It Is Only Eco-Logical: Direct Perception for XR Research

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ABSTRACT

Direct perception, as part of the ecological approach to perception, defines a relationship between an organism and their environment that is specified by lawful information. Researchers can apply the ecological approach to eXtended Reality (XR) work to obtain a richer understanding of users' perception-action coordination in novel virtual settings. To encourage widespread adoption of this theoretical framework, this methodological paper introduces four major concepts from the ecological approach that are highly relevant to XR applications. We also provide an overview of existing literature to illustrate how those concepts may be used to inform and test their designs. These elements include the study of calibration and attunement, affordances, action based responses, and intrinsic scaling for measurements. The goal of this work is to increase awareness of the value of the ecological approach, and to provide a practical, evidence-based reference for researchers interested in applying these techniques in XR research.

CCS CONCEPTS

• **Human-centered computing → HCI theory, concepts and models**.

KEYWORDS

Perception, Ecological Psychology, Theory, Affordance

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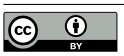
1 INTRODUCTION

The purpose of perception is to guide ongoing and future actions, so we can only truly understand an organism's perceptual system by examining how perception and action function together [Fajen et al. 2008]. Every interaction in eXtended Reality (XR) (including Augmented Reality (AR), Mixed Reality (MR), and Virtual Reality (VR)) requires some form of perception. Theories of perception provide us with a common framework and vocabulary to understand how we interpret virtual objects and environments, and ultimately determine what actions are possible within these spaces. There are two primary theories of perception: the *traditional approach* and the *ecological approach* [Blau and Wagman 2022]. The concept of *direct perception*, a cornerstone of the ecological approach, proposes that organisms directly perceive their environments through structured, lawful information detected by their sensory systems without requiring complex mental processing. This view stands in contrast to the traditional approach, which argues that sensory information is inherently impoverished—particularly due to the two-dimensional (2D) nature of retinal images failing to faithfully represent the three-dimensional (3D) world—and thus requires extensive cognitive interpretation and reconstruction. This ecological framing of perception as directly connected to environmental information offers significant methodological advantages, as it allows researchers to directly observe and measure the informational variables that guide an organism's perceptual processes.

The ecological approach to perception has already demonstrated significant value in several human factors disciplines, including architecture [Pagano et al. 2021] and sports medicine [Araújo et al. 2019], while also proving critical for engineering innovation [Bennett and Flach 2019]. Given that XR technologies aim to support and enhance numerous engineering applications across diverse domains such as process control, medical procedures, architecture, gaming, and manufacturing training [Berntsen et al. 2016], there is compelling reason to believe that ecological perception theory could similarly drive innovation within XR-based engineering contexts. We argue that employing the principles of direct perception when designing XR systems can produce environments that are more intuitive, effective, and inclusive, and that potentially require less cognitive demand and specialized expertise. By applying a theoretical framework that has succeeded in adjacent domains, XR development may benefit from the established principles of direct perception that have already been effective in other fields.

Understanding the value theoretical frameworks contribute to research is the essential first step in incorporating the ecological approach. Robust theories do more than describe relationships between variables or constructs; they explain why these relationships exist [Leong 2006]. This explanatory power shapes the entire research process, from the formulation of research questions to the selection of experimental methods and the interpretation of



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results. The theoretical lens through which researchers view perception can therefore substantially impact both the scientific inquiries conducted and the practical implementations derived from that research. For example, when designing computer displays for applications such as process control and power plants, traditional theory has stressed training, rote learning, and mental models, with meaning imposed by the operator [Vicente and Rasmussen 1990]. The application of ecological psychology has led to alternative display designs that allow meaning to be apprehended with less cognitive deliberation, rote learning, or training [Pagano and Day 2019; Pagano et al. 2021; Vicente and Rasmussen 1990]. Thus ecological theory provides a preferred methodology for the design of artificial systems intended to augment users' perceptual abilities, such as XR.

Rychlak described four primary functions of theories, that they should be: *descriptive* - describe the phenomena studied, *delimiting* - provide boundaries to the scope of the phenomena studied, *generative* - support new questions and hypotheses, and *integrative* - bring together constructs and ideas into a consistent, unified whole [Rychlak 1968]. The descriptive function for perception includes the nature of the information taken in from the world and how that information is transformed into action. Perception research for humans is delimited by the sensory information that a human can perceive and the range of scales such information that is useful. The perceptual theories a researcher employs can have a profound effect on the questions they generate and on the systems they design. For perception work in XR, the integrative function enables diverse studies to be meaningfully connected through their shared theoretical foundations.

For instance, research on audio-based calibration [Lin et al. 2022] can be systematically related to studies of visual calibration [Kohm et al. 2022] when both are grounded in the same perceptual phenomena and theoretical language. Similarly, the integrative function allows seemingly distinct research areas, such as the impact of body anthropomorphism on perception [Buck et al. 2022] and the effects of different XR technologies on perceptual experience [Gaffary et al. 2017], to be coherently synthesized within a unified theoretical framework. This integration has the potential to not only reveal previously unrecognized connections between disparate XR research but also facilitates the development of more comprehensive and consistent design principles across the field.

Our goal is not to dismiss previous XR literature that utilized the traditional approach to perception. Instead, we hope to demonstrate the strength of the ecological approach as an additional approach for future work, and discuss the implications that such a theory can have. The traditional approach encompasses various psychological theories sharing fundamental assumptions about how perception requires mental representation, and these theories collectively dominate mainstream psychological thinking. Due to this prevalence, concepts from the traditional approach seem to have implicitly guided most XR research. This methodological paper encourages an open-minded and inclusive perspective of the ecological direct perception approach as it may provide a nuanced, all encompassing, and potentially multi-faceted, comprehensive and insightful perspective.

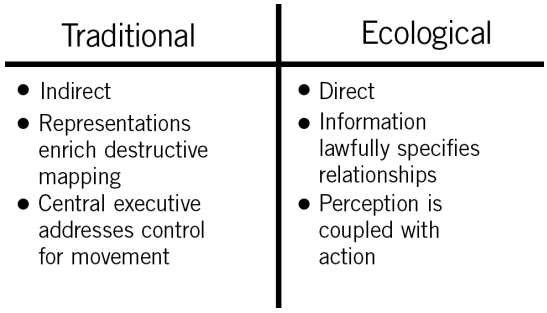

Figure 1: Key differences between the traditional and ecological approaches to perception.

2 THEORIES OF PERCEPTION

2.1 Traditional Approach to Perception

Foundations for traditional approaches to perception date back centuries to the idea of mind-body dualism, with Descartes' claiming that the mind and body were two separate entities [Mohammed 2012]. According to this perspective, the mind has to interpret the sensations that the body receives from the world for perception to occur. In this process information is lost, such as the 3D world being projected onto a 2D retina. This results in ambiguities concerning object and surface properties, such as size, shape, and distance.

Since the mind only has contact with activity from the sensing organs (i.e. eyes or ears), it has no direct contact with the outside world. The mind must employ active mental processes to construct copies of the world, and thus perception is not of the world but of these internal mental representations. In the middle of the twentieth century, the "cognitive revolution" occurred in psychology to coincide with the advent of the computer [Gardner 1987]. Descartes' spiritual mind was replaced with the computer metaphor, and its proposed neurological instantiation, completing the mechanization of the human [Kelty-Stephen et al. 2022]. With XR, the dualism is compounded and perception is even less direct because there are additional losses of information due to tracking delays, noise, lack of fidelity, restricted field of view, etc. This loss of information is associated with the fact that the light carrying information to the eyes is not originating in a natural environment, but is often being created by an artificial display such as a head-mounted display (HMD).

