Reality Rifts: Wonder-ful Interfaces by Disrupting Perceptual Causality

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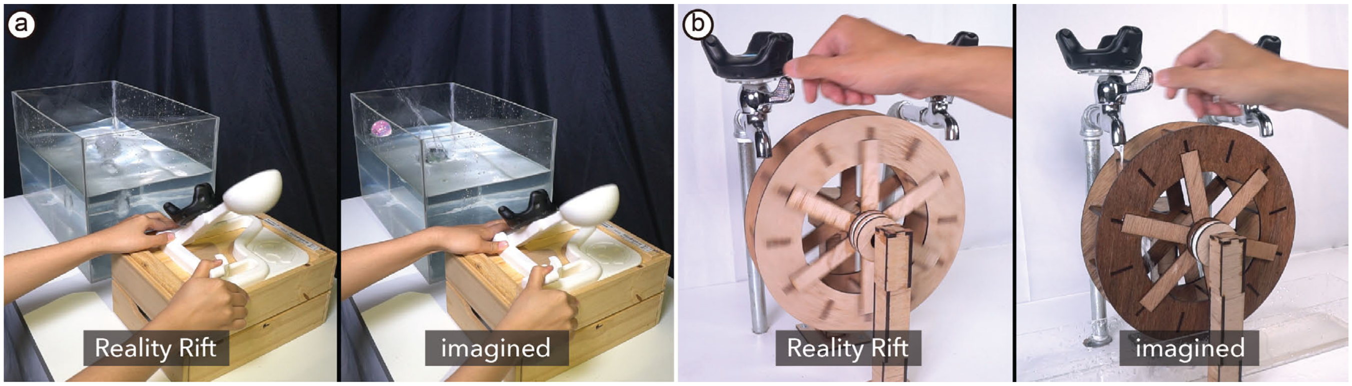

Figure 1: *Reality Rifts* inside physical interactive systems, here the missing projectile in this catapult apparatus (a) or the water stream running from the faucets (b), create a sense of *wonder*, where users implicitly *imagine* the missing component in an interactive system that explains the observed behavior. We create Reality Rifts by removing one or more components from a physical system and restoring plausible end-to-end behavior by simulating and rendering physical outcomes through embedded sensors and actuators. (a) In the case of the catapult, a connected actuation mechanism in the tank releases a splash after the arm has been activated, thereby rendering a causally accurate effect. (b) The wheel below the faucets spins in the direction and with the velocity commensurate with the degree of the faucet valve opening. In these examples of Reality Rifts, interaction with the physical prototype induces a sense of wonder that triggers the user's curiosity and enhances the enjoyment of the experience.

ABSTRACT

Reality Rifts are interfaces between the physical and the virtual reality, where incoherent observations of physical behavior lead users to imagine comprehensive and plausible end-to-end dynamics. Reality Rifts emerge in interactive physical systems that lack one or more components that are central to their operation, yet where the physical end-to-end interaction persists with plausible outcomes. Even in the presence of a Reality Rift, users can still interact with a system—much like they would with the unaltered and complete counterpart—leading them to implicitly infer the existence and *imagine* the behavior of the lacking components from observable phenomena and outcomes. Therefore, dynamic systems with Reality Rifts trigger doubt, curiosity, and rumination—a sense of *wonder* that users experience when observing a Reality Rift due to their innate curiosity.

In this paper, we explore how interactive systems can elicit and guide the user's imagination by integrating Reality Rifts. We outline the design process for opening a Reality Rift in interactive physical systems, describe the resulting design space, and explore it through six characteristic prototypes. To understand to what extent and with which qualities these prototypes indeed induce a sense of wonder during an interaction, we evaluated Reality Rifts in the form of a field deployment with 50 participants. We discuss participants' behavior and derive factors for the implementation of future wonder-ful experiences.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; *Mixed / augmented reality*.

KEYWORDS

Mixed reality, immersive experiences, physical displays

ACM Reference Format:
Lung-Pan Cheng, Yi Chen, Yi-Hao Peng, and Christian Holz. 2023. Reality Rifts: Wonder-ful Interfaces by Disrupting Perceptual Causality. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23), April 23–28, 2023, Hamburg, Germany*. ACM, New York, NY, USA, 15 pages. https://doi.org/10.1145/3544548.3581454

CHI '23, April 23–28, 2023, Hamburg, Germany

ACM ISBN 978-1-4503-9421-5/23/04…$15.00
https://doi.org/10.1145/3544548.3581454

1 INTRODUCTION

From small age on, it is our curiosity that drives us to experience and understand the world around us. We explore our physical surroundings by interacting with objects and other people to understand their characteristics and behaviors. This involves many senses, such as touch, visual, audio, or a combination thereof, all of which contribute to an immersive experience inside the world of physical matter. Through this exploration and interaction, we form a mental model of how physical behavior unfolds [41], allowing us to develop expectations for future interactions—we imagine and, thus, anticipate their outcomes and implicitly verify our expectations through observation [44].

As our mental models harden through repeated experience and observation, imagining expected outcomes turns into a routine. This becomes apparent when we witness magic tricks; we seek to understand the dynamics we observe, and we try to understand how the behavior we perceive can exist given our expectations refined from previous experience. This attempt to understand, the doubts we develop while questioning what we can see, and the resulting curiosity in how it can be—all these create a sense of 'wonder' in us, an urge to ponder and to explain the witnessed events because we know that they must follow the same principles that underlie all other physical behavior.

When interacting with digital technology, by consuming interactive behavior on TV, or by interacting inside virtual environments, our mental models no longer necessarily apply. Because anything may happen in such virtual realities, either those on video or those we interact in, particularly as pertains to fictional content, we suspend our disbelief [64]. Since there is no need for rules and laws as we know them to remain, constant surprises are possible in such environments, though such moments may no longer trigger a sense of wonder. An exception to this, however, is an interactive system that affords the user to complete a task in unexpected ways. In these cases, such systems elicit surprise and wonder similar to before when they accomplish things that cannot be explained (cf. Clarke's third law [16]).

Mixed-reality systems take advantage of this by immersing us into entire worlds that can be unlike anything we have experienced before. And yet, they create a holistic set of sensations to make the experienced surroundings credible, involving visual and audio feedback using projectors or head-mounted displays, speakers, or headphones, while maintaining the realism of physical reality by providing haptic feedback using devices or props [54, 55]. Some experiences for Mixed Reality have even brought virtual worlds into retrofit environments to provide sensations of tactile surroundings [42, 88], heat, and smell [92], all while users can normally explore the environment as they would in the real world through walking, touching, and interacting with their surroundings. The use of multi-sensory feedback makes these experiences as credible as if they were real, inducing a sense of presence in us of really being there [61, 75]. This, in turn, elicits surprise, wonder, and imagination inside these virtual settings and experiences.

In this paper, we elicit a sense of wonder in users and guide their imagination while interacting with purely physical, seemingly mundane systems—systems and behaviors they would not normally be surprised at simply because of a well-defined mental model of operation. We accomplish this by opening a *Reality Rift* inside these systems and describe a three-step process of mixing physical reality with *imagined reality* to elicit wonder when using interactive physical systems. We also outline a design space, discuss its dimensions, and prototype a series of 'wonder-ful' experiences.

Wonder-ful Experiences in Reality Rifts

We introduce Reality Rifts into physical systems as interfaces between the physical and virtual reality in the real world, where users implicitly imagine all virtual phenomena as a result of experiencing a sense of wonder. The key to our method is to 1) analyze the causal dependencies inside a physical system—the mechanical interactions of physical objects that, together, constitute the overall physical event—and to 2) specifically remove one or more components to disrupt the causality chain; 3) restoring the physical outcome through concealed actuators by simulating and rendering effects thereby ensuring a plausible conclusion of an observed causality chain.

