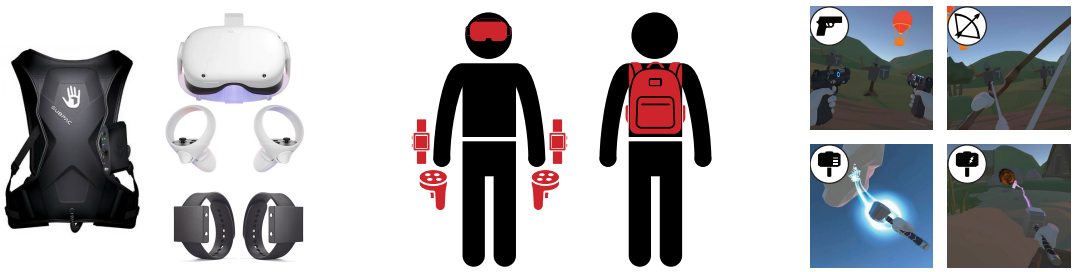
Exploring Cross-Device Haptics for Virtual Reality Experiences

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(a) (b) (c)

Figure 1: Cross-device haptics were designed for (a-b) a set of handheld and wearable devices (Meta Quest 2 headset with Touch controllers, Lofelt Basslet wristbands, SUBPAC M2 vest) and (c) three exemplar activities (*Pistols*, *Bow & Arrow* and *Hammer*).

Abstract

Haptic wearables such as smartwatches are increasingly available, yet rarely used in coordination with vibrating handheld controllers to enhance VR experiences. In this work, we explore such cross-device haptic effects between controllers, wristbands and a backpack in three exemplar activities (*Pistols*, *Bow & Arrow*, *Hammer*). A user study (N=24) was conducted to compare these cross-device haptic effects with single-device haptic effects relying on the controllers alone. Questionnaire responses revealed few differences between the two modes, but discussions with participants suggest an appreciation for cross-device haptics for at least some activities.

CCS Concepts

• **Human-centered computing** → **Haptic devices**; *Virtual reality*.

Keywords

Wearable haptics, Virtual reality, User experience

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1 Introduction

The experience of virtual reality is typically mediated solely by a headset and controllers, with limited haptic feedback during otherwise realistic interactions. Users, however, frequently wear watches with haptic capabilities while in VR without their tactile feedback being used to augment their experience. More advanced haptic wearables such as backpacks, gloves and shoes, on the other hand, are increasingly available on the market, but remain expensive and rarely used by casual users. We believe that a coordinated activation of these haptic devices could greatly enhance the experience of virtual environments, and refer to such vibration patterns as cross-device haptics, by analogy with cross-device interactions [2, 7].

In this work, we explore the design space of cross-device haptics in VR by augmenting the vibrations of handheld controllers with those of off-the-shelf haptic wearables (wristbands and a backpack). In doing so, we replicate realistic conditions with devices of limited capabilities (bandwidth, amplitude, latency) manufactured by different companies for uncoordinated use. We designed three exemplar activities (*Pistols*, *Bow & Arrow* and *Hammer*) intended to showcase cross-device haptics and demonstrate their value in game-related VR experiences. We also conducted an experiment to compare the experience of cross-device haptics with that of single-device haptics relying on handheld controllers alone.

2 Related Work

Several researchers have proposed coordinating the vibrations of a smartphone and a smartwatch to improve user experience and feedback expressivity. Harmonious Haptics, for example, explored spatio-temporal vibrations patterns between a phone and a watch to augment applications such as painting, transferring files and interacting with UI widgets [9]. Duet similarly used a sequence of vibrations between a phone and a watch to indicate a transfer

of notifications from one device to the other [2]. Vi-Bros used the relative position of a phone (in pocket) and a watch to provide intuitive vibrotactile directional signal while walking indoors [14].

More generally, most work on multi-actuator haptics uses devices designed to operate together or integrated actuator arrays, such as multi-actuator vibrotactile vests (e.g., Skinetic, Acronika), sets of wearable devices (e.g., TactSuit, TactVisor and Tactosy for Arms and Feet, bHaptics), or custom-designed prototypes and experimental setups (e.g., [4, 5, 12, 19]). These multi-actuator systems are often used to produce tactile illusions such as Apparent Tactile Movement and Phantom Sensations [10]. Apparent Tactile Motion produces the illusion of a moving vibration between actuators, while Phantom Sensations produces an illusory vibration between them. These illusions are created by carefully controlling of the duration, timing and amplitude of vibration pulses, and have been produced between the hands holding a tablet [19], between the hands with mid-air haptics [16], between bracelets during a handshake [4, 6], between armbands [12] and over vibrotactile grids [10]. While [12] suggests that these illusions are possible with mismatched actuators, the limited control over timing of commercial devices may reduce fidelity.

