Abstract Machines

Overlaying Virtual Worlds on Physical Rides

Anonymous Author(s)

ABSTRACT

Overlaying virtual worlds onto existing physical rides and altering the sensations of motion can deliver new experiences of thrill, but designing how motion is mapped between physical ride and virtual world is challenging. In this paper, we present the notion of an abstract machine, a new form of intermediate design knowledge that communicates motion mappings at the level of metaphor, mechanism and implementation. Following a performance-led, in-the-wild approach we report lessons from creating and touring VR Playground, a ride that overlays four distinct abstract machines and virtual worlds on a playground swing. We compare the artist's rationale with riders' reported experiences and analysis of their physical behaviours to reveal the distinct thrills of each abstract machine. Finally, we discuss how to make and use abstract machines in terms of heuristics for designing motion mappings, principles for virtual world design and communicating experiences to riders.

CCS CONCEPTS

• **Human-centered computing → Empirical studies in interaction design**;

KEYWORDS

Virtual Reality, Rides, Thrill, Abstract Machines, Design Knowledge, Visual Kinaesthetic Experiences

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1 INTRODUCTION

Virtual reality has great potential as an entertainment medium, including in the 'ride industry' where amusement parks have recently begun exploring how overlaying virtual worlds on existing physical rides can deliver new thrills. This reverses the traditional VR perspective which aims to stimulate our physical senses to match what we are seeing in headsets, to instead consider how to retrofit virtual worlds to existing physical experiences. It also begs questions: What kinds of mappings between physical and virtual motion will work best? and how far can we separate physical and virtual sensations of movement in the interest of delivering thrilling, unusual and challenging experiences without riders feeling truly awful?

We report the lessons learned from designing and touring a ride that mapped the experience of an existing playground swing onto four different virtual rides, describing the design rationale for each ride and how it was experienced by thousands of riders. This enables us to tackle a central research question: how can we design mappings between physical and apparent virtual movement to balance sensations of thrill and discomfort? This turns out to be a complex design challenge, involving making appropriate mappings between sensations of physical and virtual forces; designing a journey through a virtual world that matches the characteristics of a physical movement; and communicating the nature of the experience to potential riders who cannot see what is happening inside people's headsets. We reveal how our artist introduced the concept of riding a machine as a way of dealing with this complexity, constraining the design space, bridging between creative design and implementation, and communicating among the design team and ultimately with the public. This leads us to contribute the general concept of an *abstract machine* as a new form of intermediate design knowledge to support the design of future experience that remap existing physical movements onto virtual ones. We generalise an abstract machine as combining metaphor with mechanism, encouraging consideration of forces and sensation and being both implementable and rideable. We draw on our findings to reveal principles for: mapping between forces, embedding machines into worlds, and drawing on ride data profiles to communicate with the public.

2 RELATED WORK

HCI has a history of engaging with interactive ride design (e.g., [16, 18]) and also amusement parks as a context for photo work and souvenir generation [9]. Our particular focus on sensory alignment in ride design speaks to three discussions within the wider literature.

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Embodied immersion

The emergence of commodity VR headsets has fueled a resurgence of interest in embodied immersive experiences. These can broadly be understood as falling along a reality-virtual continuum [17], a spectrum of possible experiences that includes VR, in which the user feels that they are removed from their current physical environment to be immersed in to a new one and augmented reality, in which they feel that they have remained firmly in their local environment but that virtual content has been introduced into it. In between, lie interesting possibilities for combining pre-existing physical experiences with virtual worlds including Passive Haptics [12] and Substitutional Reality [24] that overlay virtual worlds on existing physical props to enhance tactility, and Visual Kinaesthetic Experiences that overlay virtual worlds onto existing physical movements to enhance kineasthethic sensations [25] as we do in this paper.

Sensory alignment

Underlying these various approaches is the question of alignment - to what extent should physical and virtual sensations be aligned with one another? Previous research approaches sensory alignment in three broad ways. Firstly, some work sees achieving tight sensory alignment as an important if difficult challenge. The desire to enhance digitally mediated visual and auditory stimuli with aligned tactile, haptic and kinesthetic ones has fueled development of interfaces including motion platforms, actuated devices and surfaces, wearables, passive haptics [12] and stimulations of muscles to simulate object impact [14]. Secondly, some research recognises that a small degree of misalignment between visual and other senses can deliver perceptions of weight [2] or of touching multiple objects when actually holding a single object [1], or can deliver useful effects such as appearing to walk in an infinite straight line in a virtual world while actually moving in a circle in the physical world [19]. In these cases, a small degree of visual misalignment is sufficient to stimulate a useful physical sensation or behaviour while remaining generally imperceptible to the user so a not to jar the overall sense of being in a tightly aligned experience.

The third camp, to which this paper belongs, is grounded in the idea of stretching the envelope to create relatively extreme misalignments that deliver unusual and typically thrilling sensations in pursuit of entertainment. Inspired by pre-digital illusions such as the Haunted Swing [28] and the idea of "vertigo play" from Caillois [8] that turn upon deliberate sensory conflict or confusion, several projects have explored more extreme misalignments. Byrne et al. [7] for example, electrically stimulated the vestibular system to cause conflict with the visual as part of a fighting game that involved playing with balance. Of particular relevance here is Tennent et al, [25] who reported an early experiment called Oscillations that overlaid a single virtual world on a physical swing to create a vertiginous experience and articulated key challenges for further research into "visual kinesthetic experiences" including understanding how to design ride trajectories, dealing with motion sickness, and designing visibility to spectators. However, little was reported on how to design appropriate mappings between physical and virtual movements or how to overlay multiple virtual experiences onto a single physical one. Our paper responds to this agenda while digging deeper into how to design and communicate multiple distinct mappings for a single physical experience.

