have to be formulated in a way that is consistent not only with evidence from other species and natural scene statistics, but also with these variants showing how very general the illusion is. Consider again Figure 5E, the variant of the Müller-Lyer illusion formed by the noses of two people facing each other versus facing away. Whereas the prevalence of straight lines and sharp angles may well vary by culture (though see the Role of Carpentry section for

Figure 5
The Illusion is Not Limited to Straight Lines or Arrowhead



Note. (A) The traditional Müller-Lyer illusion, along with variants based on (B) semicircles with lines, (C) semicircles with dots, (D) dots only, and (E) faces. These additional variants are increasingly distant from the straight lines and sharp angles present in the original stimulus. See the online article for the color version of this figure.

further discussion of this assumption), people in all cultures of course face toward and away from each other. The cultural byproduct view thus has to explain why this phenomenon is different than the traditional Müller-Lyer illusion, or make the prediction that non-Western populations would not experience an illusion when looking at Figure 5E—and the same is true for all of the other variants in Figure 5 (including those based on semicircles and dots, even with no central line).

The Illusion Arises in Multiple Modalities

The Müller-Lyer illusion is typically described as a *visual* illusion, likely owing to the prominence of the classic stimulus it is most associated with, together with the historical circumstances of its discovery. However, the illusion is in fact more general than this. Beginning nearly a century ago with the work of Révész (1934), it has long been known that the Müller-Lyer illusion arises not only in vision, but also in *touch* (for a review, see Gentaz & Hatwell, 2004, who discuss work by Casla et al., 1999, Heller et al., 2002, and Patterson & Deffenbacher, 1972, among others).

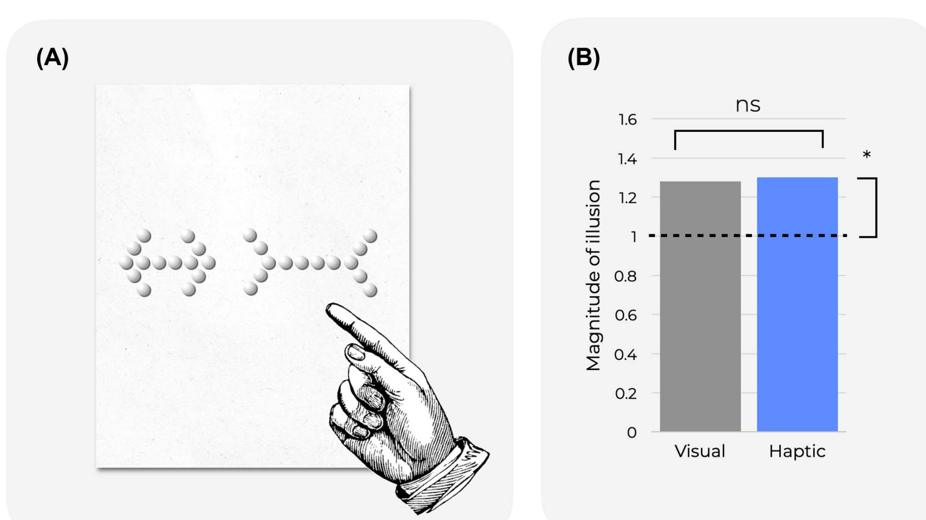
This simple observation immediately complicates canonical explanations of cultural variation in the illusion, since almost all such explanations invoke both (a) differential exposure to *visual* regularities in accounting for cultural differences in susceptibility and (b) the "projective" nature of visual perception in which the 3D world comes us to in the form of 2D images. The fact that the illusion arises in touch as well as vision suggests deeper origins than one's experience with visual input and points to explanations that go beyond some learned mapping between 2D images and the 3D world.

Consider a study by Suzuki and Arashida (1992; Figure 6). Taking a fairly standard approach (see, e.g., Tsai, 1967), the researchers created several haptic versions of the Müller-Lyer stimulus by introducing raised ridges into a sheet of braille paper, whose thick stock holds its shape when embossed. On each trial, subjects wore a blindfold, approached the stimulus (which was sitting on a table), and were instructed to trace the stimulus with their index finger. Subjects inspected the entire stimulus haptically (i.e., both the arrows-in and arrows-out figures), and then made a forced-choice judgment about which central ridge felt longer. The researchers used a staircasing procedure in which subjects made many of these judgments over multiple ratios of the lengths of the two figures, so as to calculate a point of subjective equality, the point at which the two figures appeared equal to a given observer (as indicated by their being equally likely to give one answer or another). When the ridges were in fact of equal width, subjects were much more likely to judge the central ridge of the arrowheads-in figure as longer than the central ridge of the arrowheads-out figure. The staircasing procedure instead converged on a ratio of 1.3, such that the arrowheads-out figure had to be 30% larger than the arrowheads-in figure for subjects to be equally likely to answer that it was longer/shorter than the arrowheads-in figure. In other words, the Müller-Lyer illusion exists in touch as well.

A strength of Suzuki and Arashida's approach is that their procedure allowed them to quantify the strength of the illusion and even compare its magnitude to that of the visual Müller-Lyer. Even if the two versions of the Müller-Lyer stimulus produce illusory effects, one could perhaps wonder whether they derive from a similar mechanism or instead arise independently—such that the source of the visual Müller-Lyer might be different from the source of the haptic Müller-Lyer. A helpful datum in this regard is that the point of subjective equality for the haptic version was nearly identical to that for the visual version: 1.3 versus 1.28 (which did not differ statistically). To put this figure in context, Suzuki and Arashida tested other illusions as well, including the Oppel-Kundt, Ponzo, and Poggendorf illusions; the Müller-Lyer illusion's magnitude was more similar in touch and vision than were any of these other illusions (Oppel-Kundt: 1.06 vs. 1.15; Ponzo: 1.12 vs. 1.07; Poggendorf: 1.5

Figure 6

The Lllusion Arises in Multiple Modalities



Note. (A) Susceptibility to tactile versions of the Müller-Lyer suggest that the illusion is not limited to vision. (B) The illusion is experienced in both visual and haptic modalities, and the two forms are comparable in magnitude (Suzuki & Arashida, 1992). * = statistically significant; ns = not significant. See the online article for the color version of this figure.

mm vs. 10.6 mm). Follow-up work has since found not only that the overall magnitudes of these illusions are similar, but also that these magnitudes are correlated with one another across observers; the more susceptible a subject is to the visual Müller-Lyer, the more susceptible they are to the haptic Müller-Lyer (Gentaz et al., 2004). All this provides further reason to think that it is the "same" illusion arising in vision and in touch.

Why is this discovery significant in regard to the cultural byproduct hypothesis? There are at least two reasons. First, nearly all versions of the cultural byproduct hypothesis attribute cultural differences in susceptibility to the Müller-Lyer to differential exposure to *visual* regularities across those cultures (whether the regularities concern carpentered corners, perspective in art, or some other variable). But differences in visual regularities seem like much less natural explanations for a haptic illusion, and to our knowledge there has been no attempt to argue that the *touched* environment (as opposed to the seen environment) varies across cultures in the right way for present purposes.

Second, and relatedly, even if there were such an attempt (after all, there surely are differences in the kinds of haptic stimuli encountered in different cultures), it is not at all clear that those differences would play the right role in explaining the presence or absence of a haptic Müller-Lyer illusion. The reason for this harks back to Gregory's early account of the illusion (depicted in Figure 1). That account depends crucially on the *projective* nature of visual information, such that information about the 3D world arrives to our eyes in the form of 2D images. This aspect of optics is what makes it so that walls meeting at right angles project to our eyes as arrowheads; put the other way around, inward-facing arrowheads only indicate concave corners because concave corners project to us as inward-facing arrowheads. Crucially, haptic information is not projective in this way; though we of course can only haptically sample small portions of a surface at any one time, those samples do not bear the same relationship to the 3D world as a 2D visual image does. Whereas an inward-facing arrowhead in the retinal image may well indicate a concave corner in the environment, an inward arrowhead in the "haptic image" simply does not; corners and arrowheads are not related in that way in the case of touch.[13] These findings thus challenge the cultural byproduct hypothesis by continuing to show how the illusion arises in broader and more diverse domains than the narrow circumstances that the hypothesis is tailored toward.