Figure 1 shows two examples of Reality Rifts in ordinary physical interactions. (a) Here, the user activates a catapult, which launches the arm into the air. Immediately after, a visible, audible, and tactile splash effect appears in the water tank, which concludes the process. The user's agency over the activation of the catapult and the perceivable sensations in the water tank implicitly prompt users to explain this behavior based on prior experience, here imagining the payload that launches into the water (a, right). (b) In this interaction with another degree of freedom, users can open the two faucets, which spin the wheel below depending on the valve opening. The system behaves physically plausible, correctly simulating the opposing forces caused by the streams from both faucets—despite the complete absence of water, which users imagine as they are interacting with the system to understand it (b, right).

In both cases, these physical systems comprise causality chains that begin at the moment of user activation and that end with the observed outcome and state of the physical system. The outcome is thereby clearly coupled to the input the user has provided to initiate the operation. In the case of the wheel, the causality chain may or may not be linear and may comprise several loops depending on the interaction between the two faucets.

The part of a Reality Rift-afflicted system that elicits a sense of wonder in users during interaction is the missing component; (a) in the catapult, it is the payload, and (b) for the faucets, it is the water stream. While the missing part disrupts the observable chain of causal effects, which should immediately stop as a result, the end of the causal chain remains intact, which causes users' curiosity. This is in line with Michotte's insight that "one of the keys to inducing a sense of wonder is incoherence in perceptual causality" [44].

Because the outcome rendered in the physical system is plausible, the missing components still exist and exhibit dynamic behavior, though only in the user's imagination. Therefore, despite the Reality Rift in either system, users can freely interact with the respective component despite its physical absence [6]. Our prototypes ensure this by simulating and rendering physical outcomes through hidden actuators, thereby preserving the end-to-end operation and consistency of the interactive physical system through alternative causes [25].

Decoupling the original causes of physical interactions from their outcomes through Reality Rifts allowed us to create a design space of physical displays to elicit wonder and guide users' imagination. We explore the space with six interactive proof-of-concept prototypes that render plausible outcomes.

To understand the extent to which they create a sense of wonder in users during an interaction, we conducted a field deployment of our prototypes in a local escape room study. A total of 50 participants interacted with both our Reality Rift-based systems as well as the fully implemented embodiments for comparison. Through questionnaires based on a prior interpretation of 'wonder' [69], participants reported higher ratings of curiosity and enjoyment for rift-afflicted systems than for the otherwise identical baseline systems without any imagined components. We also discuss participants' qualitative feedback in our analysis.

We conclude with a discussion of Reality Rifts and their potential to influence the future of interactive systems that integrate physical dynamics as well as imagined behavior into their operation.

Contributions

Collectively, we make the following contributions in this paper:

- a methodology that introduces a Reality Rift into a given interaction physical system with observable behavior. We discuss opportunities for physical processes to select as well as for Reality Rifts to be inserted depending on perceptual causality.
- a multi-dimensional design space of Reality Rifts and six proof-of-concept prototypes through which we explore this space, both implemented with a Reality Rift to elicit imagined behavior as well as without one for purely physical interaction and holistically observable behavior.
- a preliminary evaluation in the form of a field deployment with 50 participants who compared both embodiments of each prototype example qualitatively and quantitatively.

2 RELATED WORK

Reality Rifts take inspiration from mixed reality experiences but establish sensations in the real world. They are related to (1) immersive experiences, (2) the sense of wonder, and (3) physical displays. We discuss each of these areas while also contrasting their differences to Reality Rifts.

2.1 Immersive Experiences

Immersiveness has long been debated regarding the overall plausibility provided by the display and interaction systems in comparison to physical reality, i.e., the capability of producing a sensation of *presence* [20, 62, 75]. Slater later proposed place illusion (PI) and plausibility illusion (Psi) as the two orthogonal components to the sense of presence [74]. Since then, more studies [72, 73] have been conducted by Skarbez et al. to identify characteristics of a VR experience that influence PI and Psi.

Most of the time, people refer to VR experiences as those in HMD VR. Broadly speaking, however, immersive experiences existed before the invention of the HMD [80]. Rooms full of decor and automatons were used to immerse visitors in a fantasy world such as *Disneyland* [17]. While commercial HMDs [49, 85] have brought immersive experiences to our living rooms, on-site immersive experiences such as *escape rooms* [22, 60] remain popular in recent years [35] as they offer social entertainment [89] and team building [52]. These on-site experiences provide physical feedback as the main attraction, which is not yet widely ready in current VR technology.

Mixed reality approaches have thus been proposed and employed in immersive experiences to take full advantage of both virtual and physical realities. Many on-site immersive experiences use projectors or HMDs along with physical props to further enhance immersion with haptic feedback [21, 83, 86]. SnowballVR [76] makes physical boxes fall in response to a multi-user VR game, allowing surrounding spectators to watch a gunfight without HMDs. As for seamlessly bridging two realities, One Reality [59] provides a framework for transitioning from a physical environment to a completely virtual environment by bringing physical properties step by step into virtual reality. Remixed Reality [43], VRoamer [13], DreamWalker [93], and RealityCheck [31] propose more interactions in the mixed reality environment such as manipulating time and blending virtual and physical space. Human actuation [9–11, 14] remap users' physical actions in one reality to other plausible physical feedback in another reality. Mixed-Fantasy framework [77] further adds *imaginary reality* as a third anchor point to Milgram's mixed reality spectrum [45], forming a three-sided continuum: physical-virtual, physical-imaginary, virtual-imaginary. Imaginary Reality Game [6] is a concrete example of employing Imaginary Interfaces [30] in physical reality, where users picture the invisible imaginary basketball by themselves while physically running around the court.

Given more and more mixed reality technologies that gear towards seamlessly merging the virtual and the physical world, Latoschik and Wienrich [38] recently argue that there is no PI but congruency and plausibility of spatial cues in future mixed reality experiences. Psi is not an illusion but just plausibility, which is a condition that subjectively results from evaluating the congruence of sensory, perceptual, and cognitive information in the user's mind. AsyncReality [24] preserves the causality of physical events to maintain plausibility while users revisit it from a different timing in their own individual reality.

2.2 Sense of Wonder

The ancient philosopher Aristotle said 350 BC, "it is through *wonder* that men now begin and originally began to philosophize" [3]. Since then, wonder has been related to the seed of knowledge [5] that is inborn in human beings [7], awaiting reality to cultivate it into the desire to learn [39]. In psychology, wonder has been considered a complex emotion due to the conjunction of joy, astonishment, and curiosity [69]. Wonder is also commonly subdivided into 'active' and 'passive' in literature [53], where active wonder is akin to curiosity and passive wonder is the source of the love of mystery [66].