Thrill, discomfort and sickness

Ride designers aim to deliver thrills, as do we in exploring sensory misalignment. However, the notion of thrill is not widely discussed in the HCI literature (though related notions pertaining to fun most certainly are [5]). A previous artistic exploration of thrill drew on the literature and phenomenology to argue that thrill arises from a distinctive combination of arousal, pleasure and anxiety that are experienced when encountering novel stimuli [26]. Previous work on uncomfortable interactions within HCI considered thrill as a journey through temporary and deliberately induced discomfort - from anxiety to catharsis - in the wider interests of entertainment, enlightenment or sociality [4]. These discussions motivate our interest in designing mappings that deliver appropriate mixes of positive and negative sensation.

We note that not all forms of discomfort are equal in this regard: a degree of being scared is often a positive aspect of undertaking a thrilling ride, whereas feelings of nausea are rarely experienced as positive. Motion sickness in particular is challenging for visual kinesthetic experiences [21]. Previous research has suggested that a variety of factors affects VR motion sickness including type of display, familiarity, age, duration of the experience, physical ability and others [21]. Sensory Rearrangement Theory [20] identifies two physiological triggers of motion sickness: 1) differences between signals received from the visual and vestibular systems, and 2) differences in signals from the internal vestibular system itself (between the semi circular canals that sense rotations and the otoliths that sense linear motion). [27] suggests that applying a noisy signal to the vestibular system during moments of inconsistent visual stimulation from VR reduces the body's reliance on the vestibular system for motion sensing and so makes one feel less sick which may explain why stationary VR can be more nauseating than moving VR.

Finally, we note that people have different tendencies towards thrill seeking [23] as well as susceptibilities to and tolerances of discomforts including motion sickness. Catering for such diverse tastes is a motivation for our interest in designing multiple mappings for a single physical ride.

3 APPROACH

We follow the approach of Performance-led Research in-the-Wild' [3]. This methodology emerged from HCI's engagement with artists and cultural applications. Being performance-led means engaging with artists to create and realise artworks as a way of exploring novel uses of emerging interface technologies. Being in-the-wild means revealing how public audiences experience it under the realistically stressful conditions of public performance as a professionally commissioned work. Papers that follow this approach typically provide a reflexive account of both the artist's design rationale and the audience's experiences, reflecting across both to draw out wider lessons for HCI.

In this case we worked with professional artist [ANON] to develop a large scale touring installation called *VR Playground*. VR Playground is an extended swing ride that draws inspiration from previous work including Oscillations mentioned above. However, VR Playground layers multiple virtual worlds onto a single ride to consciously explore different physical-virtual mappings and consequent experiences of sensory misalignment. Our paper draws on data from deployments at Norfolk and Norwich Festival, Greenwich and Docklands Festival, and Stockton Festival where over 15,000 people rode VR Playground. It has since visited South Korea, Germany and the US, and continues to tour.

Figure 1: A set of VR Playground Swings

4 THE DESIGN OF VR PLAYGROUND

An installation of VR Playground consists of one or more sets of up to eight swings (figure 1). A rider wears a Samsung Gear VR headset and headphones and as they swing they experience one of four 'abstract machines': *High Roller, Shuttlecock, Jellyfish* or *Walker*. Each employs its own 'rules' of motion to map the rider's swinging action onto an apparent motion through a distinct virtual world, for example in *High Roller*, a rider's swinging leads to accelerated forward motion as they rush along a road in an abstract city: the harder they swing, the faster they appear to move. The design of the the work unfolded in two phases, *motion experimentation* and *abstract machine design*.

Motion Experimentation

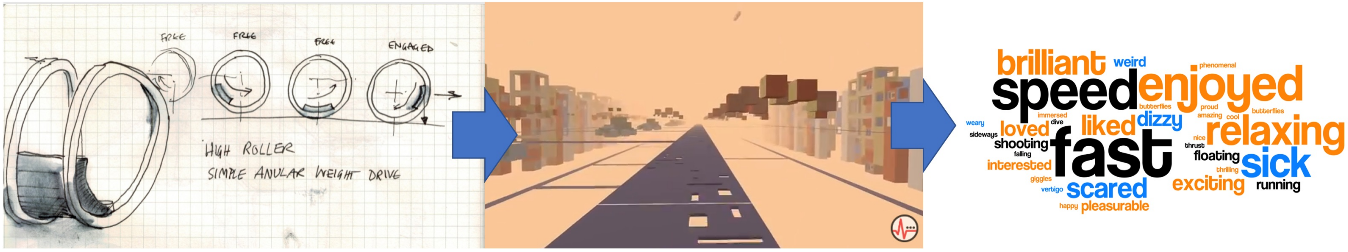
We aimed to understand the range of virtual movement(s) that a rider might be presented with while swinging. We began by exploring permutations of translation and rotation applied through a single viewpoint (a 'neck' on which real headset rotations were applied). Trying all permutations of six degrees of freedom wasn't practicable, leading us to create a test environment to experiment with a sample of different movement characteristics. The intent was to understand what types of motions felt more or less comfortable or challenging. Through this process we derived some simple heuristics (table 1), based on the idea of *off-axis* and *on-axis* movement. Off-axis means virtual movement introduced in an axis in which a rider is not physically moving, while on-axis is augmentation of an axis in which the rider is already moving. We consider the ways in which such movements can be augmented: *introduction*: adding new degree of freedom of movement, *amplification*: increasing existing movement, *suppression*: reducing existing movement, and *direction*: changing the direction of movement on an axis.