According to the traditional approach, to create an accurate representation of the world in our head the central nervous system uses "cues" extracted the 2D retinal surface [Rock 1997], which acquire meaning through associations [Berkeley 1709]. The term cue is commonly used in XR perception research (i.e. [Armbrüster et al. 2008; Wexler and Van Boxtel 2005]), and describes correlations between the information in the retina and events in the world. The underlying assumption behind the traditional approach is that these correlations are rarely perfect due to the loss or distortion of information. Cues are detected, weighed based on expected or predicted reliability, put into a common unit, and combined based on a weighted average. They are then utilized in the formation of a mental model and projected into a future state to be predictive for prospective control [Bruno and Cutting 1988]. Examples of depth cues include interposition, position or angle relative to the

horizon, relative image size, and binocular disparity [Brunswik 1952; Von Helmholtz 1867]. Cues essentially create a set of rules about how the world should be interpreted and reconstructed. The traditional approach is a highly cognitive process that relies on numerous computations performed rapidly and repeatedly, even when the organism is performing a simple task. Thus, the cognitive load for this approach is far greater than that of the ecological approach.

For motor control, the traditional approach argues that the central executive executes motor programs in the absence of peripheral feedback. These motor programs are accessed from long-term memory and can only be altered through closed-loop control. In closed-loop control, perception is combined with memory to correct for errors in actions. In contrast, open-loop actions are completed almost automatically since the actions are already stored in memory. Therefore, closed-loop interactions tend to be slower and indicate less experience or skill with a task, while open-loop interactions tend to be faster and indicate more experience with a task [Kelso 1982]. The terms open and closed-loop interactions are common in perception research related to XR. Usually open-loop control often involves "blind" manual activities performed with no feedback and closed-loop control are actions with visual feedback. The important takeaway for this form of motor control is that both open and closed-loop control involve memory and mental representations. They also rely on other cognitive processes to compensate for predicted variability in execution.

When moving parts of the body (i.e. limbs), the central executive separately addresses individual components like muscles and even the motor units within the muscles. This is known as address-specific control. Bernstein highlights two problems with this form of motor control [Nikolai 1967]. The first is a degrees of freedom problem, where the human anatomy has too many degrees of freedom for each effector to be addressed individually. The second problem is context-conditioned variability. There is so much variability in the environmental context when performing actions that motor commands are rarely executed by the end-effectors in a reliable way. Even the direction of limb motion resulting from a given muscle contraction can change depending on the current angle at the joint or the limb's position relative and gravity [Kelso 1982]. As with perception, the traditional approach proposes a large number of computations and manipulations of internal representations to overcome these problems. In keeping with the computer metaphor, their solutions are similar to those employed in robotics.

2.2 Ecological Approach to Perception

The ecological approach to perception was pioneered by James Gibson [Lobo et al. 2018]. The ecological approach rejects the dichotomies of traditional psychology which relied on impoverished stimuli and high cognitive loads, and does not rely on complex mental models. Instead, the ecological approach posits that an organism's relationship to their environment is specified by lawfully generated and accurate information [Blau and Wagman 2022; Gibson 1979; Turvey 2018]. Through this lawful specification, perception and action can be coupled rather than separated, referred to as perception-action coordination.

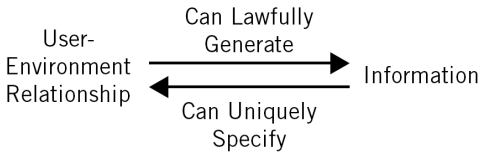

Figure 2: The relationship between an organism and their environment in the ecological approach to perception.

The ecological approach to perception stresses that information contained in ambient energy distributions, such as light and sound, is lawfully related to the world [Turvey 2006]. Light carries information from the 3D world to the 2D retina, but it has been demonstrated both analytically and empirically that a significant amount of information remains intact. It is this veridical information that is used by organisms during natural real-world perception and motor control [Blau and Wagman 2022; Gibson 1979; Turvey 2018]. In many cases, the veridical information is created by the dynamic motions of the perceiver and is generated by ongoing, self-produced activity. The traditional approaches were largely developed when visual perception was assumed to involve a series of static images that were imposed on a passive perceiver. An early contribution the ecological approach was to re-conceptualize the perceiver as actively obtaining information, where the information is often contained in transformations such as those contained in optic flow [Gibson 1966].

By moving through an environment organisms can reveal *invariants* in the ambient optical array, which are properties of the stimulation that remain constant while other properties are changing [Blau and Wagman 2022]. Some examples of visual invariants are those contained in the optical flow field that occur during locomotion [Warren et al. 2001]. The point at which this field radiates is known as the focus of expansion. It corresponds to the direction of heading and thus it can guide the organism's direction of movement as they steer though real or virtual environments (VEs) [Fajen 2021; Turvey 2006].

Consider a virtual environment like Figure 3. The traditional approach claims that size information about the cylinders is lost when they are projected onto a 2D retinal surface. Worse, the apparent size of these projections changes as the viewer moves through the VE. The traditional approach must invoke complex cognitive processes in order to explain how we perceive stable object sizes despite these changing projections. In contrast, the ecological approach demonstrates how size information is preserved through invariant relationships. Notice how the horizon line intersects all objects at the viewer's eye height, and the proportion of each light cylinder below the horizon remains constant regardless of distance or movement. This invariant relationship reveals that all light cylinders are identical in size, while the dark cylinder is larger. Rather than employing cognition to reconstruct size information from the ambiguous 2D projection, the ecological approach shows how we can directly perceive size through invariants that remain stable during motion. This is not to say that cognition is completely absent in perception from an ecological perspective. For example, the viewer must recognize the horizon line as such and cylinders as 3D

shapes. However, to perform an action like size estimation less cognitive processing is required by using physically based relationships already available in the VE.

Since users know their eye height in the real world (though perhaps not in XR), they can determine actual object sizes. When moving toward a cylinder (right panel), the focus of expansion occurs at the cylinder and at the user's eye height. The traditional approach views transformations like changing cylinder images as problems requiring mental processing to solve. The ecological approach sees these transformations as solutions that reveal invariants. Information about true object sizes was never lost, it is produced through observer motion.

Also in Figure 3, the unit for the perceived sizes of the cylinders is not an extrinsic one, such as feet or meters, but an intrinsic one in terms of the viewer's own eye-height. The environment is perceived in units of the actor's own proportions and/or movements which is best for controlling their actions. In a virtual environment the preservation of information from eye height scaling could be useful when depicting embodied avatars of varying sizes, or even 360 videos viewed in an HMD (i.e. [Rothe et al. 2019]). Optic flow and eye height scaling were among the first discoveries made by the ecological approach [Gibson 1966, 1979], and are examples of how theory informs design. The concept of affordances is important for virtual environments because they let the user know what they can and cannot do in the virtual world. For example, a gap might not afford jumping over because it is too wide. The user can tell that the gap is too wide based on the relationship between the optical information they are receiving and their own physical properties. Calibration is utilized to scale the use of this information to fit changing properties of the user or the properties of their virtual avatar [Day et al. 2019]. Further, the input devices for XR systems can alter affordances based on their capabilities. For example, some headsets allow hand tracking for inputs while others do not.