Inducing a sense of wonder has been one of the major challenges not only in education [39, 46, 51], but also in delivering experiences such as stage magic [36, 57, 79], music [33, 58], and games [37]. Vasalou pointed out that without a more reflective or *imaginative* engagement, the bare facts could not by themselves induce a sense

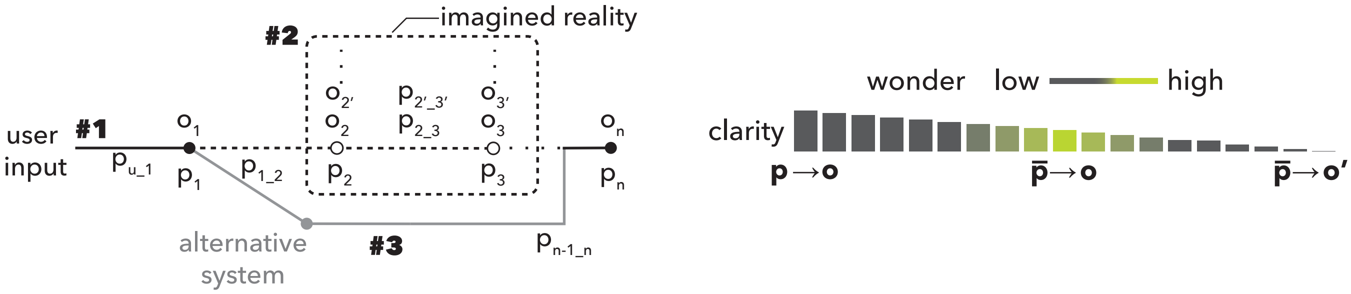

Figure 2: Left: A Reality Rift is created by (1) identifying a causally perceptible interaction, (2) disrupting the causal chain by hiding intermediate phenomena of the objects (3) restoring all other outcomes through an alternative system. Right: the spectrum of Reality Rifts. Clarity decreases as more phenomena are hidden until users feel random objects o'. A sense of wonder is induced by plausible subsets $\overline{p}$ that has the right amount of clarity to infer all objects o while having noticeable mismatches to all phenomena p.

of wonder [84], followed by Schinkel, "wonder thus implies a shift in perspective that is particularly manifest when something ordinary is suddenly seen as extraordinary." [66] The choreographic pattern of establishing then building on and stepping beyond causal expectations, i.e., perceptual causality [44], thus is a good heuristic and has been widely adopted to induce a sense of wonder in audiences. While previous studies have revolved around simple moving 2D geometric shapes that can produce perceptual causality, such as launching effect [68], perceptual causality has been embedded in our daily physical activities. This inference model may be inborn [41] or learned through repetition [29, 56].

2.3 Advanced Physical Displays

Researchers have proposed approaches to convey physical properties in the virtual world. Since visual appearances can be presented in head-mounted displays, most research focuses on providing haptic feedback such as force, texture, and touch. Shape displays [26, 40], for example, have been used to convey shape in the virtual world. In addition to rigid shape displays, researchers have proposed pneumatically-actuated interfaces [81, 94, 96] and magnet interfaces [8, 50] to provide softness to shape displays as well. Sparse haptic proxy [12] provides touch feedback in any virtual scenes using a general hemispherical prop. SPIDAR [63] provides force feedback by pulling the user's fingers. Shifty [95] and Transcalibur [70] dynamically change the inertia of the device to simulate various sensations of weight. Snake Charmer [2], ShapeShift [71] and PhyShare [32] use simple robots to provide textures and shapes at designated positions. Along with the vision of programmable matter [28], microscale swarm robots [15] and responsive materials [91] have continued advancing human and computer systems to gain more efficient control over physical properties. Several art installations [4, 18, 19] have also been created as media to demonstrate plausible future interactions.

2.4 Summary

To sum up, with Reality Rifts, we look into mixing imagined reality with physical reality to create a new form of immersive experience that sparks a sense of wonder using physical display technologies. We extrapolate from the congruence and plausibility model [38] and further look into intentionally injecting perceivable incoherence to induce counterfactual inference [87] in the user's mind. Instead of philosophical discussions, Reality Rifts allows us to investigate the inducement of a sense of wonder on a more pragmatic level by systematically hiding phenomena to introduce incoherence in perceptual causality. While one could argue that anything can engender a sense of wonder, our work explores and articulates the sweet spot. In the meantime, Reality Rifts inspire us to design new physical displays that simulate realistic effects flexibly without the constraint of the original causes using off-the-shelf sensing and actuation technology to enhance presence and attract spectators in on-site immersive experiences. Resonating with Tognazzini's view of bringing stage magic into interface design [82], we see Reality Rifts are concrete instances of 'wonder-ful' interfaces.

3 OPENING RIFTS IN REALITY

The purpose of Reality Rifts is to elicit and guide the user's imagination by triggering doubt, curiosity, and rumination through a sense of wonder. We achieve this by systematically disrupting everyday dynamics and interactions between physical objects.

Reality Rifts target *perceptual causality* [44], i.e., causal relationships that can be immediately inferred by (1) observing physical interactions. We then (2) introduce *perceivable incoherence* by hiding intermediate phenomena but (3) restore plausible physical outcomes through physical actuation. In this way, plausible outcomes verify most of the user's expectations except for the introduced incoherence, making them wonder about the believable and surprising incoherence. Meanwhile, the user's imagination is guided to fill in the *rifts* created by the incoherence and the plausible outcomes.

Figure 2 left illustrates the overview of our 3-step approach to creating Reality Rifts in everyday interactions. We see each interaction contains a causal diagram. The interaction starts with user input and ends with observable object reactions. Users infer the causal diagram including objects ($o_1, o_2, \ldots, o_n$) and their connectivity by observing phenomena ($p_{u\_1}, p_1, p_{1\_2}, p_2, \ldots, p_n$) during their interaction. The causal diagram of an interaction, while linear in the figure, could be more complex, such as a tree in the case of ripple effects or any graph as long as the causality is perceptible.

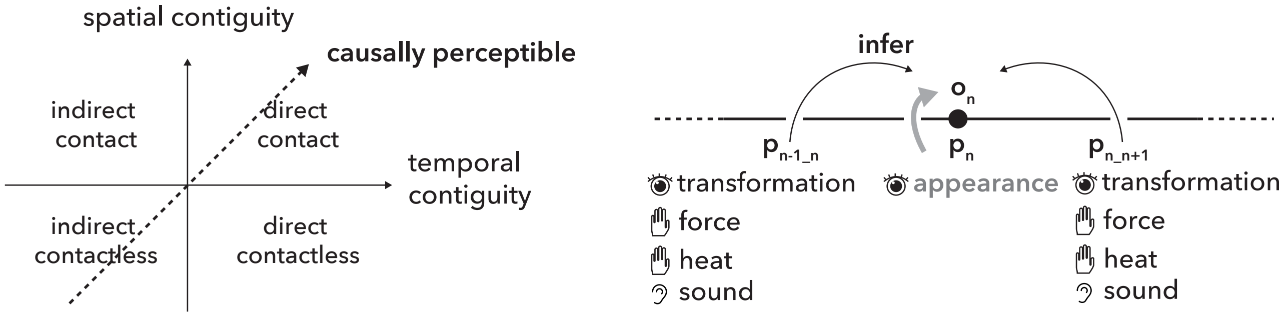

Figure 3: Left: the space for identifying causally perceptible interactions via spatial and temporal contiguity. Direct contact is the most perceptible causality, then indirect contact, direct contactless, and finally, indirect contactless. Right: the space for determining which phenomenon to take out from a phase to introduce perceivable incoherence to the perceptual causality. The most prominent one is the object's appearance as it directly infers the object.

Figure 2 right illustrates our goal. We define that an interaction has full clarity as all phenomena $\boldsymbol{p}$ are observable to infer all objects $\boldsymbol{o}$ and their connectivity in the user's mental model, i.e., everything works as expected. Clarity decreases as more and more noticeable phenomena are hidden until a subset $\overline{\boldsymbol{p}}$ makes users think all objects are random $\boldsymbol{o'}$ with random connections. Our goal is to find a plausible subset $\overline{\boldsymbol{p}}$ that has the right amount of clarity to infer all objects $\boldsymbol{o}$ while making users wonder and fill in the mismatches from $\boldsymbol{p}$ in their minds. We describe the details of our 3 steps in the following section.

Step #1: Identifying Physical Interactions

The first step of creating a Reality Rift is to target a causal impression. The space of causal impressions is broad. Generally, any user-initiated interaction with physical objects produces perceptual causality as long as reactions can be observed. User input is the cause, and object reaction is the effect. As a simple example, when a person bats a ball, it is evident that the bat is the cause and the flying ball is the effect. The key is to target a causal impression that is generally perceivable, i.e., mundane, so that users have the same initial expectation in their minds.