	Off-Axis		**On-Axis**	
Action	**Trans**	**Rot**	**Trans**	**Rot**
Introduction			N/A	N/A
Amplification	N/A	N/A		
Suppression	N/A	N/A		
Direction	N/A	N/A		

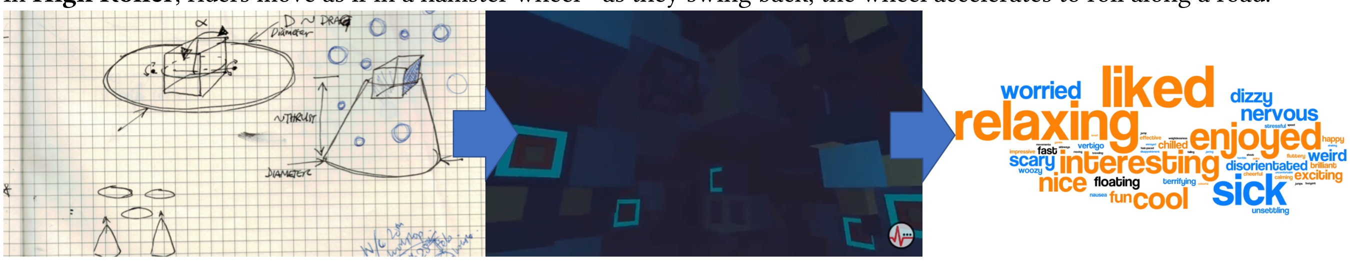
Table 1: Heuristics for selecting virtual movement remapping. Green - comfortable, yellow - somewhat challenging, red - very challenging.

Abstract Machine Design

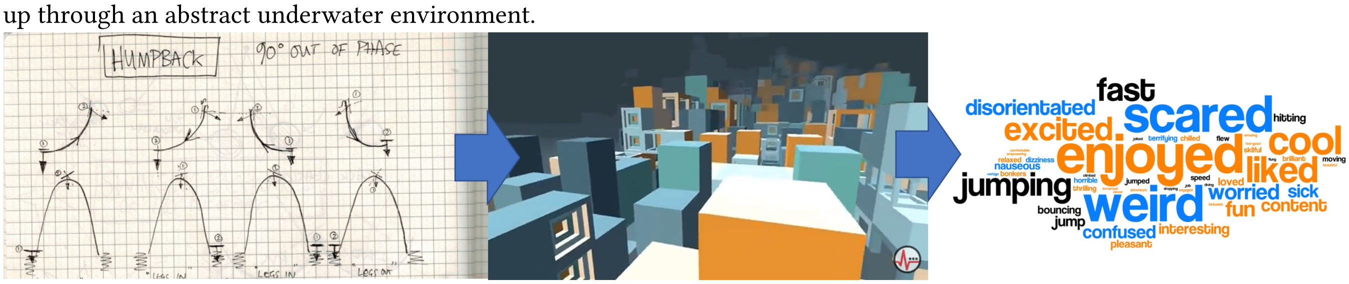
While these heuristics provided general rules of thumb for motion mapping, they were too general and open to inform the detailed design of specific experiences. Rather, the artist chose to work with the notion of riders moving around virtual worlds by riding a series of imaginary, but virtually functional, machines, each controlled by the motion of swinging but delivering a different sensation of movement. Ultimately, the artistic choice was taken to make these machines invisible and simply present the rider with motions, allowing them to draw their own conclusions about how they were moving and focus on sensations rather than the details of their 'vehicle'. However, the machines formed an integral part of how experiences were both designed and communicated from artist to development team. For each world, a diagram of a machine was provided, along with idealised physics equations that could be used to implement its movement with respect to the swing's movement (reflecting the artist's background in engineering). Once developers implemented this, one or more sessions of 'tuning' was necessary, where coefficients of equations were tweaked to make for a more



In **High Roller**, riders move as if in a hamster wheel - as they swing back, the wheel accelerates to roll along a road.



In **Jellyfish**, the downwards vertical acceleration felt on the swing is translated to upwards force as the user floats vertically up through an abstract underwater environment.



In **Shuttlecock**, as the user swings, they jump from roof to roof across a city landscape. The jumping is timed such that the zero gravity moment at the top of the jump is synchronized with the zero gravity moment at the front or back of a swing cycle.

In **Walker**, each swing is as if a giant robot is taking a step through a city. As the robot takes left and right steps, the view tilts and twists from side to side, as if the viewer is looking forward from the robot's point of view.