The Illusion Does Not Require Prior Visual Experience

In all of its forms, the cultural byproduct hypothesis points to *experience* within a given individual's lifetime as the source of the Müller-Lyer illusion. Whether emphasizing rectangular homes, objects with sharp angles, linear perspective in art, or some other variable, the thread running through such accounts is to attribute the illusion's origins to "visual exposure during ontogeny" (Henrich et al., 2010)—that is, exposure to some visual factor encountered in the individual's environment, without which the illusion would not exist for that individual. However, a final strike against this hypothesis is that the Müller-Lyer illusion also emerges in *congenitally blind* individuals: Observers who have not previously seen their local visual environment still perceive the illusion when they are first given the opportunity to do so.

How is this possible? Though many visual impairments are permanent, some forms of blindness are curable, including congenital blindness brought on by cataracts (which occur in approximately 0.03%–0.04% of infants; Sheeladevi et al., 2016; Wu et al., 2016). Cataracts are opacities of the lens that restrict—and sometimes completely prevent—light from entering the eye. In much of the world, infants born with cataracts undergo surgery to remove them, replacing their natural lenses with artificial ones and going on to see relatively normally. However, in regions of the world where this procedure is unavailable or prohibitively expensive, children with congenital cataracts often live with severe (but still curable) blindness. Recently, a humanitarian and scientific effort offered free cataract surgery to children in North India, some of whom then participated in studies of restored sight (Sinha et al., 2013).

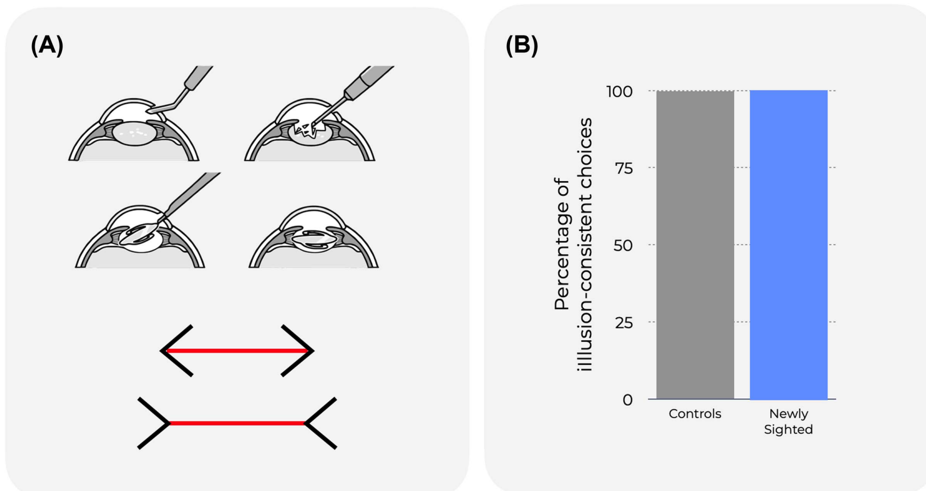
In a particularly notable study from this project, Gandhi et al. (2015) recruited nine blind children (aged 8–16 years) with dense bilateral congenital cataracts. The children underwent lens replacement surgery on one of their eyes, after which they wore an eyepatch for 48 hours to allow for healing. Then, the eyepatch was removed shortly before a testing procedure in which each child was shown multiple variants of the Müller-Lyer stimulus and made judgments about which line was longer. Remarkably, 100% of the children, on 100% of the stimulus variants, showed evidence of the illusion: They chose the arrows-in figure as having a longer central line than the arrows-out figure, only hours after having seen clearly for the first time in their lives (Figure 7).

The significance of this result cannot be overstated. The children in these studies had not only seen no carpentry, artifacts, or paintings—they had not seen *anything*.[14] And yet they still, uniformly and consistently, exhibited the Müller-Lyer illusion. Moreover, they did so despite it being clear that their vision was not "normal" in many other respects. For example, research from the same project has shown that patients with restored sight fail to segment scenes effectively (Ostrovsky et al., 2009) or match shape across vision and touch (Held et al., 2011); and there are additional limitations in acuity and other basic visual capacities. In other words, the Müller-Lyer illusion is present after sight restoration even when other visual processes and

[13] Patterson and Deffenbacher (1972), who also study the haptic Müller-Lyer, make a similar point: "Visual depth and form are mediated by cues in conjunction with a two-dimensional retinal image, but depth and form perceived haptically are mediated by the three-dimensional position of the fingers and hands; altogether different cues are involved."

[14] A natural and important question is whether and to what extent these children and other cataract patients perhaps had very limited visual capability before entering the study, even with their dense bilateral cataracts. The children in this study were not formally diagnosed at birth, in part because they came from rural areas without neonatal ophthalmic care. Instead, their blindness was initially identified by their parents, who reported evidence of visual impairment within the first months of life; follow-up examinations by the research team were then consistent with the cataracts having been congenital. At the same time, cataract patients (including some subjects in this study) may retain rudimentary sensitivity to light and dark and can sometimes appreciate motion very close to their eyes (e.g., waving one's own hand in front of one's face and detecting the shadows that result). Though it is not possible to rule out this sort of limited visual capacity in all of the subjects studied here, minimal appreciation of light and dark is manifestly *not* the kind of visual exposure proposed to explain the Müller-Lyer illusion by any cultural byproduct hypothesis that we are aware of. As Gandhi et al. (2015) noted, no child in the study could have come close to the "sophisticated spatial analysis of the scene" that would be required for the sort of visual exposure pointed to by the cultural byproduct hypothesis. Thus, even if the children could detect light, dark, and certain limited motion signals, this would still seem insufficient to explain their remarkable performance on the illusion task.

Figure 7
The Illusion Does Not Require Prior Visual Experience



Note. (A) Congenital cataracts can be replaced by a procedure in which the cataract—the clouded lens—is emulsified; an intraocular lens is then put in its place, effectively restoring vision. (B) Immediately upon the restoration of sight, newly sighted subjects are susceptible to the Müller-Lyer illusion (data drawn from Gandhi et al., 2015). See the online article for the color version of this figure.

phenomena are not—making it all the more remarkable that the illusion arises under these circumstances.

Indeed, there is even further evidence that the Müller-Lyer illusion emerges independently of visual experience. The previous section noted the existence of a haptic version of the illusion, which arises when subjects touch raised lines forming the Müller-Lyer figure. In fact, this same effect occurs not only in blindfolded subjects who otherwise can see (and so have been exposed to the visual regularities of their local environment prior to touching the figure) but also in congenitally blind subjects without any restored sight—that is, subjects who have been blind their whole lives *and* remained blind during testing.

Early signs of this pattern emerged as early as Révész's (1934) original work, and many studies since then have confirmed it more rigorously (e.g., Heller et al., 2002; Patterson & Deffenbacher, 1972; Tsai, 1967). For example, Patterson and Deffenbacher (1972) tested four different groups of subjects on the haptic Müller-Lyer illusion: sighted subjects, sighted subjects with blindfolds, subjects who lost sight in adulthood, and subjects who were congenitally blind. All four groups showed the illusion. Similarly, Heller et al. (2002) tested sighted subjects with blindfolds, subjects with low vision, subjects who lost sight in adulthood, and subjects who were congenitally blind. Again, all four groups showed the illusion. Moreover, both of these studies also quantified the strength of the illusion and found that the congenitally blind subjects exhibited an effect as strong as (or even stronger than) the other groups. For example, Heller et al. (2002) found no significant effect of visual status, concluding that "The congenitally blind subjects showed the same pattern of illusory size distortion as the other subjects. The illusion was if anything stronger in the congenitally blind subjects." Similarly, Patterson and Deffenbacher (1972) found that "the blind experience the illusion to the same extent as the sighted," and that their sighted blindfolded group experienced a *weaker* illusion.