Figure 3 left shows the space of causally perceptible interactions that we explored. We use spatial and temporal *contiguity* to denote its dimensions, a term common in studies in cognitive science in the context of perceptible causality [67, 78]. Direct contact, such as manipulation and hitting, is most causally perceptible as it is the most common interaction done by toddlers to learn objects through their kinetic reactions. Indirect contact, such as shooting an arrow to hit a target with an arrow, extends the causal chain and loosens the temporal contiguity due to the traveling delay. Spatial contiguity remains as the arrow is the actual cause that comes across the space to hit the target. Contactless interactions, such as blowing out a candle, loosen spatial contiguity, because no observable cause travels through the space. Temporal contiguity can be maintained using a proper tool, such as using a remote control to turn on a lamp. When both the spatial and temporal contiguity decrease, causality is no longer obvious to users. To continue conveying a causal impression here may require proper training to perceive the link between cause and effect. After targeting a causally perceptible interaction, we lay out the causal diagram as the connections of $\{o_1, o_2, \ldots, o_n\}$ in Figure 2 (left).

Step #2: Disrupting Perceptual Causality

Next, Reality Rifts emerge due to *incoherence* introduced in observed phenomena while maintaining its perceptual causality. Since we target interactions that are causally perceptible in Step #1, as users initiate the behavior, they perceive the first step of the causality chain and naturally trace down the causal diagram to form the expectations of potential ripple effects caused by this first outcome.

We introduce incoherence using the same technique that has been exploited in psychological experiments [67] where a mystery box is used to hide and disrupt perceptible causal *contiguity*. Specifically, incoherence can occur at each *phase* of the interactive behavior of an object that can be observed. In our case, as shown in Figure 3 (right), a phase is characterized by the behavior p_n of an individual object o_n, preceded by an interaction p_{n-1_n} with another object (or person) o_{n_-1}, and followed by another interaction p_{n_n+1} with an object o_{n_+1}. Removing one or more phases from the interactive behavior, i.e., hiding the behaviors that would normally take place at that time, leads the observer to notice that there are missing links in their mental causal graph, i.e., their imagined reality. Therefore, moments of physical interaction between two objects form the delimiters between stages, and each phase may introduce a Reality Rift that is filled in by the user's imagination.

While all intermediate phases are opportunities for introducing incoherence, the first and the last phase must remain unaltered. During the first, the user initiates the interactive behavior—concealing this phase would remove the user's sense of agency and, thus, prevent them from building up an expectation of the outcome. The last phase renders the outcome, which is a key element that must be observed to confirm or contradict the user's expectations and to conclude the causal chain.

Since our goal is to find plausible subsets $\overline{\boldsymbol{p}}$ to induce wonder as shown in Figure 2 (right), we lay out each phase as shown in Figure 3 (right) to determine the phenomena we want to take out. While users perceive these phenomena through their five human senses, we focus on visual, auditory, and haptic cues in this paper. In this phase, all cues combined indicate the existence of the object.

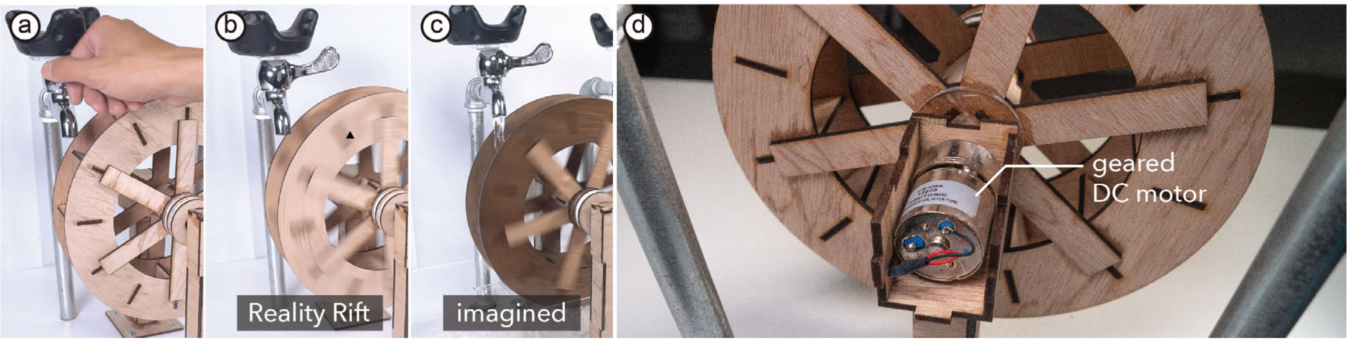

Figure 4: The motorized waterwheel responds to the turning of the faucet, resulting in the imagination of a water stream.

Since its appearance directly indicates the existence of the object, we remove the object's appearance in one phase to introduce the most noticeable incoherence. In cases when the object is not visible, we select other noticeable phenomena to remove, such as the haptic impressions of wind.

Step #3: Restoring Outcome by Systems

Finally, Reality Rifts unfold their intended effect of eliciting a sense of wonder by showing the plausible outcome of the chosen interaction to complete causal inference while leaving noticeable mismatches. However, taking out the intermediate phenomena in Step #2 may *physically* break the path to the other intermediate phenomena, i.e., aborting the interaction. To achieve other intermediate phenomena towards the final outcome, we (1) find alternative systems to simulate the phenomena, (2) redirect the causal link from the breakpoint to the alternative system, and (3) hide the alternative system to maintain the original perceptual causality.

While finding alternative systems takes a creative mind, our rule of thumb is to analyze the energy transmission of the original cause and replace it with an actuation system that has its own energy source to produce the effect. We redirect the causal link to the alternative system using a computer system that senses and transfers user input to the actuation output. To hide the alternative systems, we employ camouflage, transparency, and casing, depending on the capability of the replaced actuation system.

The use of sensors and actuators is a key component of each Reality Rift to *render holistic behavior* through an observable and controllable outcome. Ideally, we should approximate the holistic behavior of the entire interaction except for the removed phenomena as much as possible. In practice, this also opens a new space that allows us to create *simulate behaviors* that diverges from expected real-world dynamics by tuning the computer system's mapping between input and outcome. Through this, we have more control of the simulation plausibility of each phenomenon to varying and guiding 'wonder'.

4 EXPLORING THE SPACE OF REALITY RIFTS

We identified and implemented six examples to explore the design space of Reality Rifts. These involve common physical objects and everyday sensations, such as aero, thermal, fluid, and rigid body mechanics. We developed a physical proof-of-concept prototype for each of these six interactions, each time implementing the three steps for creating Reality Rifts as outlined in section 3. In addition to illustrating the design space, another goal of our exploration was to create physical instances of our concept through deployable experiences. These allowed us to evaluate our concept in a field deployment. Below, we describe our iterative approach to implementing each and list our design decisions along the way.

4.1 Water Faucet

As shown in Figure 4, users can turn on a faucet and control the intensity of water flow to spin the wheel below in this example. They can turn on a second faucet on the opposite side to counteract the force of the water running from the first faucet. In this case, the Reality Rift is the lack of water, but coherent actuation of the wheel depending on controlling the faucet and, thus, the intensity of water released from either faucet. Observing this interaction causes users to imagine the running water such that they can reconcile the cause-effect relationship between the faucets and the wheel.

Implementation. In Step #1, we chose indirect contact. The causal diagram is: $user \Rightarrow faucet \Rightarrow water \Rightarrow wheel$. In Step #2, we decided to focus on the *water* phase and took out its appearance. All other phenomena in this phase: the sound of water *while flowing through* the faucet and water *actuate* the wheel. In Step #3, we restored the perceivable outcome of the interaction by actuating the wheel depending on faucet control. A geared DC motor drove the wheel's spinning velocity and direction, which connected to a NodeMCU ESP8266 microcontroller for wireless control over WiFi. All these components were enclosed and hidden in the wheel. To track user input, we equipped both faucets with HTC VIVE trackers to resolve the amount of rotation. We implemented a tuning-continuous function that subtracts two faucet current angles and linearly maps to the duty cycle from 0 to 100 percent with the sign as the direction to drive the motor.