Figure 2: The four rides with their abstract machines. Top to bottom: High Roller, Jellyfish, Shuttlecock and Walker

engaging experience. For example, the gearing of the High Roller machine could be changed to make the ride seem faster or slower. Virtual simulations of machines were developed so that the artist could check the ride moved as intended and further refine its design. Each machine was then placed in its own virtual world whose visual elements and soundtrack were designed to reinforce intended sensations of movement. Each machine followed a distinct journey through the world with its own way of starting, finishing and varying intensity throughout. The machines were then fully implemented, tested by the team and their movements finely tuned, with further tweaks taking place in early public deployments. The following paragraphs briefly introduce key characteristics of each machine referred to in the subsequent study and discussion, though their characters are perhaps best understood by watching the video figure. Physical safety was an important consideration - none of machines' movement increased in intensity once the rider had reached a fifty degree angle and a physical constraint was introduced to prevent riders from swinging too high.

High Roller (figure 2 - top)

High Roller has you zooming through a cityscape inside an invisible monowheel. Over time, the wheel accelerates to great speed, then slows down again as you reach the end of the ride. Close blocks on both sides of the road at various points are intended to create a claustrophobic feeling and emphasise speed; large open spaces aim for an agoraphobic feeling at others; points where buildings are visible on only one side create a slightly acrophobic feeling; while trains occasionally cross your path to create a sense of peril. The machine abruptly comes to a stop at the end of the ride.

The wheel is driven by an angular weight drag - that is a weight is applying force to the wheel and the rider impelled forward only while swinging back from the forward limit to the centre of the swing. The forward movement is then subject to drag. When we consider the viewpoint movement in terms of the heuristics above, it amplifies movement on the forward (z) axis, and suppresses movement on the up (y) axis. additionally, on the backswing, the z-axis direction is reversed, so we move only forward through the environment.

Jellyfish (figure 2 - second row)

In Jellyfish, riders sit atop an invisible, mechanical jellyfish that, with each beat of the swing, propels them upwards though an underwater environment from a dark abyss to a shallow reef populated by sealife. The vertical movement sees the users travel through a somewhat vertiginous environment. Occasionally a large anchor suddenly drops past the rider. By the end of the ride, the rider is drifting in the open sea.

The machine is a deformable skirt shape, that moves from a flat plane to a cone and back with each swing. Movements are subject to both buoyancy and drag, with the deforming skirt and upwards thrust creating the impulse as the jellyfish progresses up through the environment. As with High Roller, the artist provided physics equations to calculate the movement and these were used to generate the animation of the jellyfish moving through the underwater environment.

Jellyfish is quite similar to High Roller in its movement mapping, albeit in a different axis; though here the impulse comes while the rider is swinging forwards, and the drag is significantly higher - if a rider doesn't swing, the force of gravity will pull them back down, unlike High Roller, where the drag will never pull you backwards. In the terms above, jellyfish suppresses z-axis movement, amplifies y-axis movement, and reverses y-axis movement during some points of the swinging motion.

With jellyfish, the ability to tune the ride through the coefficients of the equations proved especially important. we initially tuned it to what we thought was appropriate, however when the ride was first deployed, many riders were unable to get the jellyfish to lift off the seabed as they were simply not swinging hard enough. The mapping between swing angle and thrust had to be changed in situ to allow the jellyfish to be propelled with less movement.

Shuttlecock (figure 2 - third row)

In Shuttlecock, the rider is bounced from rooftop to rooftop across a cityscape. These 'jumps' are slightly out of phase with the swing: riders reach the peak of their jump arc when the swing is at maximum deflection and land when the swing is centred. The roads beneath the player are populated with trucks, while helicopters and zeppelins share the same airspace as the rider. The height of buildings, and the trajectory of jumps are intended to create a sense of peril.

The machine itself might be considered to be an invisible racket, which sends the rider flying like the eponymous shuttlecock. To allow the rider to progress through the city we had, for the first time, to introduce some *off-axis* movement. The path through the city takes two forms: *lateral* - in which we introduce x-axis movement to allow the rider to progress sideways along a street and *forward*, where we introduce x-axis movement to allow the player to move between buildings on the left and right side of the street. In this case we also reverse the direction of the z-axis movement on the back-swing to have the rider move only forwards. The amount of x-axis movement was defined primarily by the need to land on a rooftop - that is the shape of the environment created the constraints for this, and this same need, in conjunction with the phase of the swing was used to determine the height of the parabola of the jump so that the amplification of movement in the y-axis is highly variable between jumps.

Walker (figure 2 - bottom)

The Walker machine is an invisible giant robot with extensible legs that stomps through a city. As the ride progresses the 'robot' grows, gets too big for the road, and begins crossing rooftops. When it walks onto a bridge, it turns, steps off and walks under the water across a harbour, before emerging on the other side and shrinking back down, then fading out.

By design, Walker introduces two distinct off-axis rotations - one in the z-axis for each step, and one in the y-axis each time the robot turns a corner. It also has constantly changing values for the amplification of y-axis movement, first from the changing height of the buildings on which the robot is standing, and second because for the majority of the ride the robot is growing, causing changing amplification of both the z-axis and y-axis.