These results tell a consistent and compelling story. The fact that congenitally blind subjects see the Müller-Lyer illusion immediately after sight onset (Gandhi et al., 2015) and experience a haptic version of the Müller-Lyer just as strongly as sighted observers even without having their sight restored (Heller et al., 2002; Patterson & Deffenbacher, 1972) directly undermines the central assumptions of the cultural byproduct hypothesis.[15] Not only does this work put pressure on claims that the Müller-Lyer illusion arises due to visual exposure during ontogeny to variables of the local visual environment (specifically, variables unique to the unusual visual environments of Western cultures), it even more decisively challenges claims that variation in such visual exposure explains the alleged Western/non-Western divide in susceptibility to the illusion. Whatever minimal visual input may have been available to (some) subjects in (some of) these studies, it is highly implausible that both (a) the input they received—which at best would have involved rudimentary sensitivity to light, dark, and motion—could be sufficient to produce a robust illusory effect while (b) the input available to the (sighted) villagers studied by Segall et al. (1966) would not be. And so these findings continue to point to the illusion's origins as deeper than exposure to

[15] This pair of results also aligns nicely with yet another pattern: The Müller-Lyer illusion is stronger in children than it is in adults. Clues of this were already evident in Segall et al.'s original study, but it has also been observed more systematically (Wincza et al., 2024). This is seemingly opposite the pattern one would expect according to the cultural byproduct hypothesis, which holds that one is not born susceptible to the illusion but rather acquires this susceptibility over the course of development. Such an account would seem to predict a *weaker* effect in children that *grows* as one ages, akin to effects of reading or artificial lighting on certain aspects of visual development.

the visual information present in contemporary Western environments and cultures.[16]

Reexamining Historical, Cross-Cultural Data

Our discussion has primarily focused on empirical work that challenges the core claims of the cultural byproduct hypothesis. However, a further question remains as to the status of the cross-cultural data themselves. Why, if there is such a strong case against a culturally specific origin of the Müller-Lyer illusion, does there appear to be an equally strong empirical case *for* it? Henrich et al. (2023) posed something like this question as well, noting that "the evidence showing variation in the strength of these illusions across populations remains largely unchallenged." Here, we embrace this task and turn to a critical reanalysis of the cross-cultural evidence. Though a full account of every cross-cultural observation is beyond the scope of this discussion, we outline several reasons why the original data from Segall et al. and other historical investigations should be more cautiously interpreted, and we encourage new waves of empirical work that can better assess these claims using up-to-date standards of rigorous, reproducible, and replicable research.

Specifically, we highlight (a) contradictory results emerging from contemporaneous, cross-cultural assessments of the Müller-Lyer illusion (which often show completely opposing patterns of variation); (b) internal inconsistencies in the original Segall et al. data, as well as research practices now recognized to be problematic by modern methodological standards (including discarding inconvenient data points, and failing to conduct appropriate statistical tests); and (c) misinterpretations and/or misunderstandings regarding the degree of carpentry and rectangularity in relation to the strength of the illusion.

The Cross-Cultural Evidence Is Often Inconsistent and Self-Contradictory

To support claims that the Müller-Lyer illusion arises mostly or only in Western cultures, Segall et al. (1966) marshaled an impressive data set of nearly 2,000 participants from 16 diverse cultures. However, Segall et al. are not the only researchers to have conducted cross-cultural studies of visual perception (in general) nor the Müller-Lyer illusion (in particular). Most notably, Rivers and colleagues, working decades earlier, also compared different populations' responses to this illusion and often found patterns that *oppose* the Segall findings. In a series of studies near the turn of the 20th century (Rivers, 1905; Thurston & Rivers, 1903), these researchers assessed susceptibility to the Müller-Lyer illusion among four groups: (a) the Toda, a pastoralist group in southern India who traditionally inhabited semicircular, "half-barrel" houses (Magimairaj & Balamurugan, 2017); (b) the Aboriginal Meriam of Murray Island (Torres Strait Islanders), who traditionally hunted, fished, and gathered, and occupied distinctive beehive-shaped homes with thatched grass over bamboo poles (Fraser, 1960); (c) the agriculturalist/horticulturalist Uráli and Sholaga people of India, described by Rivers (1905) as dwelling in the "jungle" in thatched huts; and (d) English participants living in industrialized cities.

Though the earliest of these studies (Rivers et al., 1901) was largely consistent with Segall et al.'s later claims—with Murray Islanders showing a weaker illusion than the English—later studies with an improved instrument revealed an opposing pattern. Rivers (1905) found that, while the Toda participants showed a weaker effect than English participants, the jungle-dwelling Uráli and Sholagas of tropical India showed the greatest effect of all, even considering the English. Notably, this work was conducted before the advent of statistical methods such as the *t*-test or analysis of variance; indeed, the original publications report no formal statistical analyses at all. However, these reports include a summary table of the data, which provide sufficient information to analyze with modern statistics. A one-way analysis of variance suggests significant differences between the groups' mean responses to the task, $F(5, 212) = 7.15$, $p < .001$ (see Supplemental Material), and Tukey post hoc tests illuminate these differences more precisely: The Murray Islanders using the first protocol differ from English populations using both protocols and from the Uráli and Sholaga group using the second protocol; the Toda group using the second protocol differ from the English group using the first protocol and the Uráli and Sholaga group using the second protocol. Of the 15 possible comparisons, only five are significantly different, and of these, most involve comparisons between two different versions of the protocol. Importantly, one of the more reliable comparisons of the entire data set is one that is seemingly inconsistent with the cultural byproduct hypothesis: The jungle-dwelling Urális and Sholagas show a *stronger* Müller-Lyer illusion than the Todas of the same country.

More contemporaneously with Segall and colleagues, other researchers of the time documented additional results opposing Segall et al.'s reported patterns. Mixed or contradictory evidence was documented in comparisons among groups such as Aboriginal Australians (Gregor & McPherson, 1965), Lobi and Dagomba individuals in Ghana (Jahoda, 1966), Singaporeans (Richardson et al., 1972), urban and rural individuals in Canada (Jones, 1974), and among Bashi and Mbuti individuals in what is now the Democratic Republic of the Congo (Bonte, 1962). For instance, in an investigation of Müller-Lyer susceptibility between urban and rural Xhosa participants in South Africa (as well as white students), researchers again found patterns opposing the Segall findings:

[16] Henrich et al. (2023) devoted a footnote to Gandhi et al.'s (2015) study on restored sight, commenting that "this study is beleaguered by relying on a tiny sample, reporting only a crude measure of illusion susceptibility, and failing to explore how long these nearly blind children were sighted earlier in their lives." Considering these points in turn: (a) Though Gandhi et al. (2015) tested only nine children, this sample size was more than adequate for a design of this sort. If the researchers had been running a correlation or a between-subjects manipulation, nine subjects would very likely be inadequate. But Gandhi et al.'s (2015) question was only whether the nine children exhibited the illusion, and they found that each one of them did. Just as the odds of a coin coming up heads nine times in a row is 1/512, a binomial probability test on the performance of the nine children yields $p < .002$—and the result is in fact more impressive than that, since each child completed multiple trials. (For discussion of how strong conclusions can be drawn from small samples under circumstances such as these, see Schwarzkopf & Huang, 2024). (b) Henrich et al. are right that the forced-choice measure used here is "crude" compared to other measures. Nevertheless, the measure is adequate to refute the claim that visual exposure is *necessary* to produce the illusion (and we note further that the haptic studies used richer measures of illusion strength, and still found no differences among sighted and blind subjects). Finally, (c) as noted in our previous footnote, Gandhi et al.'s (2015) subjects were identified as blind by their parents within the first months of life (which, for some of these children, was over a decade before being tested), and ophthalmic exams by the research team were consistent with their dense bilateral cataracts being congenital. Moreover, Heller et al.'s (2002) study included subjects who were blind for reasons other than cataracts, including retinopathies of prematurity in which the retina is severely damaged at birth; in the case of several subjects, this led to no light/dark sensitivity at all. These subjects still perceived the Müller-Lyer illusion.