4.2 Water Catapult

In addition to hiding the water stream, Figure 5 shows an example of hiding objects being thrown into water. The user in Figure 5a repeatedly loads the catapult. Each time they trigger the catapult, they see a water splash in various intensities in the water tank after a short delay without seeing any projectile in the air. This causes them to imagine that different sizes of objects such as pebbles,

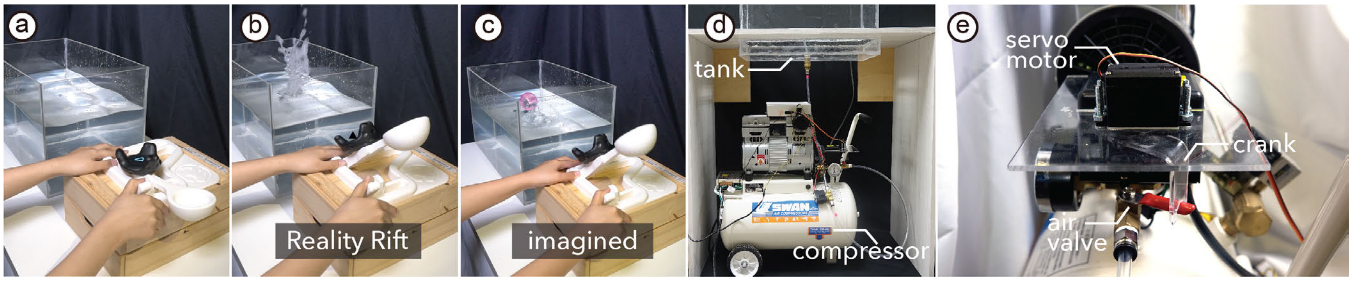

Figure 5: The water splash is created by the air compressor beneath the table, responding to the trigger of the catapult and resulting in the imagination of a projectile being launched into the water.

cobbles, or gravel are launched into the water tank. In addition, this gives the impression that the projectiles had spawned automatically in random sizes.

Implementation. In Step #1, we chose indirect contact again. The causal diagram is: $user \Rightarrow catapulttrigger \Rightarrow catapultarm \Rightarrow projectile \Rightarrow water$. In Step #2, we decided to focus on the $projectile$ phase and took out its appearance. All other phenomena in this phase: catapult arm *deformation* due to the weight of the projectile and water *splash* generated by the projectile. In Step #3, to simulate a water splash without a visible object, we used an air compressor as shown in Figure 5d to jet a burst of air from the bottom of the water tank. We controlled the duration (23 ms to 30 ms) of the burst using a motorized valve as shown in Figure 5e so as to simulate splash realistically on the surface (see video). As a side note of our implementation, the nozzle of the jet is 6 mm in diameter; the servomotor is MG996R; the air compressor is Swan DRS 207-22. We hide the entire actuation system with a tablecloth. We used a Vive tracker to sense the movement of the catapult arm and implemented a trigger detection function using a fixed velocity threshold. The trigger event is then mapped to one of the 3 preset duration (short, medium, and long).

4.3 Wind Fan

Figure 6 shows a Reality Rift in the interaction using a hand-held electric fan. Users manipulate an unpowered hand-held electric fan to make the wind vane turn. This puts wind into imagined reality.

Implementation. In Step #1, we chose the indirect contactless. The causal diagram is: $user \Rightarrow electricfan \Rightarrow wind \Rightarrow windvane$. In Step #2, we decided to focus on the *wind* phase. This time we did not take out the appearance of wind as it is already invisible. Therefore, we took out the fan-spinning phenomenon. All other phenomena in this phase: wind *actuates* the wind vane. In Step #3, to simulate the turning effect of the vane, we used a servomotor that continuously responds to the posing of the electrical fan. The vane's rotation is controlled using physics simulation where a constant force applies at the intersection point of the fan's forward and the van's plane. The control system and the motor are built into the casing beneath the wind vane.

Ideally, we wanted to build a hand-held fan that did not blow wind while making blades still rotate but did not succeed due to the difficulty of implementing well-balanced blades.

4.4 Fire Lighter

In Figure 6 right, the user lights up the candle with the flameless lighter, resulting in the imagination of fire.

Implementation. In Step #1, we chose direct contactless. The causal diagram is: $user \Rightarrow lighter \Rightarrow fire \Rightarrow candle$. In Step #2, we decided to focus on the $fire$ phase and took out its appearance. All other phenomena in this phase: the lighter *burn* fuels into flame and the fire *burn* the candle. In Step #3, we chose to use a plasma lighter instead. Although the flameless lighter is a straightforward alternative that does not require any sensing and control system, this showcases an extreme case of a simple replacement in implementation that could generate a Reality Rift experience.

4.5 Screwdriver

In Figure 7, the user operates the stick as a screwdriver. As the user rotates the stick in mid-air, the screw is also driven, resulting in the imagination of a screwdriver.

Figure 6: Left: the motorized wind vane responds to the unpowered fan resulting in the imagination of wind. Right: the candle responds to a flameless lighter resulting in the imagination of fire.

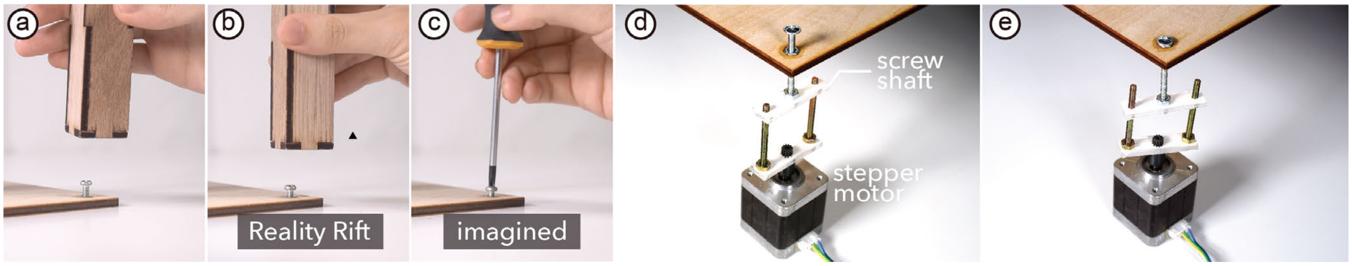

Figure 7: The motorized screw responds to the rotation of the generic stick in the user's hand resulting in the imagination of using a screwdriver.

Implementation. In Step #1, we chose direct contact. The causal diagram is: *user* ⇒ *screwdriverhandle* ⇒ *screwdriverhead* ⇒ *screw*. In Step #2, we decided to focus on the *screwdriverhead* phase and took out its appearance of it. All other phenomena in this phase: the handle is *actuated* by the reaction force of the head and the screw is *actuated* by the head. In Step #3, we used the stepper motor underneath the table to continuously rotate the screw synchronously with the rotation of the stick. To track user input, we provided the stick prop with a tracker at the end as shown in Figure 8b, resulting in a generic hand tool.

4.6 Axe

In Figure 8, the user operates the stick as an axe. The user swings the stick in the air without hitting the wooden plate while the wooden plate splits into two pieces, resulting in the imagination of using an axe.