The ecological approach demonstrates how the world can be directly perceived without requiring complex cognitive processing. The organism is coupled to the world via information that dynamically flows and changes with ongoing movements, and thus manual activities are coordinated with this external information [Fajen 2021]. Rather than motor control following perception, it provides information for perception. They are dual processes that occur simultaneously and which are mutually supportive. In this way, perception is achieved by detecting information rather than by requiring a central executive to create a copy of the world using incomplete and flawed information. Figure 2 illustrates the relationship between an XR user and their virtual environment. Both information and cues represent input to the organism, but information in the ecological approach represents lawful relationships instead of a set of rules.

Motor control in the ecological approach is quite different than in the traditional approach. Instead of address-specific control the ecological approach posits that synergies self-organize out of a system's dynamics, and are governed by the laws of nature [Nikolai 1967]. With synergies, there are fewer degrees of freedom for the organism to explicitly control. Synergies introduce constraints so that dynamical systems, like gait, have reduced complexity by controlling less degrees of freedom [Blau and Wagman 2022]. Perception and action in this framework is more closely coupled and

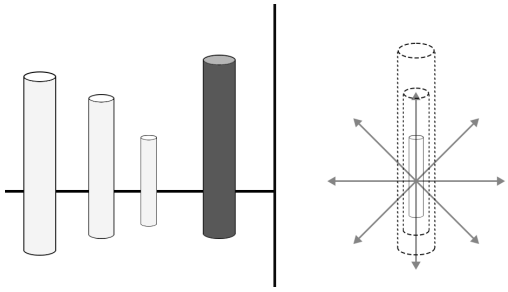

Figure 3: A sample virtual environment depicting size information.

organisms can constantly calibrate their actions instead of trying to execute motor commands from memory. In the traditional approach, closed-loop control is seen to correspond to less skilled actions, but in the ecological approach it is a hallmark of greater proficiency. Closed-loop actions in the ecological approach correspond to better coupling with the environment in such a way that the cognitive burdens are reduced. Action produces optic flow which informs ongoing action. Actions are coupled to environmental information rather than driven by internal mental representations.

A major benefit of the ecological approach is its parsimony. It requires fewer assumptions and addresses fundamental questions about information flow and perception-action coupling more directly. Rather than treating action as an obstacle creating problematic variability, the ecological approach recognizes that action is integral to perception. The perceptual information in optic flow is simultaneously generated by and used to guide action in a continuous loop. This perspective significantly reduces cognitive demand on users, eliminating the need for constant memory access and complex cognitive calculations. Figure 1 summarizes these key distinctions. By adopting an ecological approach, XR designers can create environments that prioritize conveying lawful information to users, thereby reducing the need for cognitive deliberation and creating more intuitive experiences that leverage natural perception-action relationships.

3 CALIBRATION AND ATTUNEMENT

One key aspect of the ecological approach is the improvement of perception and performance through attunement and calibration. Attunement and calibration training is a way to achieve perceptual learning without relying on cognitive abilities. Perceptual learning does not require the attainment of more complex memories, mental models, or other forms of internal mental representations or deliberations. Instead, attunement and calibration form better couplings between motor actions and the perceptual information available to the senses. Attunement is learning to base ones activities on the most accurate information available, and calibration is learning to scale ones actions appropriately. An example of proper scaling might be throwing a ball to a target without over or under-shooting or manipulating tissues in laparoscopic surgery and feeling when they are about to be damaged by those manipulations [Altenhoff et al. 2017].

Initial and often persistent errors in both perception and performance are inherent in all XR systems, though hardware advancements such as wider fields of view and higher headset resolutions have helped mitigate these effects. A good example of consistent errors in realistic environments is the pattern of underestimation for distance estimations in XR [Bodenheimer et al. 2022; Kelly et al. 2022]. These errors could be caused by alterations to the environment and/or by alterations to the user's own abilities such as with redirected walking [Steinicke et al. 2009] or alterations of body schemas and the virtual world for haptic re-targeting [Azmandian et al. 2016]. Regardless of what causes the errors, calibration can often be used to correct them, even if the calibration occurs outside of the VE [Sepahyar and Kuhl 2022]. This calibration could occur through visual only attunement or self-motion in a VE, and rapidly or over extended exposure to a VE [Kohm et al. 2022].

XR researchers often seek ways to reduce user error by increasing the fidelity of their displays or through other technological innovations, but even very low fidelity displays can contain adequate information for users to perceive and act accurately. One solution that should be part of every XR researchers' toolkit is the use of attunement and calibration training to maximize user performance. The true success of any XR design can only be known after such training has been employed, which may be missed by only evaluating them with participants that have not given a proper opportunity to attune or calibrate to the optimal perceptual information. In other words, many XR designs may be more successful than what is shown by the evaluations conducted by their developers. For virtual environments, calibration opens up a wide array of interaction techniques that, if difficult at first, may become more useful as users calibrate to the proper information.

One study of real-world calibration looked at how well monocular observers perceived egocentric distance via an artificial display [Bingham and Pagano 1998]. The researchers found that across all monocular viewing conditions participants tended to underestimate distances. When the underestimation was caused by a restricted field of view, participants were able to calibrate and reduce errors in estimation using feedback from reaching. Essentially, calibration from reaching was able to eliminate the observed underestimation across trials. Another study on calibration measured how quickly participants could adapt to perturbations in their vision that were sequentially applied, removed, and applied again [Bingham and Romack 1999]. These perturbations were the result of displacement prisms which skewed their vision while performing a reaching task and was run over the course of three days. The researchers found that the rate of calibration did not change within blocks but that less calibration was needed across days. This implied that participants were starting sessions more calibrated and thus provided evidence that calibration could carry over. These studies demonstrate calibration in non-virtual contexts and for behaviors that involved reaching, but calibration can also improve perception-action coordination in virtual environments.

Our first proposition is:

P1: Perception research in XR should consider which invariants are present in the virtual environment. They should also consider which of these invariants XR users must calibrate their actions to so that they may correct for perceptual errors.

Much of the work that has considered calibration to errors in visual perception within virtual environments has involved distance perception. Altenhoff et al. showed that distance estimates in VR became more accurate and similar to estimates in the real world after calibration via haptic and visual feedback [Altenhoff et al. 2012]. Several works have considered reaching accuracy when positive and negative gain to a virtual stylus offset a held, physical stylus [Ebrahimi et al. 2014, 2015]. In these works feedback calibrates distance estimates such that estimates counteract the gains. Ebrahimi et al. compared reach estimates in a real and virtual environment [Ebrahimi et al. 2016]. The researchers found that feedback could eliminate differences between the real and virtual environments by improving reaches in the VE even with the presence of an imposed movement gain. Kelly et al. found that brief periods of walking in the virtual environment could greatly improve distance estimations through calibration [Kelly et al. 2014]. They reported that the effects of locomotion on perceived distances occurred rapidly, then diminished with subsequent feedback.

Several studies have also started to investigate calibration that relies on non-visual information such as audio reverberation. For example, Lin et al. found that audio calibration was able to reduce underestimation in distances similar to vision based calibration [Lin et al. 2022]. They also found that the calibration still effected participants' accuracy when they were re-tested six months later, which long-term persistence of calibration has significant practical applications for XR developers. A similar studied had participants walk to perceived distance estimations based on audio feedback and found that auditory depth estimates improved through calibration [Lin et al. 2024]. Wu et al. compared visual to audio calibration for room size estimation in VR and found that while visual information was more effective, audio information was still useful to improve accuracy [Wu et al. 2024].

