Haptic Feedback Mechanisms to Enhance Virtual Reality Experiences

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Abstract

Haptic feedback is the rendering of virtual signals with physical forces to simulate the effects of virtual reality environments. There are many methods to do this and each varies in its accomplishments. This paper will review three experimental feedback methods: pneumatics, instant impactors, and electrical muscle stimulation. Pneumatic actuators reliably simulate gentle to medium forces such as hugging or slithering, while motorized instant-impactors simulate precise impacts by projectiles better. Electromuscular stimulation simulates weight and physical boundaries by stimulating opposing muscles rather than providing an opposing force.

1 Introduction

The heightened richness of VR provides for stronger creation of memories- and memories that are more likely to be recalled as actually happening in the real world (versus, for example, being observed on a screen) [8]. It engages the brain in a way more akin to actual movement and navigating a space versus a 2D video game [1, 7]. This is applicable to many areas such as gaming, education, and therapy [5].

The field of virtual reality is growing and ways to deepen the experiences that users are already having are readily sought after. Science fiction describes many ways of interacting with virtual environments. While the technology often described in these places, such as neural interfaces, does not exist, other feedback methods do and may be the closest we can get to full-immersion virtual reality. Finding the strengths and weaknesses of available feedback technologies allows users to have better virtual experiences, and developers to create better experiences.

To discuss virtual reality feedback methods, there are a number of items that should be addressed to ensure a base-level understanding of the underlying technologies and methodologies at work. The Background section addresses the important ideas of virtual reality, haptic feedback, and vibrotactile feedback. Once this is done we can begin discussing the experimental methods of rendering feedback for virtual experiences led by Delazio et al. [3], Lopes et al. [6], and Tsai et al. [10].

Each of these studies investigates a different feedback method to understand its strengths and weaknesses, but this is further enhanced in this paper by cross-comparing different studies to understand how these technologies may be used together to create a larger sum than its components.

2 Background

As addressed in the introduction, to understand the purpose and importance of haptic feedback, we must first understand virtual reality as a way of having new experiences [8], and to do this we must understand the basics of how the technology works. Understanding how virtual reality works in a basic sense and how haptic feedback equipment augments and enriches these experiences can help us realize the potential for fully-immersive virtual reality experiences.

2.1 Virtual Reality

Virtual reality itself is a fairly simple technology, speculated about since at least 1995 [9]. It blends both hardware and software to create virtual environments that users can interact with using controllers of variable precision, motion-tracking headsets, and motion-tracking cameras. This allows a user to be immersed much more than with a standard keyboard, mouse, and monitor. Due to the downsizing of technology, more efficient graphics processors, and game engine improvements, virtual reality technology has become widely available in the last decade. This includes both hardware such as head-mounted displays (HMDs), controllers, and motion trackers, and software, such as games. The adoption of industry leaders such as Oculus (founded 2012, acquired by Facebook, later Meta, 2014) has also indicated a commercial adoption of the technology.

2.2 Haptic Feedback

Haptic feedback is not a new technology and has existed in many forms for years. Phone vibrations for alerts is one form of haptic feedback. Haptics is anything that stimulates the touch sensation, either through vibration, forces, or motions. In virtual reality, haptics are used to further immerse a user into an environment. While HMDs provide sight and headphones provide sound, haptics provide touch. Common forms of haptics in VR are used as gloves or controllers, such as those in [2]. There also exist stationary and chair-mounted haptic systems. The ones we will look at in this paper are wearable and intend to provide a broader range of feedback to simulate environmental effects such as objects or impacts mostly to the torso and upper body.

2.3 Vibrotactile Feedback

Vibrotactile feedback is the most common form of haptic feedback and has been used to augment virtual reality experiences for several years, such as in [4]. It also shows up in phones, console controllers, and anything else that ‘buzzes’ to get your attention. In virtual reality, it often takes the form of small motors in either the controllers or on the body that attempt to simulate some virtual force.