As with other machines, the artist provided equations to calculate the movement. However, as the production deadline was approaching rapidly, in an attempt to 'short-cut' the process, the development team initially tried building

Walker by 'body storming' the motions based on their understanding of the machine design. When the artist visited for the scheduled tuning day, the motion was not at all as he had envisioned it (the team had produced a rather jerkier step motion that was quite uncomfortable to ride). Returning to the original process of implementing the machine based on the provided equations made the machine move with a kind of swooping motion as initially envisioned.

5 WHAT RIDERS THOUGHT

We conducted in-depth interviews with 52 riders and began our analysis by using the corpus of 15,000 captured words to create a series of ride-specific wordclouds (see figure 2). In each case we broadly categorised the words used into *positive* (orange), *negative* (blue), and *motion* (black). These wordclouds helped reveal the distinct characters of the machines. High roller riders largely talk about *speed*, *relaxation*, *excitement* and *enjoyment*, as well as some reports of *fear*, *dizziness* and *sickness*. Jellyfish riders predominantly find it *relaxing*, *interesting*, *enjoyable*, *floating* and *cool*, with some mention of *sickness*, *worry* and *nervousness*. Shuttlecock riders also comment on *speed* and *jumping*, as well as *enjoyment*, *excitement* and *cool*, the (perhaps) negative terms for shuttlecock include *weird*, *scared* and *disorientated*, with less focus on *sick* than the other machines. Finally walker includes comments on *walking*, *twisting* and *turning*, with positive terms like *interesting* and *exciting*, but has more negative words than the others, including *sick*, *disorientated* and even *bored*. The changing language used to describe the machines appears to suggest that the different machines really did create different rider experiences.

On the whole, they reported a positive experience, with the majority claiming to have had a good time (which was backed up by the VR Playground's evident popularity which often saw long queues and many repeat visits). Many riders did also report feelings of sickness, however it is worth noting that while the word sick is used a lot, there was some conflation between sick (generally negative) and dizziness or vertigo (perhaps positive in this context). Riders often qualified negative sentiments with positive ones, such as: *"the shuttlecock one was more scary, so it kind of made me laugh a lot from being terrified."* or *"I felt content, yet I mean, I was having a good time, it was scary"*. Opinions of machines were highly subjective with riders reporting different personal preferences much as they might in an amusement park.

Motions

Certain motions definitely seemed to be enjoyable, for example many riders enjoyed the sensation of speed in High Roller: *"The faster I swung, the faster I went. It was brilliant, the speed became phenomenal" "I found it quite thrilling...I was going fast when I knew I personally wasn't going fast..* Similarly, riders of Jellyfish seemed to enjoy the floating sensation *"I found it more relaxing ... you were just floating around."* Other types of motions were reported as more disorienting, though not necessarily negative for example in Shuttlecock: *"it wasn't like a straight backwards and forwards motion, it was complete pillar to post ... which is where you get disoriented ... it's great."*. The twisting motion of Walker tended to be the most challenging: for example: *"I was concentrating quite hard, to make sure that I got through it all right, you know ... and I felt, as I was swinging from side to side"*. One observed effect of the off axis movement in both Walker and Shuttlecock was a tendency for riders to twist their bodies while swinging. This appears to have been a compensation strategy for the apparent lateral movement. *"I felt like was going diagonally... but that's probably when I was twisting myself ... I kind of liked that, but it was kind of scary."*

In High Roller and Jellyfish, riders typically found motions easy to grasp: eg.*"when you went back...you could feel it almost thrust you forward"* and *"It's supposed to be a Jellyfish, kind of, squeezing, and then going up."*, whereas more complex movements in Shuttlecock and Walker were more of a mixed bag in terms of users understanding the motion. Some certainly did, for example: *"It seemed like when I went back and forth...there were greater jumps up or down."* and *Uh, yeah, walking [in Walker] with a bounce in my step.* However others found the motions more difficult to grasp: *"I've no idea because I couldn't work out whether I was swinging forward or backwards [in shuttlecock], honestly I got to one point where I'd just jumped up, but my legs felt like they were going backwards and I kind of couldn't get my body to go in time with what was going on"* or *"I was bouncing [in Walker], but that was my impression, I was expecting to walk, but I wasn't walking, I was travelling through the space."*. Other riders put their own interpretation on the motions: *"Shuttlecock's more like Spiderman. Bouncing from building to building, but you're going sideways as well as forwards, and you're really high up."*

Environments

The virtual worlds appeared to influence the experience. *"It [High Roller] makes you feel like you're flying or something very fast through a city in one direction."*. In Jellyfish, several riders commented about looking down, both as pleasant but also as scary: *"You looked down...and it's a long way down...I felt like very light...and quite nervous"*. Riders recalled key features of the worlds, for example the trains in High Roller: *"You know, how the train, the sort of simulation train running over your head are like that, yeah, so I like the full, the full immersive experience rather than just a, a straight ahead."* One rider commented on the disorientating effect of the colour palette in Walker: *"I did have a bit of motion sickness. Um, I think this was probably more just the colour vibrancy ... the contrast was quite disorientating"*.