Another study investigated the influence of self-avatar visual fidelity on reach boundary perception [Ebrahimi et al. 2018], and found that performance improved with calibration in each of the three levels tested. Day et al. found that participants were able to calibrate to virtual self-avatars altered with artificially long arms [Day et al. 2019]. They also found that calibration carried over between experimental phases. Once explicit feedback from calibration was removed, participants reverted back to their own body dimensions, highlighting the need for continuous calibration to embodied avatars with altered body anthropometric dimensions. Mohler et al. investigated the effects of altering optic flow for participants walking on a physical treadmill in a VE and found that calibration was influenced by self-motion information, not the magnitude of optic flow patterns [Mohler et al. 2007].

All of these studies showed an improvement in performance for XR users when calibration was used. From this work we would expect that errors can similarly be eliminated via calibration in other forms of perception and motor control within XR. It is worth noting that while calibration almost always shows some improvement, it does not always do so equally. Some conditions show that calibration has more of an impact than in others and calibration from some information may carry over longer. Future research should be directed toward a deeper understanding of the possible limitations of calibration.

4 MEASURING AFFORDANCES

4.1 Affordances in the Ecological Approach

Affordances are actions that are possible given the properties of environmental objects and surfaces in conjunction with the proprieties and abilities of the user [Gibson 1979]. Affordances are relational, they are neither properties of the environment nor properties of the user, but pertain to the fit between the two. In the non-virtual world this includes things like a cup being grasp-able or a door being open-able. In the real world, people change the affordances available by changing the environment (i.e. building or re-arranging furniture) and by making changes to themselves (i.e. by using a tool, wearing protective clothing, becoming more physically fit, etc.). Other changes to individuals that alter their affordances may include changing their mode of transportation, becoming fatigued, carrying or wearing equipment [Petrucci et al. 2016], or even becoming pregnant [Franchak and Adolph 2007]. In a virtual environment affordances are not always obvious to the user, in part because the properties of the virtual user are not always perceptible to them. Affordances in virtual environments may also not always be available for use, even if they appear to be. Availability of object affordances in a virtual environment may depend on whether or not the object is interactive. For example, a virtual cup may not be grab-able because the user cannot collide with the cup to grab it. Further, affordances are not always obvious in virtual environments either because the objects do not exist outside of the virtual world.

A cup in the real world is only grasp-able if the user has a hand that is able to grasp that object. User abilities are an important consideration for virtual environments, since they may vary between people and programs. Small design choices have implications for whether or not affordances are perceptible [Pagano et al. 2021]. Many affordances in the real world are undesirable, such as an obstacle that can be tripped over or a tool that can cut the hand if not used properly. Desirable affordances that are not perceptible are not usable, while undesirable affordances that are not perceived are hazardous. Safety is determined by both the number of hazardous affordances present and how perceptible they are. Analogous issues are at work in virtual environments, particularly if the environment is to be used as an operator interface for real-world engineering applications. In such cases the virtual environment can make perceptible affordances of the real world that are not perceptible with direct real-world viewing (akin to the use of night-vision goggles) [Hartman et al. 2016], or the environment can inadvertently obscure the real world affordance (both the desired ones and hazards). Additionally, in VR affordances may be available to users that are not available to them in the real world, such as when using an avatar with 'superhuman' abilities or fictitious tools.

4.2 Affordances in Virtual Environments

Prior research has shown that virtual hand representations can alter affordance perceptions [Venkatakrishnan et al. 2023]. Let's consider a scenario of a VE filled with interactable objects where two users have the same virtual representations of their hands, but one uses a controller trigger to interact with objects and the other uses a pinching gesture. For both types of interactions the objects in the virtual scene afford picking up (either by clicking or pinching). For other interactions in the environment, however, the affordances may differ. For example, there may be an interaction that requires a quick reaction and pinching may be much slower than pressing a trigger. Further, the virtual tracked hand has very different capabilities than a controller represented by a tracked hand.

Babu et al. show how fine motor controllers using different end-effectors (such as a controller vs. a tracked hand) can affect the accuracy and efficiency of interactions in a VE [Babu et al. 2020]. They studied how performance (measured by Fitt's law) differed when pointing at targets using a controller versus the participant's tracked index finger viewed via an HMD. They reported that spatial selection was better in the controller based condition. Even though both forms of input allowed participants to point at objects, the difference in performance indicates that the affordances were not equivalent. Not all changes to self-avatars result in different capabilities, however. As long as the information the XR user needs to attune to is present in the environment, they can perform the same actions regardless of altered properties like the visual fidelity of the end-effectors [Wijayanto et al. 2023]. Another work by Babu et al. leveraged the affordances of near-field object manipulation on far-field objects [Babu et al. 2024]. This highlights another case where XR designers can utilize and think about the specific affordances of their hardware and software to improve their users' experiences.

Interactions in VR that require a large variety of capabilities from VR users, such as writing (i.e. [Venkatakrishnan et al. 2022]) and painting (i.e. [Otsuki et al. 2018]). Speicher et al. evaluated various methods for selection-based text entry in VR [Speicher et al. 2018]. The researchers compared text input techniques such as head-gaze selection, standard controller pointing, and tracking of the participants' real hands. They found that participants performed best in the controller pointing condition, and they preferred this method of typing. This may seem unusual since typing with real hands (or the freehand technique as the authors described it) is how most people type in the real world. Through the ecological approach we can contextualize this finding with affordances. Both real and virtual keyboards afford typing, but the relationship between the user and their environment is different. In the real world keyboards usually are closer to the user, lay horizontally, and provide haptic feedback. In a virtual environment keyboards tend to be farther from the user, vertically aligned, and do not provide haptic feedback. How the user fits in to each of these environments is different and that altered relationship is reflected in ease and efficiency of use. By considering the environment (or ecology) and not just the interaction technique, it becomes clear why typing in the real and virtual world may differ.

Users may need explicit explanation of how to interact with objects that only exist in virtual environments. A challenge is that the relevant affordances must be easily perceived [Norman 1988]. Written directions and even metaphors are indirect forms of perception that require cognition and are thus less efficient than direct perception [cite Raveendranath et al 2024]. They are also less inclusive for users with different cognitive abilities or cultural backgrounds. Virtual environments should be designed with affordances and direct perception in mind to provide the most intuitive experience for the user.

Our second proposition is:

P2: Perception research in XR should consider the affordances available to various users in virtual environments and measure the saliency of those affordances. This will give researchers a clearer understanding of how users with different capabilities may act in the environment they are studying.

A study by Ogawa et al. investigated the influence of anthropomorphism and visibility of embodied self-avatars on participants' willingness to walk through virtual walls [Ogawa et al. 2020]. They found that a realistic, full-body self-avatar was most successful at deterring participants from going through walls in the virtual space. While the paper does not explicitly employ an ecologic approach or use the term affordance, its consideration of what was in fact the affordances of the environment and their saliency is consistant with the ecological approach. The main focus was on the self-avatar and its relationship to alterations of the environment, such as the addition of hazards, and how the altered user-environment relationship (the affordances) impacted interactions.

A study by Bhargava et al. compared affordance judgements in the real and virtual world by asking participants whether or not they could pass through an opening in each environment [Bhargava et al. 2020]. They found that while participants had similar levels of accuracy for passability in the real and virtual world, they required more explorations to reveal information in the VE. This work shows how affordances can be empirically tested in VR. Work by Buck et al. considered pass-ability judgments in social VEs [Buck et al. 2019]. Along with differences between social groups in the real and virtual worlds, they found that groups needed wider gaps in the VE to consider them as passable. Several XR works have also considered altering affordances for locomotion in VR [Interrante et al. 2007] and AR [Pointon et al. 2018].