3 Methods

To understand the different approaches to haptic feedback that create contrasting experiences, we will discuss three studies that applied distinct methods of stimulation. The first, *Force Jacket* [3], uses a jacket with a system of pneumatic airbags to apply variable force feedback. The second, *ImpactVest*, uses a vest design similar to Force Jacket’s, however the impactors use elastic bands to propel rubber balls at the wearer, rendering a much more intesnse, and instant, force that is better suited for simulating some effects such as gunshots or slashing. Finally, in [6], the concept of electromuscular stimulation (EMS) as a feedback mechanism is explored. Unlike the other methods of rendering an outside, physical force, EMS uses pads to stimulate muscles in such a way as to mimic the presence of weight in objects and physical boundaries.

3.1 Force Jacket

In [3], Delazio et al. set out to create a wearable device to simulate the physical effects of virtual experiences through the use of distributed force, where previous methods had used vibrotactile stimulation. Very few experiences can be simulated through the use of vibrotactile stimulation, however.

3.1.1 Design. Delazio et al. designed a device that uses a system of pneumatic bags to apply both vibrotactile and variable force across the torso and arms. To create this device, first the researchers needed to know where the airbags would rest. A basic design was created from a repurposed life jacket with some modifications, including 26 airbags with force sensitive resistors (FSRs) and 10 feet of tubing to connect the airbags to 26 corresponding solenoid valves. This allowed the researchers to actuate the pneumatics to quickly inflate and deflate the airbags.

After this, basic software was implemented to dynamically control the pressure of the airbags using the FSRs and Teensy microcontrollers. A basic algorithm was developed to inflate the airbags, being tested on four different mannequins simulating both male and female body types, with a large and small size for each. With this setup, the researchers were able to inflate/deflate the pressurized airbags quickly and precisely, being able to switch from 1.5 Newtons to 5.5 Newtons in under 0.8 seconds with a pressure error under 1.5 N.

3.1.2 Localization and Free Magnitude User Studies. Next, a study was done to measure user perception of the placement of the airbags, to both ensure the density of the airbags would not confuse the users’ senses and to measure the users’ perceptual biases. 16 participants were recruited. While wearing the jacket, a random airbag would be inflated and the user would be asked to identify where on a diagram they thought the airbag was. The study indicated that bag placement was sparse enough to not confuse users, with most users correctly identifying the placement of the airbags most of the time, with only some exceptions indicating small and systemic biases that may have arisen from the Jacket’s design or fit, biases in the participants’ mental body image, or low-level sensory phenomena. The positive results indicate the potential for pneumatic upper-body haptic interfaces and even imply that density of bag placement could be increased.

After this, another study was done to gauge the difference between perceived pressure by the participants and actual pressure being applied. The same participants were shown a diagram with a location that had an airbag marked. This airbag would be inflated and the user would be asked to report a free number (whole, fraction, or decimal) that they thought represented the magnitude of the sensation, the larger the number the stronger the sensation with ‘0’ being no sensation. This study found that the most sensitive areas were the shoulders and upper sides, and the measurements from this study were applied later to compensate for other areas to ensure that applied pressure somewhat matched the intended perceived pressure.

3.1.3 Dynamic Parameters Algorithm Design. With these steps taken, the researchers could design a software to define the haptic space and allow program designers to create effects to match real-world experiences. An editor was designed that allowed different parameters of the jacket to be adjusted, such as inflation pressure and target force. Designers could then use the software to create programs that would then instruct the hardware controlling the airbags when and by how much to inflate, or draw a line across a representation of the layout of airbags that would then inflate the bags along that line based on distance to it. These parameters allowed designers to create effects such as rain, pulse, enclosure, strike, or travel (the feeling of something moving across the body or the body moving across a surface).

3.1.4 Feel Effect User Study. Finally, participants were given a prompt to suggest some form of ‘feel effect’, a feeling such as "I feel the muscles growing on my upper body" and were given leeway to adjust parameters within an unidentified scope to experiment with the feeling. Adjusting these parameters would affect the pre-programmed feeling and