Ride	Mean Amplitude (degrees)	s.d.
High Roller	65	28
Jellyfish	64	27
Shuttlecock	66	26
Walker	57	29

Table 2: Mean amplitudes for each ride

6 HOW RIDERS BEHAVED

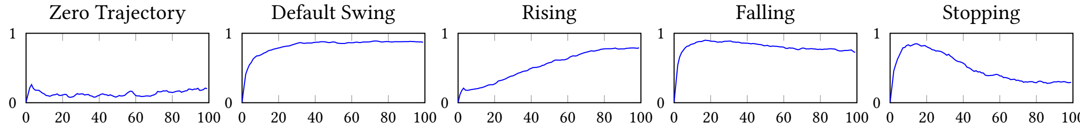
The success of VR Playground as a touring experience provided an opportunity to log swing sensor data that might yield insights into riders' behaviours on the four machines. We analysed quantitative logfile data from 6609 riders from the first three deployments to understand how they had *behaved*. We first looked at how high people swung, in terms of swing amplitude, or the angle between front and back swing. Table 2 shows the mean amplitude for the central 60% of the ride time for each machine (i.e. ignoring acceleration at start and stopping at end). On average, riders swung significantly less hard in *Walker* (Kruskall-Wallis, p<0.001).

To explore what was different, we considered each rider's behaviour over time, using 100 amplitude measurements evenly spaced over the full ride and normalised to the maximum amplitude. For each of the four machines, we applied k-means clustering to identify the five most common trajectories of amplitude. We grouped these manually into trajectories which had visually similar characteristics. Table 3 shows a breakdown of how many riders exhibited each of the five identified trajectories which were:

- **Zero Trajectory:** Approximately 5% of riders of each machine spent most of their time stopped.
- **Default Swing:** The most common trajectory is a fast start, followed by remaining swinging relatively constantly. We believe that this kind of 'default swinging' represents swinging without altering behaviour greatly in response to the virtual world.
- **Rising:** We saw patterns of slowly rising swinging on all machines - this is most likely to suggest some kind of habituation and learning to swing with the visuals during the ride time.
- **Falling:** We also saw falling trajectories - similar to the default swing initially, but then fall to 75% or less after a time, which suggests someone trying to swing as normal, but then finding the machine's movements too much and backing off to a more comfortable level.
- **Stopping:** In *Walker* only, we saw a number of riders who began to default swing, but then very noticeably dropped their swing amplitude to <25% of their peak amplitude - suggesting people were strongly affected by the ride and unable to continue swinging hard.

Looking at differences between machines, while there were significant differences between the trajectory distribution for all machines ($\chi^2(12)$=672, n=6609,p<0.001). For machines except *Walker*, these differences were minimal, of the order of ±2%, whereas Walker is clearly different, with large effect sizes. *Walker* is clearly an outlier in several ways: Firstly, default swinging only happens 41% of the time, versus 69% on other machines. This suggests that *Walker's* motion mapping and visual world has more effect on ability or desire to swing than in other worlds. In the other trajectories, more riders (21%) showed rising trajectories, suggesting they had to take time but got used to the machine; the big difference however is that 33% of Walker riders showed trajectories which started normally then dropped (with 11% practically stopping). This suggests that riders were unable to keep up their initial swinging when faced with the motions and visual environment of *Walker*, in contrast to the other machines where almost all riders were able to swing successfully.

These results demonstrate three things: first, people swing differently depending on machine and environment design; second, individuals have very different responses to rides. Third, those responses suggest different experiences and orientations towards the machine, with many riders seeming to just swing and watch the visuals (default trajectory), whilst other trajectories show strong links to the machine's program, or suggest that visuals may be interfering with ability to ride, or perhaps making it too intense to ride, as in *Walker*.



	Zero Trajectory	Default Swing	Rising	Falling	Stopping
High Roller	5%	69%	12%	14%	0%
Jellyfish	7%	67%	10%	16%	0%
Shuttlecock	5%	69%	9%	17%	0%
Walker	5%	41%	21%	22%	11%

Table 3: Per ride breakdown of ride trajectory type

7 DISCUSSION: ABSTRACT MACHINES

We now return to our central research question: how can we design mappings between physical and apparent virtual movement to balance sensations of thrill and discomfort?

The evident success of VR playground as a viable touring experience, being popular with promoters, festivals and riders alike, demonstrates that one can indeed successfully overlay multiple virtual worlds on a single physical ride so as to deliver a series of distinctly thrilling, if sometimes challenging, experiences. The above analysis of interviews and movement data reveals in greater detail how our riders experienced each of our four machines as offering a distinctive mix of positive and negative sensations. The positive included the pleasurable sensations of acceleration and relaxed floating, while the negative included fear, motion sickness and occasionally even boredom. We have have also revealed how balancing pleasure and discomfort in the pursuit of thrill is a complex design challenge requiring designers to: appreciate the experiential characteristics of physical movements; narrow down the possibilities for translating these into virtual movements; embed the resulting translation into a journey through a wider virtual world; and communicate the resulting experience to potential riders. In what follows we generalize the notion of the abstract machine as a potentially powerful approach to help address these challenges in an integrated way.

The early stages of our process explored a complex space of possibilities and yielded some useful heuristics (that we generalize below) for mapping physical movements onto virtual ones. However, such general heuristics proved insufficient to support the detailed or comprehensive design of multiple experiences as they were: (i) too open to help the team narrow down the bewildering design space of possibilities; (ii) incomplete, failing to account for all of the relevant aspects of a mapping such as the design of the surrounding virtual world and (iii) not readily actionable, failing to communicate the fine details of a design among team members or being directly implementable in rides or simulations.