Rural Xhosa participants were *more* susceptible to the Müller-Lyer illusion than urban Xhosa participants, and did not differ from White South Africans. Smith concluded:

> These results are contrary to those expected in terms of the Carpentered World type of explanation because the relative absence of carpentered artifacts in the environment of the [Rural Xhosa] group should have resulted in their being the least susceptible. (Smith, 1970, p. 96)

In other words, even when taken at face value, the full picture painted by this literature simply is not univocal: For any studies finding a pattern consistent with the cultural byproduct hypothesis, one can find others reporting the opposite pattern (with, e.g., participants in rural or nonindustrial environments showing *greater* illusion susceptibility than participants in urban or constructed environments).

Methodological Concerns and Inconsistencies *Within* the Segall Dataset

One group of researchers who were especially concerned with inconsistencies in the data was, admirably, Segall et al. themselves: "While our data generally conform to the hypothesis, the fit is not so exact or so uniform as to rule out the possibility of other factors" (Segall et al., 1966, p. 191). Indeed, in a self-critical section titled "Inconsistencies in our Own Data"—rarely if ever discussed in the secondary literature on this study—Segall et al. highlighted interpretive issues with their own work. We briefly review these issues here.

First, beyond contradictions between Segall et al.'s findings and those of other cross-cultural investigations—for example, jungle-dwelling Uráli and Sholaga showing the greatest illusion susceptibility (Rivers, 1905)—Segall et al.'s data are also *internally* inconsistent. As the authors noted, the three groups who showed the weakest Müller-Lyer susceptibility were the hunter-gatherer "Bushmen" (the San) of Southern Africa, the Bété subsistence farmers of the Ivory Coast, and a group referred to as the "mineboys," who appear to be a group of diverse laborers working at a gold mine near Johannesburg. Of these, the only group that "belongs" at the bottom, according to Segall et al., are the San, since "their environment is very likely the least carpentered of any." The responses of the other two groups are much harder to interpret. South African miners, for instance, whose entire profession involves laboring in the manmade, constructed environment of a mine, should presumably not have been at the bottom. (Segall et al. agreed: Their "very low degree of susceptibility is surprising.") Similarly, the Bété of the Ivory Coast were also not expected to be at the bottom, as they live in a "moderately carpentered environment" (p. 192). Even within the Segall et al. study, then, it is difficult to generate an account that neatly predicts the observed patterns of high and low illusion susceptibility.

An alternative interpretation of these surprising and inconsistent results, then, is that other factors may have inadvertently influenced participants' responses. For example, all of the task instructions had to be translated into local languages and dialects, and it is not clear that this process was wholly successful or bias-free; indeed, Segall et al. (1966) noted that some colleagues "expressed some concern that their use of interpreters meant they were not completely sure of exactly what was communicated to the respondents at all times" (p. 178; a similar concern was raised by Gillam, 1980). (Obviously this concern would not arise for the Western samples, where English was used and where the methods would thus be most reliable.) Compounding this concern further, Segall et al. even worried about bias introduced by the experimenters:

> One administrator reports that after testing 10 or 20 respondents, he developed very strong expectations of what answer the respondents should give to a given item, and if a respondent gave the *other* answer, there was the impulse to correct the respondent to ask him to reconsider. (p. 178)

This is essentially a textbook description of *experimenter effects*, whereby knowledge of an experimental hypothesis leads researchers to (consciously or unconsciously) bias various procedures in their favor (Rosenthal & Rubin, 1978).

In addition to potential issues in the administration of the tasks themselves, there are other issues regarding how data were handled and analyzed. For instance, out of concern that some respondents may have been confused or biased, the authors excluded data from participants who demonstrated side biases in responses, or those that alternated between items. One especially notable basis for exclusion was the respondent choosing the line segment with illusion-supporting arrowheads every time, with the logic being that when the discrepancy between the items was low, respondents should be closer to chance. Using these criteria, the authors excluded large numbers of participants from the sample, in some cases more than half. These exclusions were often highly consequential and self-serving (whether intentionally or not). For example, one "highly errorful" sample was the Zulu; though Segall et al. ultimately reported the postexclusion data for this sample, they also noted that, if all data were included, "the score places the Zulus closer to the Western samples in Müller-Lyer susceptibility" (p. 184). Today's methodological standards recognize data exclusion as a "researcher degree-of-freedom" that can bias results toward favorable conclusions (Wicherts et al., 2016); one cannot rule out that something like this practice occurred here.

We acknowledge that the brief discussions here and in the previous section do not fully account for every pattern of cross-cultural data observed; such an account may not even be possible given inconsistencies within and across datasets. Nevertheless, it seems to us that these considerations not only make extant cross-cultural data unreliable in terms of their support for the cultural byproduct hypothesis, but also make it unclear whether to interpret the Segall et al. data as instances of cultural variability *in the strength of the Müller-Lyer illusion* itself. When one conducts a similar study 16 times in 16 different situations, one does not expect to produce a plot of 16 bars of the very same height. But what *does* one expect? We know now that (a) efforts to translate the experiment materials into local languages were variable or unreliable across non-Western samples (but not Western samples), (b) the experimenters reported administering the protocol in ways that biased respondents' answers in favor of the hypothesis, and (c) cultures who showed an illusion strength similar to Western samples were subject to post hoc data exclusions that weakened their reported susceptibility. Given this, one might well predict (a) haphazard or irregular patterns of reported illusion susceptibility across cultures and also (b) a special exception for the Western samples. These two predictions are, of course, exactly what one finds—that is, a highly reliable illusion in the Western samples and a seemingly unprincipled mix of findings everywhere else.

The Role of Carpentry

Our discussion has mostly focused on evidence for and against the claim that the Müller-Lyer illusion emerges from exposure to visual regularities peculiar to certain cultures, without as much concern for what those regularities might be. However, given the prominence of the view that carpentered environments in particular are the key variable that should be related to—and indeed cause—susceptibility to the Müller-Lyer illusion, it is worth discussing whether Segall et al.'s data actually support this auxiliary claim of the cultural byproduct hypothesis. We have already gestured at reasons to think they do not. For example, among the groups least susceptible to the illusion were South African miners, who would have spent hours each day in the highly carpentered environment of a gold mine. (Mines are known for the ubiquitous presence of railway tracks, which are such a canonically rectilinear visual stimulus that they are often used in perception textbooks to illustrate linear perspective.)

However, we can also approach this question more comprehensively. Intriguingly, while Segall et al. took great care to precisely quantify susceptibility to the Müller-Lyer illusion, there was significantly less precision in their construction and characterization of the key independent variable: the degree of carpentry in the participants' environments. Indeed, there appears to be no systematic quantification of this variable at all; rather, the authors relied on what they themselves called "crude estimates" of rectangularity in each setting—a single questionnaire for each field site in which a sole administrator generated, rather subjectively, an inventory of the visual environment. This survey included questions about the natural visual environment (e.g., dense jungle, flat land), the shape of dwellings and other buildings, and the shape of artifacts (e.g., pots and tools), along with a subjective rating of a rather-amorphous criterion: the "degree of acculturation to EuroAmerican ways" (p. 215).