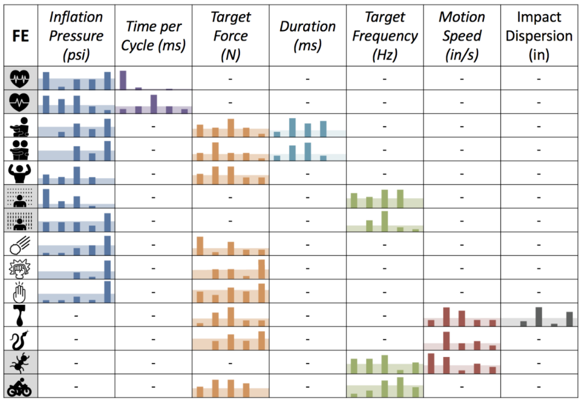


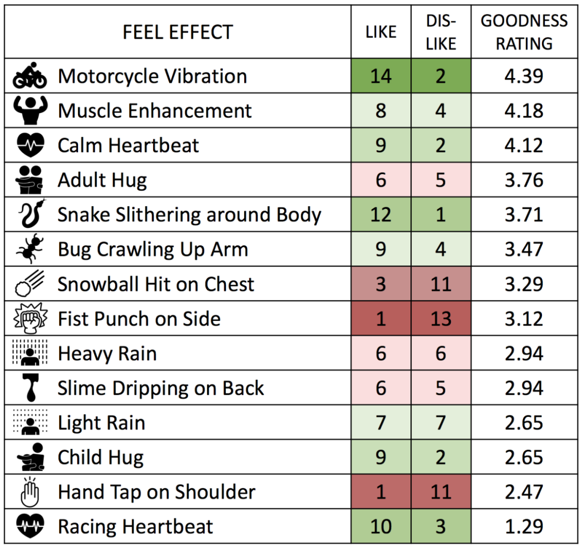
Figure 1. Histograms of choices for varied parameters of each feel effect.The x axis of each box represents increasing values of the parameter. The y axis varies but all distributions sum to 17, the number of participants in the study. The order of feel effect on left column takes same order as Table 1. A gray field indicates that the vibration mode was used.

then they were asked to rate the feeling on a scale from 'Unacceptable' (unrealistic) to 'Perfect' (realistic). The list of feel effects can be found in Figure 2. After this study they were given a short survey to state which feelings they liked and which they disliked. With these two sets of data the researchers found that some effects were liked much more than others, while some were much more realistic than others. For example, the 'Motorcycle Vibration' feeling had a 14-2 like-to-dislike ratio and a goodness rating of 4.39 out of 5. This means the participants enjoyed the sensation and thought it was realistic. Other feelings varied, with some being liked and unrealistic (Racing Heartbeat), unliked and somewhat realistic (Snowball Hit on Chest), and unliked and unrealistic (Hand Tap on Shoulder).

A few other examples of effects the participants thought were realistic were 'Muscle Enhancement', 'Calm Heartbeat', 'Adult Hug', and 'Snake Slithering around Body'. All of these effects were simulated with the Force Jacket using simple programming and pneumatic airbags. Evidence from Figure 1 and Figure 2 indicate some limitations of the Force Jacket. The Feel Effects that were liked the most but had the lowest 'Goodness Ratings' were the 'Racing Heartbeat' and 'Child Hug', and if we look at Figure 1 we can see the participants regularly selected the highest settings. This implies that the Force Jacket suffers in rendering haptic feedback that is precise or frequent in its current configuration.

3.2 ImpactVest

Following the work of Delazio et al. [3], Tsai et al. [10] set out to develop their own haptic feedback wearable, with slightly different parameters. The ImpactVest was created with the underlying principles of *realism, comfort, safety, and versatility*, and finally *mobility*. To accomplish the first, the



FEEL EFFECT	LIKE	DIS-LIKE	GOODNESS RATING
Motorcycle Vibration	14	2	4.39
Muscle Enhancement	8	4	4.18
Calm Heartbeat	9	2	4.12
Adult Hug	6	5	3.76
Snake Slithering around Body	12	1	3.71
Bug Crawling Up Arm	9	4	3.47
Snowball Hit on Chest	3	11	3.29
Fist Punch on Side	1	13	3.12
Heavy Rain	6	6	2.94
Slime Dripping on Back	6	5	2.94
Light Rain	7	7	2.65
Child Hug	9	2	2.65
Hand Tap on Shoulder	1	11	2.47
Racing Heartbeat	10	3	1.29

Figure 2. Feel effects ordered based on goodness rating out of 5, where 5 is perfect and 1 is unacceptable. Results of post user study survey regarding likes / dislikes are shown as a gradient from most liked (green) to most disliked (red).

pneumatic airbag system was replaced by motor-actuated elastic impactors. These impactors, using a motor to wind and unleash a rubber ball attached to an elastic band, would be capable of rendering much more impactful, and instant, force than the pneumatic system of [3] while also keeping a balance to maintain the user's comfort and safety. To improve on the capabilities of the Force Jacket, the Impact Vest would also be able to simulate more experiences while keeping mobility in mind in terms of design and weight.