5 ACTION BASED RESPONSES

Since perception and action are viewed by the ecological approach and a single unitary process, the ecological approach has pioneered methods for using participants' action to directly measure perception. One way to achieve this is by utilizing action based responses in XR perception work. Previous work in both real world and virtual settings has shown that verbal responses, such as in a distance estimation task, are less accurate and more variable than action based counterparts such as reaching [Napieralski et al. 2011]. Therefore, action based responses can give a clearer view of the underlying phenomena in question. Researchers have shown that the type of instructions given to participants can change their verbal judgments without affecting action-based ones, even when the two responses are made simultaneously and are based on the same view of the target [Pagano and Isenhower 2008]. Speech and communication are also cognitive processes [Sperber and Wilson 1986]. Since the ecological approach argues that perception requires little to no cognition, it does not make sense to try and measure perception with cognition. By filtering perception through cognition, verbal reports have been found to be less accurate, more variable, more influenced by cognitive biases such as expectancies, more indicative of relative perception rather than absolute perception, and less amenable to calibration [Pagano and Isenhower 2008].

Our third proposition is the following:

P3: Perception research in XR should utilize action based responses since perception and action are coupled. This will lead to more accurate results and tie in more closely with the underlying mechanisms for perception.

An example of the use of action-based measures is when participants are asked to estimate distances by walking in a VE [Interrante et al. 2006]. Mohler et al. used action-based responses to investigate how the appearance of a self-avatar in a VE influenced space perception [Mohler et al. 2010]. Westermeier et al. used action-based reaching methods to analyze the impact of inter-pupillary vs. inter-camera distance in VR vs. video see through (VST) AR on distance estimation [Westermeier et al. 2025]. Using this approach, these researchers were able to find an underestimation in the VST AR condition compared to the VR condition and an effect of the inter-pupillary/inter-camera discrepancy without the interference of verbal-based estimations. For example, Chiu et al. compared verbal and physical size perception judgments in VST AR and the real world and found that physical judgments were more accurate in both viewing conditions [Chiu et al. 2025].

Functional transparency has been demonstrated in XR by examining attunement and calibration in a haptic virtual laparoscopic surgical trainer [Altenhoff et al. 2017; Hartman et al. 2016; Long et al. 2016]. Laparoscopic surgery, also referred to as minimally invasive surgery (MIS), is preferable to traditional open surgery because the incisions are much smaller and thus trauma to the body and associated infection and recovery rates are greatly reduced. The surgeon, however, cannot directly view tissue manipulations which must be performed and perceived via intervening tools. As a result, surgeons are more likely to break or tear healthy tissue during MIS. Long et al. identified haptic distance-to-break (DTB), an invariant that specifies to the observer when they are about to break a tissue [Long et al. 2016]. They investigated the ability of subjects to perceive DTB using simulator consisting of a laparoscopic surgical tool attached to a torque motor that was directed by computer software to simulate artificial materials being pressed against, deformed by the tool, and ultimately broken if deformed too far. With only 15 minutes of training, novice participants with no experience in MIS learned to detect DTB and use it to position a tool within a few millimeters of a tissues' break point [Altenhoff et al. 2017; Hartman et al. 2016]. Experienced surgeons improved their ability to attune and calibrate to DTB after the same brief training [Long et al. 2016]. That novices reached a commendable level of performance, and experts improved, underscores the efficacy of attunement and calibration training to perceptual invariants in an applied task. This underscores the efficacy of using aspects of ecological theory, including action-base measures, to develop XR displays for training both experts and novices.

The goal is to achieve for XR displays the level of functional transparency that has been achieved with haptic displays and industrial engineering applications. Instead of viewing XR as inherently inferior to real-world viewing, relevant perceptual invariants can be made more salient in XR than they are in the real-world or they can be made to be artificially present where they me be lacking in the real world (such as when conditions are degraded). They can also be presented in a manner that promotes perceptual learning through attunement and calibration training [Hartman et al. 2016]. The

possibility of functional transparency in various XR applications should be a topic of further study.

6 INTRINSICALLY SCALED METRICS

We have discussed how information such as invariants are revealed through self-motion. We have also discussed how organisms see the world from their own eye height and make affordance judgments based on their own body scale, because the ambient optic array is intrinsically scaled. Our perception of the world is based on the scale of our body [Warren 1984]. If an organism were to try and perceive the world around them in extrinsic units like centimeters or inches, it would require a great deal of cognition to run calculations for distance, size, time to contact, etc. [Blau and Wagman 2022]. It is simplest to talk about scaling in geometric terms like body size, but flexibility, strength, and other biomechanical factors should also be considered [Cesari 2005; Cesari et al. 2003]. Therefore, instead of measuring in extrinsic units, XR researchers should consider measuring in body scale units.

A study with robot teleoperators showed that they misjudged the affordances of the robot they were controlling due to the "eye height" of the camera [Moore et al. 2009]. The operators viewed openings as passable that were actually too small for the robot to fit through. This was because they were used to their own eye height scaling, and a lower eye height made openings appear larger than they really were. This mirrored the experience of robot operators during the aftermath of the 9/11 terror attacks, where they often lost or damaged teleoperated robots by driving them into openings that were too small [RR 2004].

Our fourth proposition is:

P4: Perception research in XR should utilize intrinsically scaled metrics since, in the real world users make perception judgments based on their own body size. This will allow users to interact more naturally with the virtual environment and generate specific recommendations based on the affordances for different individuals.

Venkatakrishnan et al. investigated how avatar representation investigated performance and perception in MR for a peg-transfer task [Venkatakrishnan et al. 2024]. They found that co-located avatars significantly improved performance, supporting that XR users are more capable at performing tasks with intrinsically scaled metrics. Although extensive research has shown that perceived distances are compressed in VR compared to perception in the real world, preliminary work has suggested that this difference disappears when subjects instead make judgments about intrinsic affordances [Masoner et al. 2021]. Kohm et al. examined how calibration influenced reach based estimates for depth perception over time using target distances scaled to participants' maximum arm reach [Kohm et al. 2022]. This 12 week study in VR had participants reach to these target distances with and without a tool. The results of the study showed underestimation at first, which was mitigated over time via calibration. Participants were able to calibrate to the intrinsically scaled target distances, which was especially important as they became familiar with the environment over their prolonged exposure. This allowed participants to leverage the information about their body scaling in the real world to the virtual world, but more can be done to use intrinsic measurements for accurate VE perception measurements.

7 LIMITATIONS OF THE ECOLOGICAL APPROACH FOR XR

The main limitation of the Ecological Approach for XR research is its claim that perception can be direct, since perception in XR is mediated by artificial displays. Much of the empirical work within the ecological approach, including work presented in this paper, involves analytically uncovering the presence of information in feedback such as light and sound, then empirically verifying that users employ such information. Though the information from the VE may be delivered to the user via mediation, that does not mean mediation is required *within* the user to guide their perception-action coordination.

A second consideration for implementing the ecological approach is difficulty applying it to cognition intensive phenomena, such as memory retrieval, problem solving, and insight learning. Therefore, the implementation of this technique in XR should focus on research that pertains to the users' ability to successfully achieve basic perceptual and motor control functions instead of cognitively demanding tasks.