The abstract machine was a creative response to these limitations - one that we believe has wider possibilities beyond this single project. This idea first emerged as a way of conceptualizing different designs, but subsequently played a significant role in communicating, testing and ultimately implementing them. The notion of the abstract machine proved useful throughout the design and implementation process and it is notable that the one occasion the team tried to bypass creating an abstract machine - the realisation of Walker - resulted in an unsatisfactory design followed by the introduction of an abstract machine to help correct this.

Generalising from our specific examples, we define an abstract machine to be a virtual mechanism that embodies a mapping between real and virtual movements. We therefore propose that Abstract machines exhibit several key characteristics that enable them to provide a common design language:

- **Metaphor**: the abstract machine provides a metaphor to communicate how the design is intended to work between designer, implementers and potentially even the public. This also helps communicate a sense of what a rider might be intended to feel and may suggest appropriate theming and design for the virtual world.
- **Mechanism**: beyond offering a general metaphor, the clarity of the machine as a mechanism, for example being expressed through detailed mechanical sketches and even equations, helps communicate the specifics of design and resolve ambiguities between designer and implementer - for example axis naming conventions.
- **Implementable**: a machine-like mechanism tends to focus attention on implementability from an early stage. We saw how abstract machines were implementable both as simulators to support testing and ultimately as the final rides.
- **Forces**: working with a machine-like mechanism encourages consideration of the forces felt by riders and hence the sensations of movement. This contrasts with the more conventional approach of thinking about degrees of freedom of movement of input devices (e.g., when mapping an general input device such as a 2D mouse to interactions such as controlling perspective in a virtual world).
- **Rideable**: an abstract machine is not just a mechanism, but is one that is designed to be rideable (even if in a fantastical way). In particular, an abstract machine is set on controlled trajectory through a virtual world that changes over time to reflect the temporal characteristics of the underlying physical experience.

The first three characteristics enable abstract machines to communicate design at three distinct levels of abstraction - metaphor, mechanism and implementation - which may be suited to different stages of the design process but also to different stakeholders - artist, world designer, programmer and also users. The last two are specific characteristics that help designers wrestle with the complexities of the design space. In more general terms, abstract machines are a form of intermediate design knowledge [11], sitting somewhere between specific design instances and general theory. They are more general than individual ride designs that include details of virtual worlds, but also more specific than heuristics or guidelines. To some extent, they reflect aspects of design patterns [6] and might potentially be published and made reusable as part of libraries (a contribution of our paper is to publish four initial designs for abstract machines) but also place a heavy emphasis on simulation and implementation. We shall see below in our discussion of motion sickness how they might also potentially help designers make connections to general theory from other disciplines.

We now consider three key aspects of designing abstract machines in greater depth: mapping between physical and virtual forces; designing a journey through a virtual world; and communicating with potential riders.

Mapping between physical and virtual forces

At the heart of each abstract machine is the mapping of experienced physical forces into apparent virtual ones. Our experience of VR Playground suggests three high-level heuristics to guide the design of such mappings.

- **Heuristic 1:** Amplifying or diminishing apparent forces along existing physical dimensions of movement can lead to powerful sensations of movement at relatively low risk of motion sickness. They can amplify sensations of acceleration or floating up high that, even if sometimes scary, are often seen a being positive aspects of rides. High Roller and Jellyfish both amplify and diminish forces along existing axes: High Roller zooms forward without apparent upwards motion while Jellyfish floats up without apparent forwards motion.
- **Heuristic 2:** Reversing the direction of forces along an existing physical axis of movement is a potentially powerful tactic but with somewhat higher risk. In Shuttlecock each forwards jump is made from half of a backswing and half of a forwards swing, while the effects of gravity are applied normally. The resulting effect is more extreme and thrilling than High Roller and Jellyfish, as can be seen in our rider interview data, suggesting higher potential for thrill but higher risk of nausea than simple amplification.
- **Heuristic 3:** Introducing off-axis movement delivers the most extreme and challenging ride experiences with the highest risk of nausea. It may also cause people to move in odd ways as they try and respond to the apparent motion. The addition of a side-to-side rocking motion to Walker resulted in a more extreme ride with greater risk of nausea (perhaps similar to adding rotation to non-moving VR users [13] and some riders felt the need to swing sideways in synchronisation with it.

The aim in introducing these heuristics is to help balance positive and negative sensations to deliver a suite of thrilling ride experiences, so while machines may draw on the first two heuristics, some judicious application of the third may be appropriate to create some more extreme machines as part of a wider collection.

These heuristics also broadly reflect the theoretical accounts of motion sickness discussed earlier. On the one hand noticeable differences in the signals between visual and vestibular systems, potentially compounded by differences within the vestibular system arising from angular movements, may contribute to motion sickness as accounted for by Sensory Rearrangement Theory [20]. However, it maybe that the swinging motion also sends a noisier signal to the vestibular system which helps reduce motion sickness as described in [27], so that experiencing VR while swinging might potentially be less sickening than while seated for example, though this needs investigating further.