3.2.1 Design.

To create a "one size fits all" vest, the researchers first decided the general areas that the impactors should go. They then conducted a study of five participants (three male, two female) to determine the best placements. Participants wore the vest while holding and moving an impactor to find the best positions for the impactors. The participants were instructed to think aloud and attach stickers to acceptable areas. Using the spaces indicated by each participant, overlapping areas were found such that a 3x3 rectangle with 14cm between rows and 10.5cm between columns was created (see Figure 3). It was also noted that the impactors felt best the tighter the vest so three adjustable velcro straps were added to each side to secure the vest to the user. Each impactor only weighs 93g and the vest weighs 345g, bringing the total weight to 1182g. This fits with the researcher's design goal of making the vest comfortable and preserving mobility.

3.2.2 Just-Noticeable Difference Force Study.

Next, a Just-Noticeable-Difference (JND) study was performed to find the minimum differences between force applications that

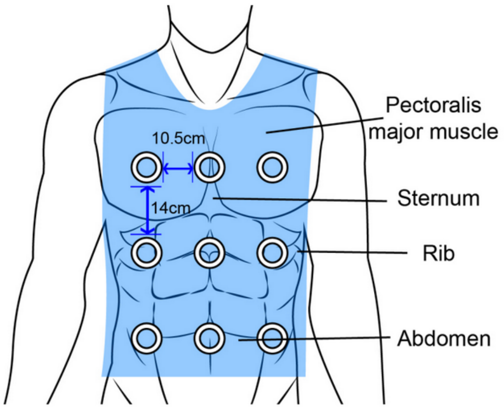


Figure 3. The decided placements of impactors.

users could distinguish as different magnitudes of force. A ‘best case’ (pectoral) and ‘worst case’ (pectoral concave) were identified where force was either translated well because of fit, or not well because of the potential air gap between the vest and the body. Keeping these in mind, the researchers would apply differing levels of force using the impactors on participants and ask them which they thought was different from the others. Consecutive correct answers would decrease the step size of the different force level by 0.2N to a minimum of 0N, while incorrect answers would inversely increase the difference in forces by 0.2N to a maximum of 1.1N. The JND study revealed that for impacts of different forces to be distinguishable in the worst case positions, there must be a 47.1% difference in magnitudes. Surprisingly, this difference was almost exactly (46.75%) the same for the best case positions. Participants did observe that by breathing or otherwise expanding their chest and increasing the contact between the pectoral concave and the vest, this difference was decreased.

3.2.3 Time Interval Threshold Study. Before the researchers could perform the study to gauge the overall experience, they needed to distinguish simultaneous, continuous, and discrete impacts. Simultaneous impacts are meant to be perceived as all belonging to the same effect. Continuous impacts are meant to be similar to simultaneous, except perceived to be moving, such as a slashing effect. Discrete impacts are meant to be perceived separately. To effectively render these different types of impacts, times $t1$ and $t2$ needed to be established, where these times are a lower and upper bound of times where the user could distinguish impacts in the 0ms-$t1$ range as simultaneous, $t1$-$t2$ as continuous, and the rest as discrete. Similar to the JND study, a staircase study design was used where impacts were rendered to 12 participants (4 female, 6 previously had participated in studies) and they were asked whether they felt the ‘discrete’ impact stimuli or not. Following this, the time bounds would be adjusted and following several reversals of these adjustments the step size would be decreased. After eight reversals at the smallest step size the study would conclude. From this the researchers found a lower (29.79ms) and upper (68.99ms) bounds. This study also revealed that, contrary to prior thinking, the distance between the impactors did not significantly affect the time bounds. Averaging the highest lower bound (32.57ms) and the lowest upper bound (61.87ms), the researchers found a 47.22ms time interval between stimuli to render continuous impacts.