8 SUMMARY

Theory is an integral part of the scientific process by directing the generation of research questions, the choice of experimental methodologies, and the interpretation of results. This work presented an argument for the wider adoption of ecological theory within XR research. While the traditional approach has been invaluable, we discussed shortcomings of the traditional approach and how the ecological approach may overcome them. We highlighted the fundamental differences between traditional and ecological theories, and provided examples of how the ecological approach has begun to shape work in this field. The practical applications are based on a consideration of how the user fits into their virtual environments and how this determines the information that should be presented to them. The ecological approach leverages off ways in which the mapping of the real world to the senses is not destructive and how the information present puts the organism in direct contact with the world. Past work has shown that XR applications can be designed so that similar lawful information is present, and by doing so performance in XR can match and even excel performance in the real world.

From this work, we ask researchers to consider how their past and future studies might benefit by integrating and applying the ecological approach to perception or any well-defined theoretical framework. While there is still more work to do to calibrate for visual information, we also challenge you to consider all of the various modalities that information can be supplied to an XR user. These could include haptic perception, audio perception, proprioception, smell perception, taste perception, and more. XR researchers may also consider calibration to volume or even speed perception in dynamic situations in the future [Tolchinsky et al. 2023]. We also encourage readers to learn more about the ecological approach, such as in the work by Blau and Wagman which offers much more detail

on ecological psychology and the original ecological psychology paper by Gibson [Blau and Wagman 2022; Gibson 1979].

We have provided four propositions to help guide XR work that adopts the framework we have presented in this paper. These include a focus on measuring invariants for calibration and attunement, considering the affordances of the users and/or their self-avatars, utilizing action based responses for perceptual estimations, and utilizing intrinsic measurement scaling. These propositions do not encompass every aspect of the ecological approach, nor do they cover every aspect that may be useful for XR. Instead, we intend for them to act as a starting point for future XR research.

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REFERENCES

Bliss M Altenhoff, Phillip E Napieralski, Lindsay O Long, Jeffrey W Bertrand, Christopher C Pagano, Sabarish V Babu, and Timothy A Davis. 2012. Effects of calibration to visual and haptic feedback on near-field depth perception in an immersive virtual environment. In *Proceedings of the ACM symposium on applied perception*. 71–78.

Bliss M Altenhoff, Christopher C Pagano, Irfan Kil, and Timothy C Burg. 2017. Learning to perceive haptic distance-to-break in the presence of friction. *Journal of experimental psychology: Human Perception and Performance* 43, 2 (2017), 231.

D Araújo, E Brymer, H Brito, R Withagen, and Keith Davids. 2019. The empowering variability of affordances of nature: Why do exercisers feel better after performing the same exercise in natural environments than in indoor environments? *Psychology of Sport and Exercise* 42 (2019), 138–145.

Claudia Armbrüster, Marc Wolter, Torsten Kuhlen, Will Spijkers, and Bruno Fimm. 2008. Depth perception in virtual reality: distance estimations in peri-and extrapersonal space. *Cyberpsychology & Behavior* 11, 1 (2008), 9–15.

Mahdi Azmandian, Mark Hancock, Hrvoje Benko, Eyal Ofek, and Andrew D. Wilson. 2016. *Haptic Retargeting: Dynamic Repurposing of Passive Haptics for Enhanced Virtual Reality Experiences*. Association for Computing Machinery, New York, NY, USA, 1968–1979. https://doi.org/10.1145/2858036.2858226

Sabarish Babu, Ming-Han Tsai, Ting-Wei Hsu, and Jung-Hong Chuang. 2020. An evaluation of the efficiency of popular personal space pointing versus controller based spatial selection in VR. In *ACM Symposium on Applied Perception 2020*. 1–10.

Sabarish V. Babu, Wei-An Hsieh, and Jung-Hong Chuang. 2024. The Benefits of Near-field Manipulation and Viewing to Distant Object Manipulation in VR. In *2024 IEEE Conference Virtual Reality and 3D User Interfaces (VR)*. 408–417. https://doi.org/10.1109/VR58804.2024.00062

Kevin B Bennett and John Flach. 2019. Ecological interface design: thirty-plus years of refinement, progress, and potential. *Human factors* 61, 4 (2019), 513–525.

George Berkeley. 1709. *An essay towards a new theory of vision*. Aaron Rhames.

Kristina Berntsen, Ricardo Colomo Palacios, and Eduardo Herranz. 2016. Virtual Reality and Its Uses: A Systematic Literature Review. In *Proceedings of the Fourth International Conference on Technological Ecosystems for Enhancing Multiculturality* (Salamanca, Spain) *(TEEM '16)*. Association for Computing Machinery, New York, NY, USA, 435–439. https://doi.org/10.1145/3012430.3012553

Ayush Bhargava, Kathryn M Lucaites, Leah S Hartman, Hannah Solini, Jeffrey W Bertrand, Andrew C Robb, Christopher C Pagano, and Sabarish V Babu. 2020. Revisiting affordance perception in contemporary virtual reality. *Virtual Reality* 24, 4 (2020), 713–724.

Geoffrey Bingham and Jennifer L Romack. 1999. The rate of adaptation to displacement prisms remains constant despite acquisition of rapid calibration. *Journal of Experimental Psychology: Human Perception and Performance* 25, 5 (1999), 1331.

Geoffrey P Bingham and Christopher C Pagano. 1998. The necessity of a perception–action approach to definite distance perception: Monocular distance perception to guide reaching. *Journal of Experimental Psychology: Human Perception and Performance* 24, 1 (1998), 145.

Julia JC Blau and Jeffrey B Wagman. 2022. *Introduction to Ecological Psychology: A lawful approach to perceiving, acting, and cognizing*. Taylor & Francis.

Bobby Bodenheimer, Haley Adams Adams, Jeanine Stefanucci, and Sarah Creem-Regehr. 2022. Judging Distances to Virtual Objects Generated by Optical and Video See-Through Augmented Reality. *Journal of Vision* 22, 14 (2022), 4407–4407.

Nicola Bruno and James E Cutting. 1988. Minimodularity and the perception of layout. *Journal of Experimental Psychology: General* 117, 2 (1988), 161.

Egon Brunswik. 1952. The conceptual framework of psychology.(Int. Encycl. unified Sci., v. 1, no. 10.). (1952).

Lauren E Buck, Soumyajit Chakraborty, and Bobby Bodenheimer. 2022. The impact of embodiment and avatar sizing on personal space in immersive virtual environments. *IEEE Transactions on Visualization and Computer Graphics* 28, 5 (2022), 2102–2113.

Lauren E. Buck, John J. Rieser, Gayathri Narasimham, and Bobby Bodenheimer. 2019. Interpersonal Affordances and Social Dynamics in Collaborative Immersive Virtual Environments: Passing Together Through Apertures. *IEEE Transactions on Visualization and Computer Graphics* 25, 5 (2019), 2123–2133. https://doi.org/10.1109/TVCG.2019.2899232

Paola Cesari. 2005. An invariant guiding stair descent by young and old adults. *Experimental aging research* 31, 4 (2005), 441–455.

Paola Cesari, Federico Formenti, and Paolo Olivato. 2003. A common perceptual parameter for stair climbing for children, young and old adults. *Human movement science* 22, 1 (2003), 111–124.

Chao-Kuo Chiu, Jung-Hong Chuang, Christopher C. Pagano, and Sabarish V. Babu. 2025. Comparing Absolute Size Perception in Optical See-Through Augmented Reality and Real World Viewing Using Verbal and Physical Judgments. In *2025 IEEE Conference Virtual Reality and 3D User Interfaces (VR)*. 307–317. https://doi.org/10.1109/VR59515.2025.00055

Brian Day, Elham Ebrahimi, Leah S Hartman, Christopher C Pagano, Andrew C Robb, and Sabarish V Babu. 2019. Examining the effects of altered avatars on perception-action in virtual reality. *Journal of Experimental Psychology: Applied* 25, 1 (2019), 1.