Implementation. In Step #1, we chose direct contact. The causal diagram is: *user* ⇒ *axehandle* ⇒ *axehead* ⇒ *woodenplate*. In Step #2, we decided to focus on the *axehead* phase and took out its appearance. All other phenomena in this phase: the handle is *impacted* by the reaction force of the head and the wooden plate is *shatter* by the head. In Step #3, we used motorized latches to release the pre-cut pieces of the wooden plate from the stand. We used the pose of the stick to trigger the latches. This shows an example of mapping the high freedom input pose to a triggering outcome.

5 FIELD DEPLOYMENT — A PRELIMINARY EVALUATION

The purpose of this evaluation was to understand the extent to which the demonstrator prototypes of our design space elicit a sense of wonder during use. Because 'wonder' is a complex emotion [66] without an objective means for quantification yet, we conducted this evaluation as a deployment study in a minimally controlled setting. Based on previous experiments that studied 'wonder' [69], we collected participants' qualitative feedback and added two quantitative measures: curiosity and enjoyment through the extended Short Feedback Questionnaire [48, 90]. While this evaluation allowed us to record participants' impressions and reactions, we acknowledge that this deployment was not a formal study.

For deployment, we chose an escape room studio, which allowed us to recruit a diverse set of participants including experts in designing immersive experiences. The scale of the site also suits our Reality Rifts experience and prototypes. We gathered all six demonstrators in Section 4 as a 10-minute experience and set them up such that all control and computing equipment was outside the participants' experience. Figure 9 shows an overview of the installation. For comparison, we created a baseline installation for each of our prototypes with the same experience yet with exclusively physical and observable behavior (e.g., Figure 5c). Our installation ran as a one-week interactive exhibition. In addition to walk-in users, we attracted more participants through posts on social media.

5.1 Task and Procedure

Our evaluation had two conditions: (1) In BASELINE, all the prototypes were purely physical, exhibited no simulated or rendered behavior, and all phases of interaction were visible. (2) In RIFT, prototypes with matching appearance implemented Reality Rifts as described in section 4.

Participants experience all prototypes in both conditions. Each condition was limited to five minutes, during which each participant was free to discover, inspect, and interact with each prototype.

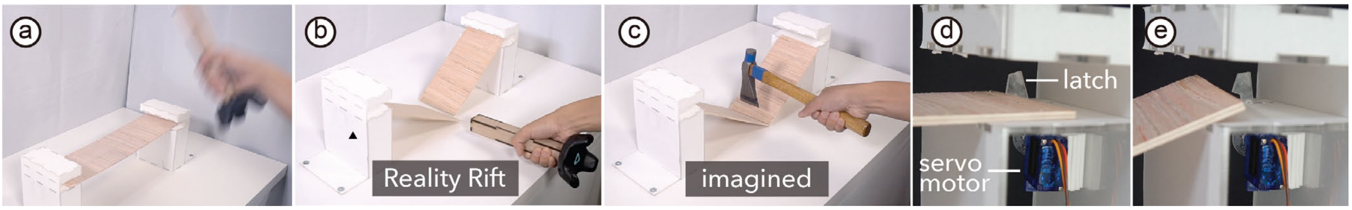

Figure 8: The platform releases the pre-cut wooden plate when the user strikes in the air with the generic stick, resulting in the imagination of using an axe.

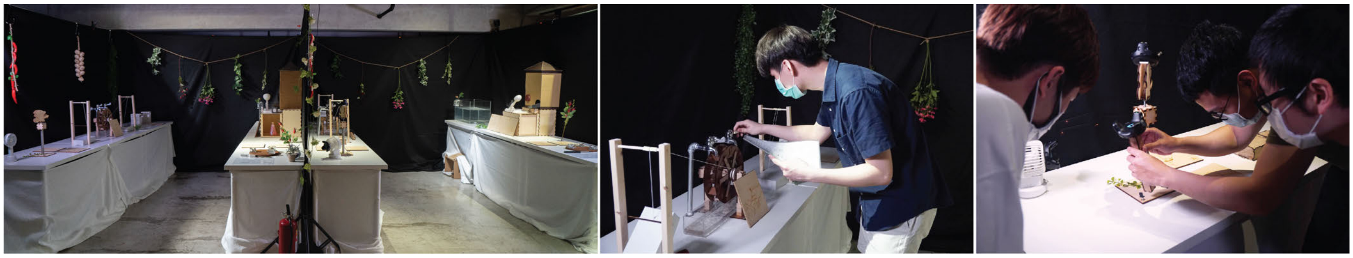

Figure 9: An overview of our Reality Rifts set-up in a local escape room studio and users interacting with our prototypes.

The order of conditions was counterbalanced across participants. While a participant experienced our deployment, we allowed up to seven bystanders to accompany them, but participants could also individually proceed.

Before each evaluation, participants were told to follow the instructions for each prototype. We illustrated instructions on plates as shown in Figure 10 about the actions that the user needs to initiate without revealing the missing components and placed each of them next to each corresponding prototype.

After each condition, participants individually filled out a questionnaire. They rated their perceived enjoyment and curiosity while experiencing the particular prototype on a 7-point Likert scale. The details of the indexes we evaluated were:

- **Enjoyment:** The level of enjoyment during the game. A higher score represents higher enjoyment. This index is commonly measured for immersive experiences.
- **Curiosity:** The level of perceived curiosity triggered during the process. We adapted the curiosity questionnaire from previous works [48, 90]. Specifically, we asked their level of agreement to the following statements: (1) *"I want to continue playing because I wanted to see more of the game world"*, (2) *"I was curious about the next event in the game"*, (3) *"Playing the game made me inquisitive about the game world"* and (4) *"I sought explanations for what I encountered in the game"*. A higher score stands for higher agreement. The overall curiosity for each individual is the average score of all 4 questions.

After filling out a questionnaire, participants reported qualitative feedback in a short semi-structured interview. The experimenter asked how participants developed their mental model during the interaction as well as how the RIFT condition affected their sense of wonder.

Finally, after interacting with all prototypes in our deployment, participants reported the prototype that they considered most 'wonder-ful' and least 'wonder-ful' for BASELINE as well as RIFT. For the expert participants, the experimenter probed their opinions on our proposed concept as well as the pros and cons of putting it into practice. For bystanders who observed participants, we separately interviewed them briefly and anonymously and collected qualitative feedback without any quantitative measures. Overall, each evaluation took about an hour. Participants received a hand-made souvenir after finishing the experience.

5.2 Participants

We recruited 50 users in total (ages 9–52, mean=25.38, std=6.50, 28 female, 22 male) from places around the deployment site and through social media posts. 11 participants had no experience with escape rooms, 6 had participated in an escape room only once, and 33 had experienced two or more escape rooms including 10 expert participants who had experience designing and building commercial escape rooms. In addition, around another 50 bystanders in total were interviewed without demography.

5.3 Results

Figure 11 shows the overall result. Figure 11 left shows the average enjoyment and curiosity scores in RIFT and BASELINE. RIFT was significantly more enjoyable than BASELINE(RIFT: $M = 6.00$, $SD = 0.78$; BASELINE: $M = 4.98$, $SD = 0.93$; $p = 4 \times 10^{-6}$, Wilcoxon signed-rank tests) and triggered curiosity RIFT: $M = 6.03$, $SD = 0.77$, BASELINE: $M = 4.17$, $SD = 1.14$; $p = 2.06 \times 10^{-9}$), and was preferred by 84% of the participants (RIFT: $N = 42$; BASELINE: $N = 8$).

Figure 11 right shows the histogram of the most wonderful and wonderless interaction in RIFT. The interaction that most users thought was the most wonderful was the screwdriver ($N = 18$), followed by the catapult ($N = 16$). The axe ($N = 16$) was chosen by most users as the most wonderless, followed by the fire ($N = 14$).