3.2.4 VR Experience Study. Finally, Tsai et al. conducted a study to determine whether the ImpactVest had met their design goals (realism, versatility, comfort, safety, and mobility) and to determine whether the device improved VR experiences. In this study, 12 participants (6 female) were recruited who had not participated in the previous experiments. Each participant was given the vest, a head-mounted display, and a controller. They were loaded into a pre-built virtual experience where they encountered two soldiers, two swordsmen, two boxers, and a cannon. Each used a different weapon that the impactors would simulate. These effects were a shot from a pistol, a shot from a rifle, two different sword slashes, a light punch, a heavy punch, and a blast from a cannon. This routine was repeated with vibrotactile actuators in the same layout as the instant impactors. After these encounters, each participant was asked to fill out a survey and give open-ended feedback. The survey asked the participant to rate each experience in regards to realism, distinguishability, and enjoyment.

From Figure 4 we can see that the ImpactVest has already accomplished the design goals of realism, scoring well against vibrotactile in the shooting and slashing categories, as well as versatiility, beating vibrotactile in all aspects for both the shots and slashing. Among the open-ended feedback the participants gave, there were no complaints about the vest being unwieldy, blocking movements, or the impactors using too much force. In fact, multiple participants stated that they wished the force was greater. Combining these, we can see that the final design goals of comfort, safety, and mobility were accomplished.

The results from the study confirmed the accomplishment of the design goals, but they also confirm that the ImpactVest is not a catch-all solution for haptic feedback mechanisms in VR. In fact, they highlight the need for a solution that incorporates both vibrotactile feedback and instant impact feedback that can complement each other. One of the researchers speculated that the instant impactors could render the initial impact of an object, and the vibrotactile actuators could render the latent effects such as a numbness.

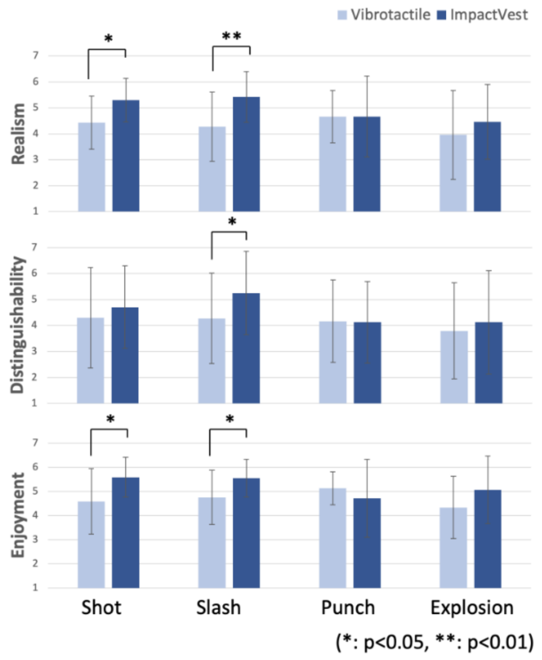


Figure 4. The results of the VR experience study in a 7-point Likert scale.

3.3 Electro Muscular Stimulation

The final method of haptic feedback we will discuss is electrical muscle stimulation, or ‘EMS’. EMS is relatively straightforward and lightweight. A user would have a series of electrodes placed on particular muscles and, when activated, these pads provide a variable, non-painful electrical pulse to the muscle that stimulates it. Placed correctly, these can create the illusion of resistance when interacting with objects in VR.

3.3.1 Design. Like [3, 10], Lopes et al. set forth design principles to guide them in this study. The four they chose, in order of decreasing importance, are: *believable*, do users ‘buy into’ the illusion of the virtual object causing the experience, *impermeable*, does it prevent users from passing through the object, *consistent*, do the visual and haptic sensations match, and *familiar*, do experiences from the real world align with these virtual ones.

After creating design goals, Lopes et al. began piloting to determine what scenarios their configuration would work in. It was quickly discovered that hard surfaces are difficult to simulate with EMS, as although the stimulation increases the difficulty of moving ‘through’ the object, it is still possible. Increasing the stimulation voltage only made it more apparent that the thing blocking the movement was the pad, not the virtual environment and hence the *believable* principle was violated. From this, however, a design to use ‘soft’ walls that appear to resist similarly to magnetic fields was created. These would still be believable, as now the user would understand that this force increases, but can be overcome, whereas it doesn’t make sense to be able to overcome a physical boundary. Another design was also created, referred to as ‘repulsion’. This design would quickly and intensely stimulate the user when they got close enough to an object (in the virtual environment) so that it would appear to forcefully repel them, like a wave of force.