Elham Ebrahimi, Bliss Altenhoff, Leah Hartman, J Adam Jones, Sabarish V Babu, Christopher C Pagano, and Timothy A Davis. 2014. Effects of visual and proprioceptive information in visuo-motor calibration during a closed-loop physical reach task in immersive virtual environments. In *Proceedings of the ACM Symposium on Applied Perception*. 103–110.

Elham Ebrahimi, Bliss M Altenhoff, Christopher C Pagano, and Sabarish V Babu. 2015. Carryover effects of calibration to visual and proprioceptive information on near field distance judgments in 3d user interaction. In *2015 IEEE Symposium on 3D User Interfaces (3DUI)*. IEEE, 97–104.

Elham Ebrahimi, Sabarish V Babu, Christopher C Pagano, and Sophie Jörg. 2016. An empirical evaluation of visuo-haptic feedback on physical reaching behaviors during 3D interaction in real and immersive virtual environments. *ACM Transactions on Applied Perception (TAP)* 13, 4 (2016), 1–21.

Elham Ebrahimi, Andrew Robb, Leah S Hartman, Christopher C Pagano, and Sabarish V Babu. 2018. Effects of anthropomorphic fidelity of self-avatars on reach boundary estimation in immersive virtual environments. In *Proceedings of the 15th ACM Symposium on Applied Perception*. 1–8.

Brett R Fajen. 2021. *Visual control of locomotion*. Cambridge University Press.

Brett R Fajen, Michael A Riley, and Michael T Turvey. 2008. Information, affordances, and the control of action in sport. *international Journal of sport psychology* 40, 1 (2008), 79–107.

John Franchak and Karen Adolph. 2007. Perceiving changing affordances for action: Pregnant women walking through doorways. *Journal of Vision* 7, 9 (2007), 116–116.

Yoren Gaffary, Benoît Le Gouis, Maud Marchal, Ferran Argelaguet, Bruno Arnaldi, and Anatole Lécuyer. 2017. AR feels "softer" than VR: Haptic perception of stiffness in augmented versus virtual reality. *IEEE transactions on visualization and computer graphics* 23, 11 (2017), 2372–2377.

Howard Gardner. 1987. *The mind's new science: A history of the cognitive revolution*. Basic books.

James Jerome Gibson. 1966. *The senses considered as perceptual systems*. Vol. 2. Houghton Mifflin Boston.

James J Gibson. 1979. *The Ecological Approach to Visual Perception*. Houghton Mifflin.

Leah S Hartman, Irfan Kil, Christopher C Pagano, and Timothy Burg. 2016. Investigating haptic distance-to-break using linear and nonlinear materials in a simulated minimally invasive surgery task. *Ergonomics* 59, 9 (2016), 1171–1181.

Victoria Interrante, Brian Ries, and Lee Anderson. 2006. Distance perception in immersive virtual environments, revisited. In *IEEE virtual reality conference (VR 2006)*. IEEE, 3–10.

Victoria Interrante, Brian Ries, and Lee Anderson. 2007. Seven League Boots: A New Metaphor for Augmented Locomotion through Moderately Large Scale Immersive Virtual Environments. In *2007 IEEE Symposium on 3D User Interfaces*. https://doi.org/10.1109/3DUI.2007.340791

Jonathan Kelly, Taylor Doty, Morgan Ambourn, and Lucia Cherep. 2022. Distance perception in the oculus quest and oculus quest 2. (2022).

Jonathan W Kelly, William W Hammel, Zachary D Siegel, and Lori A Sjolund. 2014. Recalibration of perceived distance in virtual environments occurs rapidly and transfers asymmetrically across scale. *IEEE transactions on visualization and computer graphics* 20, 4 (2014), 588–595.

JA Scott Kelso. 1982. *Human Motor Behavior: An Introduction*. Psychology Press.

Damian G Kelty-Stephen, Paul E Cisek, Benjamin De Bari, James Dixon, Luis H Favela, Fred Hasselman, Fred Keijzer, Vicente Raja, Jeffrey B Wagman, Brandon J Thomas, et al. 2022. In search for an alternative to the computer metaphor of the mind and brain. *arXiv preprint arXiv:2206.04603* (2022).

Kristopher Kohm, Sabarish V Babu, Christopher Pagano, and Andrew Robb. 2022. Objects may be farther than they appear: depth compression diminishes over time with repeated calibration in virtual reality. *IEEE transactions on visualization and*