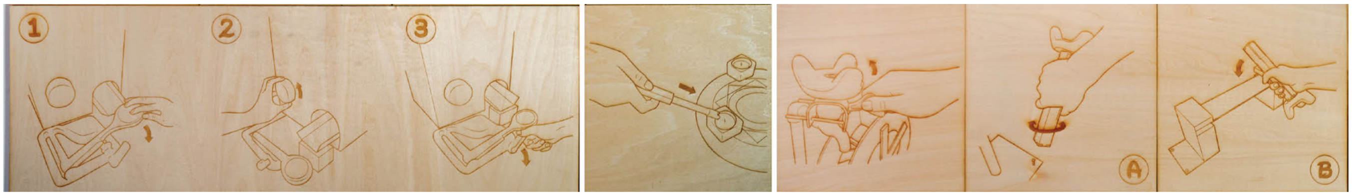

Figure 10: The instruction plates are parts of Reality Rifts. The drawings tell the users to initiate actions without revealing the missing components.

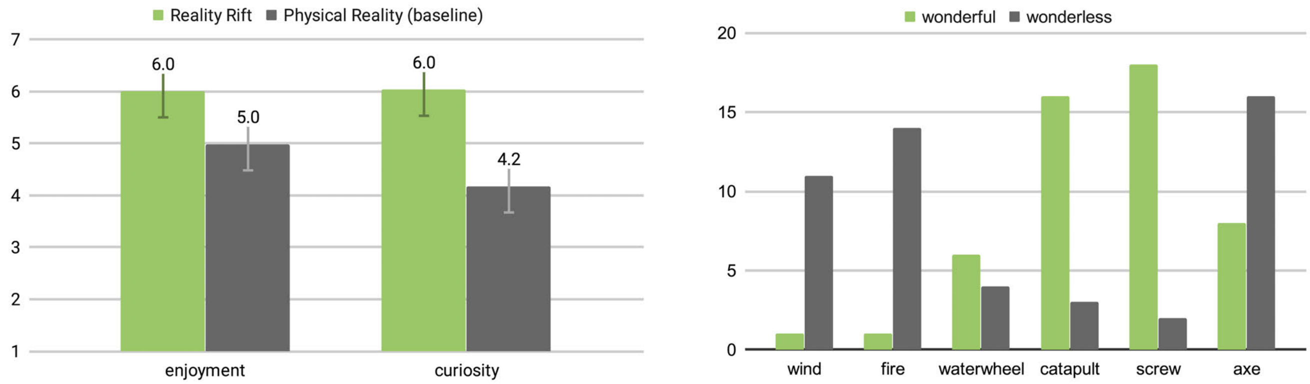

Figure 11: Left: the average enjoyment and curiosity scores of Riftand baseline. Right: the histogram of the most wonderful and wonderless interaction in Rift.

In general, Reality Rifts were well received by the users. Reality Rifts was a *novel* (P1, P2, P17, P18, P24, P25, P43, P45) and *unexpected* (P4, P5, P9, P12, P20, P23, P35, P37) experience which immersed users in the *magical* (P8, P11, P15, P22, P46, P47) and *surrealistic* (P44) environment. "I feel like I just entered a space mixed with logic and fantasy. Everything was uncommon but worked as expected," P45 said. "The experience made me notice things that I never paid attention to. Some normal things that happen in daily life were transformed into tiny but exquisite moments. I would like to explore more in this terra incognita," P50 said. "Holding the stick which was a screwdriver one second and then became an axe in the next second gave me a sense that I was really a wizard and was able to enchant the surroundings," P47 said.

While many participants appreciated the process of imagination and the mysterious interactions in Reality Rifts, some preferred the purely physical experience: "When everything was visible, the mechanism and the feedback were more intuitive," P48 said. "Completing the tasks on my own without the help of any technology provided me with a greater sense of achievement," P26 said. "I am a person who lacks imagination, and I'm not used to putting excessive thought into interactions. The imaginary version of the game might be a bit too difficult for me," P6 said. In spite of their preferences, they still saw Reality Rifts as a new and interesting form of experience.

We were specifically interested in the result from 10 experts to see the potential of Reality Rifts in real practice. Among all the experts, Reality Rifts was recognized as a more enjoyable (Rift: $M = 5.70$, $SD = 0.78$; baseline: $M = 4.30$, $SD = 0.78$; $p = 0.021$) and intriguing (Rift: $M = 5.58$, $SD = 0.75$; baseline: $M = 3.63$, $SD = 0.89$; $p = 0.0058$) experience compared with the baseline condition and was preferred by most of the experts (Rift: $N = 9$; baseline: $N = 1$).

All of the experts saw a great potential to adapt Reality Rifts into current and future immersive experiences. "I would say that the flow of Reality Rifts is very neat. Everything is controlled by computing devices so accidental errors can be reduced. The execution of the tasks can be done agilely while the experience itself is still brimming with imagination. The easiness of the restoration could be another advantage of this concept when putting it into practice. For instance, there was no water flowing out from the faucets so no additional cleaning needed to be done. I believe this concept has great potential to be mixed into escape room experiences if the story and the atmosphere were properly designed," P11 said.

Another expert provided her suggestions on possible integration: "The magical morphing stick could be one starting point. For example, the whole experience could be executed by using the same stick so that it could not only fasten the screw or chop the wood but also become a rod for fishing or turn into a butterfly net to catch bugs. However, I worry that if the crew had no technical background, the robustness of the devices would affect how easily and quickly we could fix the system if technical errors occurred during the game. But if the error rate is fairly low and we could devise a standard routine to solve the issues, then I actually think this kind of concept could possibly be integrated into one of our current horror escape rooms as a tool for users to explore the world and see eccentric changes in the environment," P46 said.

We also collected qualitative feedback from the bystanders who accompanied our participants to experience Reality Rifts together as a group. Despite the lack of hands-on participation, all the bystanders stated that spectating the experience was amusing and surprising. "Since I was not the person who was in charge of manipulating everything, I had more opportunities to observe all the triggered phenomena carefully and think about the mechanisms that were working behind the presentation," B6 said.

Another bystander expressed that besides the interesting mechanisms, his satisfaction mainly stemmed from the reactions of the user: "my friend's reactions during the game were as enjoyable as the experience itself. When the water splashed after the catapult was triggered, I was surprised by the effect at the beginning, but then I was also amused by my friend's reaction since her surprise was way too funny. I hope this game could last longer so I could capture more of her reactions," B2 said.

6 DISCUSSION

From the results, we conclude that our deployment was successful and that the preliminary results demonstrate that experiences with Reality Rifts induced a sense of wonder in participants. We now interpret the results and discuss our findings and insights in this section.

6.1 From Wonder-ful to Wonderful Interfaces

We consider Reality Rifts a promising component of future interaction design. We draw inspiration from the long-established feedback loop in interaction design and make the analogy in Figure 12.

Every person exists in three types of reality. First, people live in a physical reality where things follow the common laws of physics. Second, people have their individual imagined realities where things act as wishes. Third, using computer technologies, people can create virtual realities in which the existence and behavior of people's representations and objects are programmed and can follow arbitrary rules, defined entirely by people and not by the boundaries of physics.

These three realities are highly correlated but not necessarily the same. Reality Rifts reside in the chasm between and, thus, bridge these three realities. By exploring the mismatch (i.e., *rift*) between these three realities, we see new imaginations, new interactions, and new devices loop back to each other and extend these three instantiations of reality toward one ultimate reality.

In section 3, we start by choosing an interaction in our imagined reality. We assume that others have the same perceptual causality as ours, just like we assume there are affordances [27] present in our interaction design. In section 3, we look for where to better interface, i.e., hiding a redundant component, and make people notice that where there is something being hidden but they can still interact smoothly as they expected in the interaction's causal graph. In section 3, we implement the final component of our interaction design using computer systems and deploy it, reconciling an integrated reality for the user in which they will interact and use objects.