In the years since the Segall work was published, researchers have tended to focus primarily on carpentered corners, such as those found in buildings (e.g., Figure 1), as a proxy for the degree of carpentry in a cultural environment. In light of this, we offer readers a summary of key quotations from the surveys, with a focus on buildings and dwellings (see Table 1). Examination of responses to this survey suggests considerable rectangularity in nearly all of the samples studied, with the large majority of site descriptions explicitly mentioning the presence of rectangular buildings, dwellings, and artifacts. To highlight a few examples: For the Ijaw people of the Niger Delta, who showed below-average illusion susceptibility, the surveyor wrote that "the houses are nearly perfectly rectangular," and even commented on the rectilinearity of various artifacts ("The sign of a good weaver is that the lines are straight and truly parallel"); for the Bété farmers of the Ivory coast, who also showed very weak illusion susceptibility, it was noted not only that their homes are rectangular but also that the "doors and windows are rectangular" too; by contrast, the Zulu people, who showed slightly *above*-average illusion susceptibility—and, as we noted in the previous section, become comparable to the Western samples once their full data set is included—actually had *less* carpentry than most other sites, with the surveyor noting that "the predominant type of house is the cone-cylinder hut, roughly circular." Indeed, summarizing their descriptions, Segall and colleagues stated that only "two samples (Zulu and Bushmen) live in circular houses … . All other non-Western samples live predominantly in rectangular houses" (Segall et al., 1966). (Still, there was plenty of rectangularity present even in the Zulu sample, including in 25% of houses, as well as European-style boxes and trunks.)

Granted, Segall and colleagues were concerned less with the mere presence or absence of rectangularity in one's environment but rather the relative degree. Nevertheless, we make three observations about these data. First, there are much higher rates of rectangularity among these cultural sites than the secondary literature tends to acknowledge.[17] Second, it is not clear how these descriptions could support confident rankings of the relative presence of carpentry, especially as Segall and colleagues did not have a clear definition of carpentry or rectangularity (i.e., it could be found in pots or houses or vistas) and appeared to rely rather heavily on experimenters' rankings of "degree of acculturation to EuroAmerican ways" (p. 215), which is left open to each site administrator's interpretation. Third, and finally, even if one could generate such rankings qualitatively, it is not at all obvious that they would be related to illusion susceptibility in ways that implicate carpentry as the variable of interest—since, again, there are low-susceptibility societies with quite a bit of carpentry and high-susceptibility societies with much less.

Other Visual Illusions

Our discussion, like many others in this domain, has focused almost exclusively on the Müller-Lyer illusion, which has been the empirical backbone of the cultural byproduct hypothesis and which has more relevant data associated with it than perhaps any other visual phenomenon. Nevertheless, it is also the case that (a) proponents of the cultural byproduct hypothesis have sometimes pointed to cross-cultural variation in other illusions as well, and also that (b) our theoretical and empirical arguments similarly apply beyond this case. Here, we comment on the evidence for and against culturally specific origins of other visual processes and phenomena (especially other visual illusions). Though we cannot here be as comprehensive as in earlier section (in part because no visual illusion has been studied as extensively as the Müller-Lyer illusion), multiple relevant illusions turn out to be amenable to the same arguments and sources of evidence (Figure 8).

Cross-Species Evidence

Nonhuman animals experience many other visual illusions originally discovered in humans. Comparative visual perception is a massive research literature, but it is sufficient for our purposes to briefly review some examples. The same research group that demonstrated Müller-Lyer susceptibility in guppies has conducted similar studies with other visual illusions, including the Ebbinghaus illusion (Santacà et al., 2022) and the horizontal–vertical illusion

[17] For example, it has been claimed that "Zulu villages have no objects with sharp angles" (Feldman Barrett, 2016). In fact, not only did Segall et al.'s site descriptions document the presence of "roughly rectangular" houses, but the Zulu are independently known for their sharp-tipped weaponry, including the *assegai* throwing spear and the *iklwa* stabbing spear. Gregory (1965) made similar errors, written that "people who live in environments largely free of right angular corners and parallel Iines—such as the Zulus who live in a 'circular culture' of round huts—do not suffer these distortion-illusions"; again, not only are Zulu villages not "largely free of right angular corners and parallel lines," but they *do* experience the relevant illusions, perhaps even more strongly than most of the groups tested.

Table 1
Select Quotations From the Visual Environment Survey of Segall et al. (1966), Revealing a Strong Presence of Rectangularity in the Vast Majority of Societies Studied

No.	Sample	Sample size	Segall's classification	Assessments of carpentry and rectangularity in housing and artifacts, as quoted from Segall et al. (1966)	Evidence for rectangularity?
1	Ankole	344	Non-European	"Many well-built structures, some multiple-storied. A typical house in this town is very nearly perfectly rectangular" "Rectangular tables are the rule" "Small general stores dot the district and make possible a very wide distribution of factory-made textiles, cooking implements, camp stoves, bottled soft-drinks, etc."	Yes
2	Toro	109	Non-European	"most Toro furnish their houses with European-style tables and chairs" "Well-constructed commercial buildings" "Rectangular houses" "A virtual replication of the Ankole sample"	Yes
3	Suku	76	Non-European	"All dwellings are rectangular and virtually perfectly so" "This rectangular emphasis is also found in household furnishings such as beds, stools, and storage platforms"	Yes
4	Songe	98	Non-European	"Live in houses that are nearly perfectly rectangular" "European-made objects abound"	Yes
5	Fang	110	Non-European	"Rectangularity is dominant" "The ethnographer encountered only one non-rectangular building" "Practically all furnishings, e.g., beds, benches, etc., tend toward angularity. … The 'rightness' of angles is, in fact, of first importance in Fang judgment when examining buildings or furnishings."	Yes
6	Bété	95	Non-European	"The characteristic Bété house is … rectangular" "Doors and windows are rectangular"	Yes
7	Ijaw	162	Non-European	"The houses are nearly perfectly rectangular" "European-style furniture predominates … rectangular benches, manufactured locally, are also in constant use" "The sign of a good weaver is that the lines are straight and truly parallel"	Yes
8	Zulu	100	Non-European	"The predominant type of house is the cone-cylinder hut, roughly circular" "[But] as many as 25 percent of the houses in the region are roughly rectangular" "Furnishings are virtually lacking"	Some
9	Bushmen	46	Non-European	"Sheltered in simple windbreaks, consisting of semicircular or parabolic arrangements" "No rectangular tools are reported" "[S]pears and arrows are in use. The ethnographer also reports some European-like pocket-knives."	No
10	Senegalese	262	Non-European	"With the exception of one small subsample ($N = 7$)… this sample consists of agriculturalists inhabiting rectangular houses"	Yes
11	Dahomean children	65	Non-European	"Houses are usually roughly rectangular" "Some reasonably, well-carpentered houses can be found" "Most artifacts are non-angular in cross-section. … Most furniture is rectangular, however."	Yes
12	Hanunóo	57	Non-European	"Hanunoo houses are all roughly rectangular" "Roughly rectangular benches and shelves"	Yes

(*table continues*)

Table 1 *(continued)*

No.	Sample	Sample size	Segall's classification	Assessments of carpentry and rectangularity in housing and artifacts, as quoted from Segall et al. (1966)	Evidence for rectangularity?
13	South African Europeans	44	European	"Large, modern, urban center" "Highly carpentered rectangularity pervades such environments"	Yes
14	South African mine laborers	72	European?	"All have spent time in an environment that contains much of European origin" "Some members of the sample come from areas in which rectangular dwellings are the rule"	Yes
15	Evanstonians	208	European	"This environment is representative of the highly carpentered sort of environment that is assumed to be most characteristic of the Western world" "Some residents of Evanston, however, are migrants from more rural environments"	Yes
16	Northwestern University students	30	European	"Comparable to the Evanstonian sample" "Administered … in a laboratory setting at the university"	Yes

Note. See the online article for the color version of this table.