computer graphics (2022).
Frederick TL Leong. 2006. *The psychology research handbook: A guide for graduate students and research assistants*. Sage.
Wan-Yi Lin, Rohith Venkatakrishnan, Roshan Venkatakrishnan, Sabarish V. Babu, Christopher Pagano, and Wen-Chieh Lin. 2024. An Empirical Evaluation of the Calibration of Auditory Distance Perception under Different Levels of Virtual Environment Visibilities. In *2024 IEEE Conference Virtual Reality and 3D User Interfaces (VR)*. 690–700. https://doi.org/10.1109/VR58804.2024.00089
Wan-Yi Lin, Ying-Chu Wang, Dai-Rong Wu, Rohith Venkatakrishnan, Roshan Venkatakrishnan, Elham Ebrahimi, Christopher Pagano, Sabarish V Babu, and Wen-Chieh Lin. 2022. Empirical Evaluation of Calibration and Long-term Carryover Effects of Reverberation on Egocentric Auditory Depth Perception in VR. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 232–240.
Lorena Lobo, Manuel Heras-Escribano, and David Travieso. 2018. The history and philosophy of ecological psychology. *Frontiers in Psychology* 9 (2018), 2228.
Lindsay O Long, Chris C Pagano, Ravikiran B Singapogu, and Timothy C Burg. 2016. Surgeon's perception of soft tissue constraints and distance-to-break in a simulated minimally invasive surgery task. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, Vol. 60. SAGE Publications Sage CA: Los Angeles, CA, 1600–1604.
Hannah Masoner, Jonathan Doyon, Joseph Clark, Alen Hajnal, and Gabor Legradi. 2021. Perception of action-relevant egocentric distance is not underestimated in virtual reality. *Journal of Vision* 21, 9 (2021), 2076–2076.
Akomolafe Akinola Mohammed. 2012. A Critique of Descartes' Mind-Body Dualism. *Kritike: An Online Journal of Philosophy* 6, 1 (2012).
Betty J Mohler, Sarah H Creem-Regehr, William B Thompson, and Heinrich H Bülthoff. 2010. The effect of viewing a self-avatar on distance judgments in an HMD-based virtual environment. *Presence* 19, 3 (2010), 230–242.
Betty J Mohler, William B Thompson, Sarah H Creem-Regehr, Peter Willemsen, Herbert L Pick, Jr, and John J Rieser. 2007. Calibration of locomotion resulting from visual motion in a treadmill-based virtual environment. *ACM Transactions on Applied Perception (TAP)* 4, 1 (2007), 4–es.
Kristin S Moore, Joshua A Gomer, Christopher C Pagano, and D DeWayne Moore. 2009. Perception of robot passability with direct line of sight and teleoperation. *Human Factors* 51, 4 (2009), 557–570.
Phillip E Napieralski, Bliss M Altenhoff, Jeffrey W Bertrand, Lindsay O Long, Sabarish V Babu, Christopher C Pagano, Justin Kern, and Timothy A Davis. 2011. Near-field distance perception in real and virtual environments using both verbal and action responses. *ACM Transactions on Applied Perception (TAP)* 8, 3 (2011), 1–19.
Bernstein Nikolai. 1967. The coordination and regulation of movement.
Donald A Norman. 1988. *The psychology of everyday things*. Basic books.
Nami Ogawa, Takuji Narumi, Hideaki Kuzuoka, and Michitaka Hirose. 2020. Do you feel like passing through walls?: Effect of self-avatar appearance on facilitating realistic behavior in virtual environments. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–14.
Mai Otsuki, Kenji Sugihara, Azusa Toda, Fumihisa Shibata, and Asako Kimura. 2018. A brush device with visual and haptic feedback for virtual painting of 3D virtual objects. *Virtual Reality* 22, 2 (2018), 167–181.
Christopher C Pagano and Brian Day. 2019. Ecological interface design inspired by "The meaningful environment". In *Perception as Information Detection*. Routledge, 37–50.
Christopher C Pagano, Brian Day, and Leah S Hartman. 2021. An Argument Framework for Ecological Psychology and Architecture Design. *Technology| Architecture+ Design* 5, 1 (2021), 31–36.
Christopher C Pagano and Robert W Isenhower. 2008. Expectation affects verbal judgments but not reaches to visually perceived egocentric distances. *Psychonomic bulletin & review* 15 (2008), 437–442.
Matthew N Petrucci, Gavin P Horn, Karl S Rosengren, and Elizabeth T Hsiao-Wecksler. 2016. Inaccuracy of affordance judgments for firefighters wearing personal protective equipment. *Ecological Psychology* 28, 2 (2016), 108–126.
Grant Pointon, Chelsey Thompson, Sarah Creem-Regehr, Jeanine Stefanucci, Miti Joshi, Richard Paris, and Bobby Bodenheimer. 2018. Judging Action Capabilities in Augmented Reality *(SAP '18)*. Association for Computing Machinery, New York, NY, USA, Article 6, 8 pages. https://doi.org/10.1145/3225153.3225168
Irvin Rock. 1997. *Indirect perception*. Mit Press.
Sylvia Rothe, Boris Kegeles, and Heinrich Hussmann. 2019. Camera heights in cinematic virtual reality: How viewers perceive mismatches between camera and eye height. In *Proceedings of the 2019 acm international conference on interactive experiences for tv and online video*. 25–34.
Murphy RR. 2004. Trial by fire-Activities of the rescue robots at the World Trade Center from 11-21 September 2001. *IEEE Robotics & Automation Magazine* 11 (2004), 50–61.
Joseph F Rychlak. 1968. A philosophy of science for personality theory. (1968).
Soheil Sepahyar and Scott Kuhl. 2022. Vr distance judgments are affected by the amount of pre-experiment blind walking. In *ACM Symposium on Applied Perception 2022*. 1–5.
Marco Speicher, Anna Maria Feit, Pascal Ziegler, and Antonio Krüger. 2018. Selection-based text entry in virtual reality. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–13.
Dan Sperber and Deirdre Wilson. 1986. *Relevance: Communication and cognition*. Vol. 142. Citeseer.
Frank Steinicke, Gerd Bruder, Jason Jerald, Harald Frenz, and Markus Lappe. 2009. Estimation of detection thresholds for redirected walking techniques. *IEEE transactions on visualization and computer graphics* 16, 1 (2009), 17–27.
Mark Tolchinsky, Rohith Venkatakrishnan, Roshan Venkatakrishnan, Christopher C. Pagano, and Sabarish V. Babu. 2023. Empirical Evaluation of the Effects of Visuo-Auditory Perceptual Information on Head Oriented Tracking of Dynamic Objects in VR. In *2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. 1074–1083. https://doi.org/10.1109/ISMAR59233.2023.00124
MT Turvey. 2006. Perception: The ecological approach. *Encyclopedia of cognitive science* (2006).
Michael T Turvey. 2018. *Lectures on perception: An ecological perspective*. Routledge.
Roshan Venkatakrishnan, Rohith Venkatakrishnan, Ryan Canales, Balagopal Raveendranath, Christopher C. Pagano, Andrew C. Robb, Wen-Chieh Lin, and Sabarish V. Babu. 2024. Investigating the Effects of Avatarization and Interaction Techniques on Near-field Mixed Reality Interactions with Physical Components. *IEEE Transactions on Visualization and Computer Graphics* 30, 5 (2024), 2756–2766. https://doi.org/10.1109/TVCG.2024.3372050
Roshan Venkatakrishnan, Rohith Venkatakrishnan, Chih-Han Chung, Sabarish V Babu, and Yu-Shuen Wang. 2022. Investigating a Combination of Input Modalities, Canvas Geometries, and Inking Triggers on On-Air Handwriting in Virtual Reality. *ACM Transactions on Applied Perceptions (TAP)* (2022).
Roshan Venkatakrishnan, Rohith Venkatakrishnan, Balagopal Raveendranath, Christopher C. Pagano, Andrew C. Robb, Wen-Chieh Lin, and Sabarish V. Babu. 2023. How Virtual Hand Representations Affect the Perceptions of Dynamic Affordances in Virtual Reality. *IEEE Transactions on Visualization and Computer Graphics* 29, 5 (2023), 2258–2268. https://doi.org/10.1109/TVCG.2023.3247041
Kim J Vicente and Jens Rasmussen. 1990. The ecology of human-machine systems II: Mediating'direct perception'in complex work domains. *Ecological psychology* 2, 3 (1990), 207–249.
Hermann Von Helmholtz. 1867. *Handbook of physiological optics: with 213 woodcuts and 11 plates printed in the text*. Vol. 9. Voss.
William H Warren. 1984. Perceiving affordances: visual guidance of stair climbing. *Journal of experimental psychology: Human perception and performance* 10, 5 (1984), 683.
William H Warren, Bruce A Kay, Wendy D Zosh, Andrew P Duchon, and Stephanie Sahuc. 2001. Optic flow is used to control human walking. *Nature neuroscience* 4, 2 (2001), 213–216.
Franziska Westermeier, Chandni Murmu, Kristopher Kohm, Christopher Pagano, Carolin Wienrich, Sabarish V Babu, and Marc Erich Latoschik. 2025. Interpupillary to Inter-Camera Distance of Video See-Through AR and its Impact on Depth Perception. In *2025 IEEE Conference Virtual Reality and 3D User Interfaces (VR)*. IEEE, 537–547.
Mark Wexler and Jeroen JA Van Boxtel. 2005. Depth perception by the active observer. *Trends in cognitive sciences* 9, 9 (2005), 431–438.
Ignatius Alex Wijayanto, Sabarish V. Babu, Christopher C. Pagano, and Jung Hong Chuang. 2023. Comparing the Effects of Visual Realism on Size Perception in VR versus Real World Viewing through Physical and Verbal Judgments. *IEEE Transactions on Visualization and Computer Graphics* 29, 5 (2023), 2721–2731. https://doi.org/10.1109/TVCG.2023.3247109
Dai-Rong Wu, Tyler Duffrin, Roshan Venkatakrishnan, Rohith Venkatakrishnan, Sabarish V. Babu, Christopher Pagano, and Wen-Chieh Lin. 2024. Room Size Perception in Virtual Reality by Means of Sound and Vision: The Role of Perception-Action Calibration. In *2024 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. 426–435. https://doi.org/10.1109/ISMAR62088.2024.00057