A virtual machine in a virtual world

In order to deliver an overall ride experience the mapping defined by an abstract machine needs to be embedded in a virtual world through which the rider appears to move. Our experience reveals that there are two key aspects to this. First, it is necessary to recognize that each existing physical movement has its own natural trajectory, shaped by physical properties such as momentum, that will determine how it begins and ends and accelerates and decelerates throughout. It takes time, effort and skill to get a playground swing moving from a standing start (with some riders needing a helping hand) as it does to bring it to a halt and dismount. Adjusting intensity also takes time and then there is the need to back off if riders swing dangerously hard. We note that other existing physical movements, from rollercoasters to vehicles, will bring their own distinctive patterns of acceleration that need to be matched to the dynamics of the abstract machine as it moves through the world. Second, the world design needs to be sympathetic to the movement of the machine. It is well understood that the visual design of virtual worlds can influence the experience of physical sensations, for example in reducing perception of pain [15] or tricking people into believing they are touching multiple physical objects when there is in fact only one [1]. Our experience reveals how world design can complement sensations of movement: closed corridors with low overhangs and onrushing objects amplify speed and evoke the peril of collision while open landscapes with elements floating far below the rider reflect the sensation of floating but with the peril of falling. The placement of specific features may encourage riders to look fixedly ahead and so help prevent motion sickness or alternatively, may encourage looking around while they swing to experience unusual viewpoints such as the powerful moment of looking down at the apex of the swing in Jellyfish. Sound design also plays a part in the apparent sensation of movement, such as the swish of acceleration in High Roller and the re-equalisation when going from above to under water in walker.

Figure 3: The artist's cartoon renderings of the machines

Communicating machines to riders

Our final application of abstract machines concerns communicating the experience of machines to potential riders. Theme parks and fairgrounds cater for a diverse range of visitors, from adult thrill seekers to families with young children. Moreover, objective physiological responses to thrill rides are strongly modulated by personality factors such as sensation seeking tendencies [23] while susceptibility to motion sickness appears to vary according to a variety of factors including exposure, age, illness and alcohol consumption [10]. In response, parks provide a variety of rides to cater to many tastes alongside resources to help visitors choose rides that suit their personal preferences and tolerances including: seeing the ride as a spectator, theming, zoning and explicit ratings and warnings. Our approach of layering multiple virtual experiences on top of a single physical ride delivered differentiated ride experiences. However, it was difficult for riders to gauge them simply by watching others as distinguishing features of each were largely hidden inside virtual reality headsets. In HCI terms, our rides are 'intriguing' spectator interfaces in which manipulations of the interface are amplified while consequent effects are hidden [22].

All of this suggests the need for additional resources to communicate rides to riders. Our artist had already drawn on the four abstract machine designs as simple cartoons on a ride menu (figure 3) to help communicate the character of each, however, our analysis reveals considerable scope to extend this with more in depth ride profiles. We might, for example, present versions of our word clouds to riders, or draw on the evidence of rider behavior (their different patterns of swinging) to assign intensity ratings and scores grounded in measurements of actual rider behaviour. We might also recommend a default order in which people experience the rides; in our case this would begin with High Roller or Jellyfish before moving onto Shuttlecock and then Walker. We therefore suggest that abstract machines, and by extension their virtual 'ride' experiences could be packaged in terms of their *mechanics* (a representation of the machine to suggest the motion), *environment* (a representation of the world to suggest what the machine is moving through) and *experience* (a representation of what the machine feels like to ride). We have applied this method of packaging our four abstract machines in figure 2.

We suggest that in the longer term, published abstract machines may be associated with ride profiles, data summaries that characterize how riders feel about them and behave on them, and that this could be matched with rider profiles, based on captured data about riders own experiences to recommend specific rides to specific riders. At a more mundane level, we saw potential riders often seek advice from operators and each other in the queue and around the ride while some notably performed their ride experience as a spectacle. Such behaviours might be encouraged by the physical organisation of the ride or translated onto social media.

8 CONCLUSION

We have shown it is possible to overlay one physical ride with multiple virtual worlds to create differentiated ride experiences that offer different balances of positive and negative sensation to create thrilling experience. We revealed that this is a complex proposition involving constraining and tuning motion mappings between physical and virtual movements then embedding these into a journey through a virtual world and ultimately into an overall ride experience. Based on our experience, we introduced the idea of *abstract machines* - an intermediate form of design knowledge that communicates at the levels of metaphor, mechanism and implementation.

Our findings have significant practical implications for ride designers and operators as they support the process of reskinning expensive physical infrastructure with relatively inexpensive virtual content to deliver differentiated ride experiences. While amusement parks already differentiate their rides through their types (e.g., 'round rides' and 'coasters' of varying types and scales) and their theming, zoning and rating, the step change here is to enable more fine-grained differentiation by tuning the mappings between physical and virtual movements alongside the designs of the worlds in which they are embedded. Such fine-grained differentiation may help personalize the park experience to diverse visitors and also encourage repeat business as visitors return to try out different variations.

Our approach raises directions for further research including: exploring beyond swings, not just other rides, but potentially also more everyday experiences such as 'planes, trains and automobiles'; extending data-driven approaches to profiling rides towards techniques for automatically recommending them and even dynamically adapting them, for example adjusting intensity as riders speed up or slow down; profiling riders as well as rides to better understand individual preferences and tolerances as so match people to rides and worlds; and more systematically exploring the complex relationships between the perceived sensations that contribute to thrill.

9 ACKNOWLEDGMENTS

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