The most optimistic result is that what we propose is a wonder-ful, or we should say a wonderful interface to make the physical reality becomes our imagined reality for users using computers, i.e., one ultimate reality. However, in practice, this is a design iteration that expands not only users' but also our imagination through interactions, which eventually reflects into the physical reality. We thus argue that the sense of wonder is the key, and Reality Rifts are interfaces to future realities.

6.2 Working with Reality Rifts

Our participants also proposed many other immersive experiences incorporating Reality Rifts. For instance, one participant who is an amateur magician told us that he believed Reality Rifts could be a novel form to present a live magic show. To implement this idea, they suggested that the trackers should be as concealed as possible so that the audience would not be able to notice the technology. The entire system could also serve as an editing tool for them to create performances. Other participants pointed out that this kind of exhibition could be held in an art gallery as the concept involves Wabi-Sabi [34] and the digital sublime [47].

Other participants also considered our concept to be used in educational demonstrations to induce wonder. A participant with medical background proposed the idea of combining the concept of Reality Rifts with gross anatomy. Another user proposed the idea of a fire extinguisher simulation that teaches the students how to correctly use the fire extinguisher. The system based on Reality Rifts can be used to spoon-feed the parts to be wondered by students.

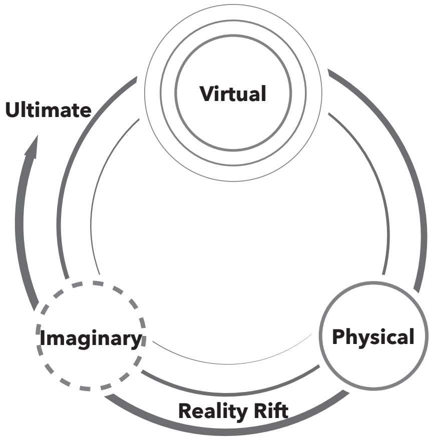

Figure 12: Reality Rifts close the loop by bridging the mismatches between the virtual, physical and imaginary realities.

Since the key interactive object in our experiences is basically imaginary and invisible, the participants also envisioned that our interactions could be transformed into an accessible physical experience for blind people under careful design. For example, the *catapult* with tactile feedback could be an accessible prop for blind users to experience the water splashes caused by the imaginary and infinite projectiles on the catapult. Another possible adaption would be to make the magical morphing stick an accessible and universal prop for blind users to explore the environments. Some crucial challenges still need to be overcome to realize the idea of a truly accessible experience, including proper guidance and route design for the blind to get through the level easily and safely, as well as intuitive and accessible hints for them to manipulate mechanisms throughout the experience. It could also be interesting to observe how people with and without sight can collaborate in Reality Rifts.

6.3 Formation of Wonder

From the qualitative feedback and quantitative measures, our Reality Rifts experience involved many elements in forming the sense of wonder [69]: unexpected, surprising, magical, surreal curious, and enjoyable. In our deployment, while BASELINE also triggered curiosity and brought enjoyment, RIFT resulted in significant improvements and augmentation with other elements of wonder. "The discovering and inferring process enabled stronger connections between users and the environment than the more common representations of feedback used in current escape rooms, such as a light blinking or door opening. Also, the process pushes users to go back and forth between observing and learning, resulting in unlimited imaginary and joyful spaces to envision," P44 said. "When I turned on the faucets, no water came out, but the waterwheel still spun. I felt that something was missing, but I was not quite sure. After activating the mechanism to turn the stick prop into a screwdriver, I found that I needed to use it to fasten the screw. Since the appearance of the stick looked only like the handle of the screwdriver, I imagined I was holding a screwdriver that had both visible and invisible parts and tried to use it to fasten the screw a bit.

Figure 13: (a)The user is catching an imaginary fish with a fishing rod. The user feels the force from the fishing rod where its string is pulled by a motor and (b) sees the splash caused by the air compressor used in the catapult example. (c) The user pours imaginary wine into the kettle and sees (d) real wine being filled in the container through hidden tubing underneath it that is connected to a wine pump.

The moment the screw rotated corresponding to my movement, the phenomenon met my expectations for the fantasy world and was so fun and satisfactory. In my opinion, the enjoyment the experience provided is way beyond the puzzle-solving itself – even more, originated from the learning and discovering process throughout the entire journey," P4 said.

In the meantime, the histogram of the most wonderful interaction supports our speculation that each interaction's clarity induces a different level of wonder. As in Figure 11 right, hiding formless phenomena such as wind does not introduce noticeable incoherence while reducing too much simulation plausibility such as axe also breaks perceptual causality. However, we observed that perceptual causality could be learned through experience to facilitate the induction process and compensate for the gap. All the users who went through BASELINE first also noted that they took the operations performed in BASELINE as a reference during the Reality Rifts condition. "I think the order of the experiences enabled me to get on track quite easily. I can quickly pick up the idea that the waterwheel is spinning without visible water and the water splashing without launching visible projectiles," P20 said. From the histogram, we also confirm that the plausibility of the simulated effects may influence the inference process.

We should note that wonder is a metaphysical concept and has a broader scope to be covered. For example, awe, another aspect of wonder [65], was not engendered in our experience. The debate is also open to whether 'fun' and 'wow' factors should be conflated with wonder [1, 23]. Therefore, our results should be seen as preliminary proof of concept.

6.4 More Examples

Figure 13 shows our additional examples based on or extended from the concept of Reality Rifts.

Fishing: the user is fishing the imaginary fish with a rod with its string pulled by a motor. As the user feels the fish and pulls it out, they see the water splash that is produced by the air compressor in the catapult example.

Infinite Barrel: is a magic prop filled with an infinite amount of imaginary wine. The user can pour the imaginary wine infinitely into the physical container. As the user pours the imaginary wine, real wine appears in the physical container. This is achieved using a wine pump and hidden tubing underneath the container.

7 LIMITATION AND FUTURE WORK

While Reality Rifts was well received with positive feedback from the users, we also discovered several limitations in the current implementation. Firstly, the more realistic simulation, the more technical limitations to realize Reality Rifts. For example, a better simulation of our wind vane example would be to only hide the wind with the fan powered on and spinning as normal. However, in our current prototypes, we only used off-the-shelf sensing and actuation systems and could not achieve this perfection. Our sensing components, trackers, were also revealed in plain sight. While there are physical constraints, we see that Reality Rifts inspires new technical challenges to sensing and actuation systems.

The current duration of the Reality Rifts experience was comparatively short. We plan to build a more complex experience to further study Reality Rifts and the sense of wonder. We will also look into bringing multi-user interactions to Reality Rifts. In the future, systems with Reality Rifts could be designed with different perceptual abilities in mind.

8 CONCLUSION

We have presented *Reality Rifts*, a new mixed reality that blends in imagination. The main benefit of Reality Rifts is to induce a sense of wonder by introducing incoherence in perceptual causality to elicit and guide users' imagination. We have described the 3-step design process where each step has its own design space to open a Reality RiftẆe have explored the design spaces of Reality Rifts with 6 proof-of-concept prototypes, where we have showcased possible designs and implementations of Reality Rifts using off-the-shelf sensing and actuation systems. We have discussed the findings and insights of our 50-participant deployment that supports a spectrum of clarity levels that induce different levels of the sense of wonder. Our qualitative feedback and the quantitative measures preliminarily show that Reality Rifts induce a sense of wonder. With Reality Rifts, we understand more about designing wonderful interfaces toward one ultimate reality that merges physical, virtual, and imaginary realities.

ACKNOWLEDGMENTS

This work was supported by National Science and Technology Council in Taiwan (NSTC 112-2636-E-002-002). We thank Der-Shin Elise Cheng, Yu-Chen Chan, and Ting-Yi Chang for organizing the field deployment. We also thank EnterSpace for providing us with space and feedback while running the field deployment.

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