(Santacà & Agrillo, 2020b), which have sometimes been claimed as other examples of phenomenoa with culturally specific origins. Guppy behavior suggests that they perceive all of these illusions. For example, guppies who must pass through holes of various sizes when navigating through a tank prefer to pass through larger holes; Santacà et al. (2022) showed that this is true not only for holes that are actually physically larger but also for holes made to *appear* larger through the presence of inducers characteristic of the Ebbinghaus illusion.

The horizontal–vertical illusion has also been demonstrated in hens (Révész, 1924), as well as various nonhuman primates, including capuchin, mangabey, and stump-tailed monkeys (Dominguez, 1954; Harris, 1966). Of course, different perceptual phenomena (including visual illusions) show greater and lesser degrees of universality across species (for discussion, see Feng et al., 2017, as well as Fujita et al., 2017). But the presence of any given visual illusion (such as Müller-Lyer illusion, horizontal–vertical illusion, or Ebbinghaus illusion) in both humans and other animal species makes it unlikely that the origin of that illusion is specific to certain human cultural contexts.

Modeling Natural Scenes

Since their demonstration that the Müller-Lyer illusion can be accounted for in terms of the scene statistics of the natural world without any additional explanatory role for the constructed environment, Howe and Purves have extended their approach to an extraordinary number of other visual phenomena. These include the horizontal–vertical illusion, the Ebbinghaus illusion, the Ponzo illusion, the Hering illusion, and the Poggendorf illusion—to only scratch the surface.

Consider, for example, their discussion of the Ebbinghaus illusion, in which the very same circle appears larger when surrounded by small circles than when surrounded by large circles. Howe and Purves again sampled their image range database to find physical sources whose projected images roughly match the Ebbinghaus configuration—and specifically how the sizes of the physical objects that would project the central target circles of the Ebbinghaus illusion vary as a function of the sizes of nearby objects that would project surrounding circles. As in the case of the Müller-Lyer, the *world itself* (and indeed the *natural* world itself) obeys the regularities of the Ebbinghaus illusion: Circular retinal projections tend to come from larger objects in the real world when flanking objects would project smaller circles versus larger circles.

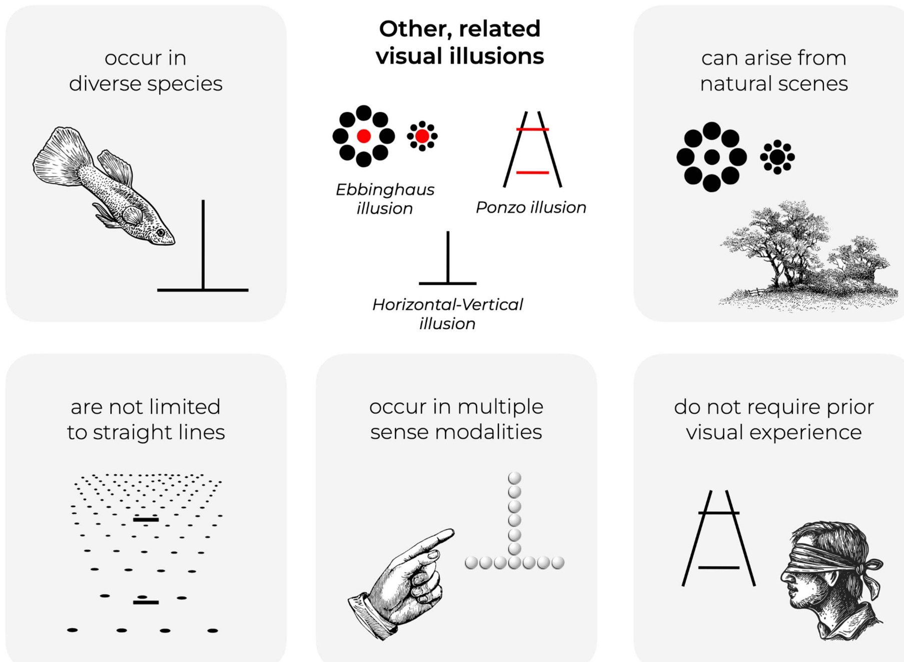
The fruits of this impressive research program accounting for visual phenomena in terms of "statistical regularities between retinal images and real-world sources that must have determined the evolution of human vision" extend even further than this, and are reviewed in detail in their book-length treatment of these issues (Howe & Purves, 2005a).

Curvilinear Stimuli

Most visual illusions are not canonically associated with straight lines and sharp angles in quite the same way the Müller-Lyer illusion is; for this reason, it is not immediately clear how broadly curvilinear variations of normally angular illusions apply beyond the case study we explore in our earlier discussion. (For example, the Ebbinghaus illusion is already associated with curvilinear features, as its classic presentation involves circles of differing sizes.) However, there are

Figure 8

A Visual Summary of the Ways in Which Other, Related Visual Illusions Exhibit Similar Characteristics as the Müller-Lyer Illusion



Note. See the online article for the color version of this figure.

indeed cases of illusions previously thought to depend on the presence of such features, such as straight lines and sharp angles, that later turned out not to after all.

One example is the Ponzo illusion, whose typical presentation includes two straight lines angled inward as if converging. This has similarly led researchers to wonder whether the illusion arises due to exposure to straight lines in one's environment. However, also like the Müller-Lyer, Ponzo-like effects can arise even without straight inducing lines (or indeed any inducing lines at all). Leibowitz et al. (1969) created a real-world version of the illusion in which the stimuli whose sizes are to be judged were simply placed on an open field; the illusion still occurred, even without any inducing lines present. Worried that subtler cues in the (somewhat manicured) field could have been responsible, Fineman and Carlson (1973) showed that the Ponzo illusion also occurs for stimuli placed on a plain array of dots, as long as the dots are arranged along an appropriate texture gradient. This work validated a hypothesis earlier put forward by Gibson (1950).

Other Sense Modalities

Many visual illusions have haptic counterparts, beyond the Müller-Lyer. In Suzuki and Arashida's (1992) study reviewed earlier, it was observed not only that the Müller-Lyer illusion arises in touch, but also that the horizontal–vertical, Ponzo, and Oppel-Kundt illusions do as well.

For example, to test the horizontal–vertical illusion, blindfolded subjects were handed a sheet of braille paper with two embossed lines on its surface, one vertical and one horizontal, and then traced their fingers along the raised lines. Subjects judged the vertical line to be longer than the horizontal, even though they were in fact the same length. Moreover, as in the case of the Müller-Lyer illusion, the magnitude of the haptic horizontal–vertical illusion was nearly identical to the magnitude of the visual version of the illusion.

This latter pattern did not extend to every figure studied; in some cases the haptic illusions were in the same direction as the visual illusions but differed in magnitude, and in at least one case (the Zöllner illusion), there was actually evidence for the *opposite* effect in touch as in vision. However, our purpose is not to argue that every visual illusion has a haptic counterpart (not least because many visual illusions would not be possible to reproduce haptically in the first place), but rather to note that our arguments are not somehow peculiar to the Müller-Lyer illusion: Multiple visual illusions, including those that have been suggested to originate from exposure to certain culturally specific visual regularities (or at least show population-variability in susceptibility; Henrich et al., 2010), also arise in domains far outside of vision (see also the recent discovery of a haptic Ebbinghaus illusion; Ziat et al., 2014).

Restored Sight

Data on the illusion susceptibility of individuals with restored sight are unusually difficult to obtain, even compared to the cross-species and cross-cultural data reviewed earlier. This is due to (a) the rarity of such patients in the first place, (b) the further rarity of opportunities to enroll them in studies exploring visual illusions (as opposed to, e.g., more basic visual capacities), and (c) the narrow time window in which to study them, such that the results could bear on the present issues.

Nevertheless, other illusions beyond the Müller-Lyer have been investigated in this way. Most prominently, the same group of subjects who exhibited the Müller-Lyer illusion moments after seeing for the very first time also showed susceptibility to the Ponzo illusion under the same conditions (Gandhi et al., 2015). This pattern held over multiple variations, and indeed was most similar to the sighted controls for the most canonical version of the illusion. The authors thus conclude of this illusion too that susceptibility is "based not on an individual's learned contingencies about the visual world, but rather on processing mechanisms that do not depend on visual experience" (p. 359).