3.3.2 Design Validation Study. To validate the *repulsion* and *soft wall* designs, Lopes et al. conducted a user study. This consisted of 13 participants (4 female, age 22.4 ±2.1 years), 6 had previous experience with VR headsets and 5 had previous experience with EMS. Each participant was loaded into an environment with 5 walls, each representing a different design. These were: *soft wall, repulsion wall, soft wood (identical to soft wall except the visual design was that of a wooden wall), soft vibro wood (soft wood with vibrotactile motor on back of hand),* and *vibro only*. Each wall was assigned a number at random and users were asked to try to penetrate each wall with their hand. After, users were asked to pick their ‘favorite’ wall, and were asked to rate statements pertaining to design goals such as "what I feel matches what I see". Results from this study indicated that the *repulsion* design was by far the favorite (8 picks), while also scoring the highest in realism (6.3). It rated well in impermeability (6.2) and had the least average penetration (3.6 cm). Lopes et al. note that this design was a standout, with *soft* and *soft wood* coming close. *Soft vibro wood* was close to the other *soft* designs, but the addition of the vibrotactile motor did not seem to add to or lower performance. The *vibro only* design was consistently rated the lowest of the five designs.

3.3.3 VR Experience Study. This study combined the EMS prototype with the designed walls in a virtual reality environment to truly test the overall experience. Of the 6 new participants (1 female, 22.0 ±2.09 years), five had previous VR experience and two had used EMS. Each was outfitted with the full suite of electrodes and the device was calibrated to each user, like in the previous study, to determine a ‘maximum’ stimulaton. They were dropped into a virtual world containing multiple rooms and objects to interact with, including the wall designs from the previous study, and objects whose weight would be simulated with the EMS system. Each participant went through the environment twice, once with the EMS turned on, and once without. After both runs, the participant was asked to rate each experience on a 7-point Likert scale.

The study collected a minimal amount of data but the data did show that the experience with EMS ranked better than the experience without in both enjoyment (5.3 with EMS, 3.5 without) and realism (5.3 with EMS, 2.7 without). Additionally, every individual participant ranked the EMS-enabled environment higher than the EMS-disabled. This confirmed Lopes et al.'s hypothesis that the EMS prototype would lead to a better user experience than the control without.

4 Conclusions and Discussion

We've discussed three different types of feedback methods for virtual reality, including haptic and EMS. Each of these methods accomplishes something different but, according to the results of each study, they all increase immersion in some way.

The *Force Jacket* [3] was good at rendering soft force feedback to the user's torso and upper body. This worked well for simulating some feelings such as a motorcycle vibration, muscle enhancements, and a calm heartbeat. This implies that the *Force Jacket* may be better at simulating more relaxing experiences overall, as opposed to action games, for instance. It falls down slightly in rendering precise, forceful, and frequent feelings such as a punch, a hand tap, or a snowball hitting. One technology that is good at rendering precise and forceful impacts is the *ImpactVest*. This feedback method uses instant impactors to strike the torso with more precision than vibrotactile or pneumatic impactors. In [10], Tsai et al. even speculate about combining the *ImpactVest* with existing technologies, such as vibrotactile actuators. The *ImpactVest* was shown to effectively render feelings like a gunshot or a sword slash, but missed the target on larger feelings like explosions or punches. It is possible that combining Delazaio et al. and Tsai et al.'s works may create a product that is more than the sum of its parts. This could be complemented further by EMS as a feedback method, as demonstrated by Lopes et al. [6], which showed the ability to create virtual boundaries and heavy objects in real environments.

Immersion is one be one of the main factors that sets virtual reality apart from normal computer virtual experiences, as the user can explore and interact with the environment much more than traditional 2D environments. This may be why it has been shown that virtual reality can trick our brains into thinking virtual experiences happened in real space [8]. With wearable haptics that allow the user to move and interact with the environment, these experiences are enriched and more enjoyable.

Acknowledgments

Thanks to Kristin Lamberty for advising me in composing, creating, and editing this paper. Thanks to my peers Kyle Day, Lloyd Hilsgen, and Isabelle Hjelden for their feedback and suggestions. Special thanks for further feedback from alumni Ian Buck and Andy Korth.

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