Still other, more high-level illusions, arise in cataract-treated subjects as well, including phenomena that integrate across vision and other senses (Piller et al., 2023). Experimental work with cohorts of cataract patients stands out for its degree of control, as well as the ability to test multiple subjects in similar conditions, making progress over the isolated case studies that had arisen in previous decades. This approach thus remains a promising avenue for future work.

Outstanding Questions and Future Directions

Other Perceptual Phenomena That May Vary Across Cultures

Our discussion of the evidence for cultural influences on perception has focused on a particular set of claims regarding the origins of classical visual illusions. Though we have concluded that such evidence is ultimately unable to support the very consequential claims that have attached to it, there may well be theoretically significant cultural variation in other perceptual phenomena. In this final empirically oriented section, we briefly point to other candidates for cross-cultural variation in visual perception and assess their promise for supporting theoretical perspectives related to the cultural byproduct hypothesis.

Ocular Disorders

One way for different people to see the world differently is for their eyes to function differently. Along these lines, certain differences in ocular function—specifically, those resulting from ocular disorders—arise at least in part due to environmental factors, and it is possible that different cultural practices could play a role in the development of such disorders.

One much-discussed example is myopia, or near-sightedness, a refractive disorder in which light from distant objects is focused in front of the retina, making such objects appear blurry. Myopia is more common in industrialized societies than elsewhere (Foster & Jiang, 2014), and a major risk factor is engaging in "near-work" activities—those that involve focusing on stimuli within arm's reach, such as reading or playing computer games (Huang et al., 2015).[18] Since members of different cultures engage in such activities at different rates, and those activities are correlated with the prevalence of myopia, this would seem to be a case where culture impacts visual perception. As Henrich et al. (2023) wrote, discussing this sort of evidence, "It's a short step from the effects of culture on our anatomy and physiology to its impact on our senses and perceptions."

Short though it may be, however, this step is actually quite significant when it comes to the broader implications of cultural influences on perception. As noted earlier, one reason the cultural byproduct hypothesis is so exciting and potentially revolutionary is that it interfaces with questions about the modularity of mind, theory-neutral observation, and other issues related to how processing of sensory input may be influenced by nonperceptual factors. But myopia, a condition of the eye, causes changes to the *input* that reaches the perceptual system, not to the manner in which such input is processed. In this respect, cultural differences in perception as a result of myopia are not so different from, say, cultural differences in perception as a result of eye injuries acquired in military conflicts—unambiguous changes in perception, certainly, but not the sort that violate modularity or arise from one's background beliefs.

Attention

A more downstream source of cultural variation in perception might be found in patterns of *visual attention*. An influential research program has suggested that members of "Western" societies (e.g., Europeans and Americans) attend to visual scenes in subtly different ways than members of "Eastern" societies (especially East Asia, including China, Japan, and Korea), with Western observers tending to focus more on individual objects and East Asian observers tending to focus more on holistic scene content (Nisbett & Masuda, 2003; Nisbett & Miyamoto, 2005).

For example, Masuda and Nisbett (2006) showed American and Japanese observers scenes in which a focal object (e.g., a truck) appeared on a typical background (e.g., a city street), after which a change occurred to either the focal object or the background context; observers' task was to report the change as soon as they noticed it (a standard change-blindness paradigm). The results showed an interaction of culture and change type: Japanese observers detected contextual changes faster than American observers did, and American observers detected focal changes faster than they detected changes in contextual information—a result that the researchers attributed to broader differences in analytic versus holistic processing across cultures (Norenzayan et al., 2002).

These and related results are controversial both theoretically and empirically, as researchers have questioned the validity of the relevant cultural categories (Killen & Wainryb, 2000; McSweeney, 2002) and in some cases the replicability and/or generalizability of the core results (e.g., Cao et al., 2022; Ji et al., 2000; Willey & Liu, 2022). However, results such as these may come closer to the issues raised by the cultural byproduct hypothesis. Attentional effects are not traditionally considered violations of modularity or instances of cognitive penetration of perception (for discussion, see Gross, 2017; this consideration may also apply to work on cultural influences on the interpretation of a bistable image, see Kroupin et al., 2024); nevertheless, they may well interface with the issue of theory-neutral observation, especially concerning the role of perceptual experience in epistemic justification (Silins & Siegel, 2019). Given the mix of theoretical promise but also methodological concern, this strikes us as an area ripe for future work.

[18] A related hypothesis points to time spent in sunlight, which is held to reduce the risk of myopia (Lingham et al., 2021) and may be (anti-)correlated with near work activities (which are typically pursued indoors).

Global and Local Perceptual Biases

A related source of evidence sharing themes with work on the Müller-Lyer illusion comes from a more recent research program exploring cultural influences on global and local perceptual biases (which are distinct from the attentional biases reviewed in the Attention section; Caparos et al., 2013). Perhaps most prominent is work on the Ebbinghaus illusion, in which a central circle flanked by larger circles appears smaller than when flanked by smaller circles. The Ebbinghaus illusion was reported by de Fockert et al. (2007) to be weaker among the seminomadic Himba people of Namibia—who supposedly have "no words for geometric shapes" (p. 738)[19]—than English subjects. It has also been reported that Himba children living in more traditional environments show a weaker Ebbinghaus illusion than Himba children living in urban areas do (Bremner et al., 2016). Perhaps most strikingly, it has even been claimed that more traditional-living Himba observers who become exposed to urban environments—even briefly visiting a local town a single time—show a stronger illusion than those who remain in more traditional communities (Caparos et al., 2012).

This work comes closer to the spirit of the cultural byproduct hypothesis in that it alleges a cultural influence on a fairly canonical perceptual phenomenon (rather than an effect on the functioning of the eye itself, or attentional selection). However, there are several factors that make it a weaker—or, perhaps, less directly relevant—case than it may seem, at least as concerns the cultural byproduct hypothesis. First, some of the most striking data in this domain remain tricky to interpret. For example, the remarkable finding that even a single exposure to an urban environment dramatically alters the strength of the Ebbinghaus illusion is tempting to interpret causally; however, the study was in fact correlational (relying on visits that Himba observers organically made to a nearby urban settlement), and the researchers noted that reasons to visit that settlement included health and other uncontrolled factors. Additionally, the *duration* of exposure (number of visits) to this urban environment did not correlate with the strength of the Ebbinghaus illusion, whereas most of the mechanisms posited by proponents of the cultural byproduct hypothesis would indeed predict such a relationship. Second, the illusion was still present in Himba living in more traditional environments, and indeed the researchers who conducted this work only claim that one's environment can push around the illusion, not that the environment *creates* the illusion in the first place. This latter claim is the one made by the cultural byproduct hypothesis, which states that phenomena like the Müller-Lyer illusion would not even exist in the first place if not for cultural factors (and exceptional cultural factors at that). Third, and finally, nearly all of the considerations we present in the Other Visual Illusions section apply to the Ebbinghaus illusion as well. For example, it is present in nonhuman animals (Santacà et al., 2022), it is well-captured by the statistics of natural scenes (Howe & Purves, 2005a), it arises in the tactile modality (Ziat et al., 2014), and of course it is not hypothesized to require straight lines or sharp angles in the way the Müller-Lyer illusion has been (indeed, the typical presentation of the Ebbinghaus illusion involves purely circular stimuli). While we are not aware of studies of restored sight that have explored the Ebbinghaus illusion, it is plausible to predict that it arises in those populations as well (as long as observers are able to individuate the stimuli). In that case, the Ebbinghaus illusion seems susceptible to the same analysis as the Müller-Lyer, and this is true even in light of the relatively newer work associated with it (which, in any case, makes more conservative claims about the illusion's origins than proponents of the cultural byproduct hypothesis make about the Müller-Lyer).

Novel Perceptual Phenomena

Evidence even closer to the heart of the cultural byproduct hypothesis could arise from novel perceptual phenomena that in some sense *must* have culturally specific origins. A perhaps underappreciated source of evidence might come from *reading*. Written text is a cultural invention; not only is text present in some historical societies but not others, but contemporary writing systems work differently in different cultures, which use different scripts and may employ glyphs, signs, logograms, alphabets, and so on.

Intriguingly, certain perceptual phenomena seem to be modulated or even generated by experience with reading. For example, Tse and Cavanagh (2000) reported that calligraphic knowledge can bias apparent motion of Chinese characters, whose strokes have canonical orders and directions known only to those who can read them. This seems to be a case where a perceptual process—motion perception—is modulated by culturally specific knowledge or experience (though see follow-up work by Li & Yeh, 2003; as well as discussion by Firestone & Scholl, 2016).

An even more compelling case would be a genuinely novel visual illusion created by reading (akin to claims that the Müller-Lyer illusion is caused by carpentry or other culturally specific factors). An intriguing example of such a case may be the *illusory letters phenomenon*, also known as *graphemic restoration* (Jordan et al., 1999). If certain characters within a word are replaced by nonsense symbols (e.g., gabor patches; we will indicate them here with the # sign), they may nevertheless appear like letters when viewed from far enough away. For example, h##d might look like head, hand, or hard; v##t might look vest or vent; w##t might look like west, went, or wart, and so on. (A similar phenomenon arises in Arabic text, though tellingly only for Arabic speakers; Jordan et al., 2015.) Moreover, the experience is quite subjectively compelling: Rather than being evident only through analyzing behavioral data and collapsing over many subjects, the phenomenon works as a "demo" that any reader of the relevant scripts can see for themselves (which has not always been true of related effects; Firestone & Scholl, 2015). This case thus seems especially strong as a perceptual phenomenon that is truly a cultural byproduct.

Yet, interpretive care is warranted even here. First, it is not clear whether these effects are generated by higher level *knowledge* of which characters belong in place of the nonsense symbols. In a follow-up study, Firestone (2017) embedded the nonsense-character-containing words into sentences whose context should have

[19] While the claim that the Himba do not have words for regular geometric shapes appears frequently in print (e.g. Roberson et al., 2002), the evidence for this claim is murky. For example, a prominent dictionary translating English to Herero (a language spoken by the Himba) has an entire figure dedicated to words for geometric shapes (Nguaiko, 2010)—circle is "ouputuputu," square is "ovikorovine," and triangle is "ovikorovitatu." More recent work with the Himba testing for comprehension and vocabulary of geometric shapes also shows that the majority of Himba in the study explicitly used these words for shapes like rectangles ("otjinavikorovine" or "otjinatjozohukiine"; Kroupin et al., 2024). It is possible that these are more recent linguistic innovations; but even so, much of the perceptual work in question was conducted in the last 10–15 years.

resolved the ambiguity in different ways for different characters. For example, readers would see the sentence "She w##t to the doctor for a w##t on her foot," and then report what they saw. Surprisingly, observers did *not* see the nonsense characters as the letters that "should" be there given the context (here, "went" and "wart") but instead sheepishly reported seeing the rather bizarre sentence "She west to the doctor for a west on her foot." This suggests a much lower-level statistical explanation of the phenomenon, perhaps ruling it out as a case of *cognitive* penetration of perception.

Second, however, a phenomenon like this, if it withstands scrutiny, may in some sense be an exception that proves the rule. The core interest of the cultural byproduct hypothesis is its claim that seemingly *basic* or *foundational* aspects of visual processing—illusions of perceived space included in nearly all perception courses and textbooks—arise from culturally specific factors. Our discussion here has suggested that this claim is false for most, if not all, of the illusions considered as part of this hypothesis. This leaves only more marginal phenomena such as the illusory letters phenomenon—which, though fascinating, is hardly considered a basic aspect of visual processing. If it turns out that the only culturally specific perceptual phenomena are of this more peripheral nature, then this observation is in some sense a testament to the inflexibility of perception in the face of cultural factors: Perception is so stubborn, as it were, that it can only change at the margins, and even then only after a lifetime of experience.

A Need for More Interpretable Empirical Research

Where do we go from here? Though we have identified new inroads for cross-cultural investigations of perception, interest in classical visual illusions is likely to persist (and rightly so). However, it is clear that the time is ripe for improvements to such approaches. Though some of the issues with previous work were identified by the researchers themselves (e.g., Segall et al.'s concerns about inadequate translations and biased experimenters), the cost of other practices such as flexible analytical decisions and post hoc data exclusions have become better understood only more recently, as the field of psychology has made tremendous progress in embracing research practices that promote the quality, validity, and generalizability of experimental data and inferences made on their basis (Open Science Collaboration, 2015). For these reasons, the field is now better equipped to thoroughly evaluate the claims of the cultural byproduct hypothesis and extend our understanding of culture's potential effects on basic cognitive processes. Thus, we suggest that future work on these topics pay careful attention to measurement validity (e.g., by ensuring translation validity across contexts through translation and back-translation, Brislin, 1970) and experimenter demands (e.g., by employing hypothesis-blind experimenters and minimizing opportunities for demand effects to arise), more carefully quantify predictor variables (e.g., by systematizing "carpentry" or any other cultural force at play through a reproducible and replicable protocol), and preregister all aspects of the investigation (including a priori exclusion decisions).

Encouragingly, the field is already moving in this exciting and more rigorous direction. For instance, in a recent investigation, Cao and colleagues revisited historic patterns of cultural differences in cognition and perception across the United States and China (Cao et al., 2022). Using online samples of adult participants, the team conducted large-scale replications of 12 canonical tasks previously reported to show difference across cultures and failed to find those differences in most of the tasks assayed (and indeed, in two tasks, documented the reverse of the canonical patterns). Notably, this investigation included preregistration, internal replication, open data, and open methods with the aim of establishing a "robust and replicable science of cross-cultural difference" (Cao et al., 2022 p. 44). These efforts represent a laudable model for future work on the interplay between culture and cognition.

Conclusions

Culture is a powerful force that shapes many aspects of our minds. But are some mental processes beyond culture's reach? In our view, the foregoing discussion refutes the strongest and most theoretically consequential formulations of the cultural byproduct hypothesis, according to which core visual processes—exemplified by illusions of perceived space—arise from culturally specific factors encountered over development. Our empirical and theoretical case shows that such illusions arise in diverse species, in congenitally blind individuals, in multiple sense modalities, and in ways that go beyond the presumed influence of the built environment. The leading sources of data in support of the cultural byproduct hypothesis are laden with both long-known and newly understood flaws, as well as contradictory findings that together fail to tell a compelling and coherent story in favor of cultural specificity.

At the same time, the questions at the heart of this debate are live. There are research domains that may reveal more durable cultural effects on processing of sensory input, and modern conceptual and methodological tools show promise in producing more rigorous and interpretable results. Our own speculation is that cross-cultural effects are more likely to emerge at the margins of visual processing than at its core, but this is ultimately an empirical claim that may be assessed by future work. Of course, any investigation, no matter how methodologically sound, will still have to grapple with the evidence already on record: Even if improved methods do reveal reliable cross-cultural differences in the Müller-Lyer illusion or related phenomena, it will still be the case that guppies and congenitally blind humans perceive the illusion, that natural scenes provide the relevant statistical basis all on their own, and so on—such that a unified theory of these phenomena must go beyond cross-cultural differences in the visual environment.

Cultural influences on perception pose deep and enduring questions about the nature of our minds and their relation to the world, with multiple philosophical, sociological, and scientific issues hanging in the balance. Determining the answer to these questions remains an exciting and consequential area for future research, just as it has been in the preceding century.

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