Our work also broadly ties into cross-device interactions as well as haptics for VR. Although not generally focused on haptics, cross-device interactions aim to allow seamless interactions across a wide range of devices such as computers, smartphones, watches and AR/VR headsets (e.g., [2, 7]). Haptics for VR, on the other hand, is often limited to vibrations in handheld controllers but shows promise to enhance immersion, embodiment and presence through more advanced devices [3]. Wearable haptic devices for VR include gloves (e.g., [8, 18]; Nova Gloves, SenseGlove; Gloves G1, HaptX), exoskeletons (e.g., [15]) and haptic suits (e.g, Teslasuit Dev Kit, Teslasuit).

3 Cross-Device Haptic Experiences

3.1 Equipment

The virtual environment was produced with a VR headset (Meta Quest 2), handheld controllers (Meta Quest 2 Touch) and noise-cancelling headphones (Bose Quiet Comfort). The VR headset was driven by a wired connection (Meta Link Cable) to a PC (Intel i7-8700, Intel UHD Graphics 630, 16 GB RAM, Windows 10 Pro) running Unity. The headphones were used for audio immersion and to reduce the influence of audible noise from haptic actuators.

The cross-device haptic feedback was produced by the controllers and two off-the-shelf haptic wearables (SUBPAC M2, Lofelt Basslet), as shown in Fig. 1ab. The Meta Quest 2 Touch controllers feature vibrotactile actuators, are connected wirelessly to the headset, and are controlled through an SDK. The SUBPAC M2 (SUBPAC, Canada) is a backpack (or vest) that produces a strong vibration in the back based on an audio signal. The Lofeft Basslet (Lofelt, Germany) is a watch-like wristband that produces vibrations on the wrist, also based on an audio signal. Two Basslets were used, one under each wrist for increased perceptibility. The SUBPAC and Basslets were driven by the PC through a wired connection to a multi-channel USB audio card (StarTech ICUSBAUDIO7D). The Basslet, however, relies on a wireless signal from a transmitter to a wrist-worn device.

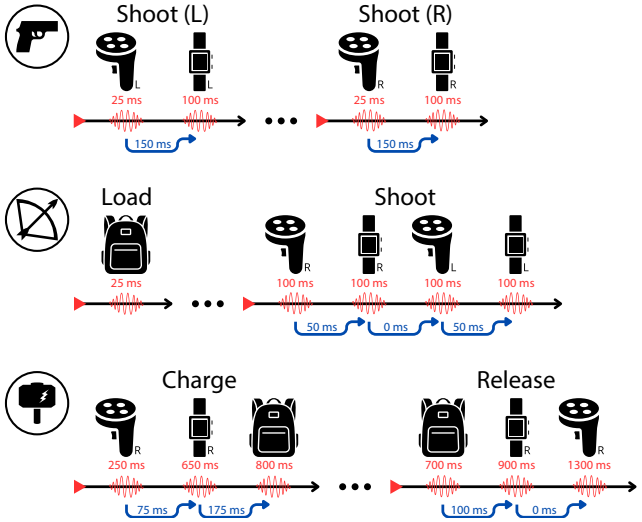


Figure 2: Design of cross-device haptic effects with pulse duration in red and the inter-pulse pauses in blue.

Together, these haptic devices produced vibrations in the hands and on the wrists and back. Off-the-shelf devices from different manufacturers with different actuators and control methods were purposefully chosen to emulate real usage situations with varying latencies and vibration bandwidths [12].

3.2 Exemplar Activities

Three exemplar activities were developed to explore the design space of cross-device haptic experiences. The activities were programmed using Unity version 2021.3.9f1 and the XR Interaction Toolkit. The activities were designed to showcase the added value of cross-device haptics and span device combinations. They were also designed to be sufficiently visually appealing (Fig. 1c), fun and challenging to maintain engagement and avoid distractions. **Pistols**: This activity involves shooting pistols. The player picks up a pistol in each hand and shoots at straw dummies to release balloons, which can also be shot. A cross-device haptic effect was designed to simulate the recoil of the pistols: the corresponding controller vibrates first, followed by the wristband (Fig. 2).

Bow & Arrow: This two-handed activity involves drawing an arrow from a quiver, mounting it on a bow, pulling the bowstring, and releasing the arrow. The player shoots arrows at straw dummies to release balloons, which can also be shot. A vibration is felt in the backpack when drawing an arrow. A cross-device haptic effect was also designed to feel the motion of the arrow: the vibration travels from controller to wristband for recoil, first on the hand holding the arrow and then on the one holding the bow (Fig. 2).

Hammer: This activity involves charging a magic hammer by raising it to the sky and releasing a lighting bolt by pointing it at a target. A cross-device haptic effect was designed to simulate the flow of the lighting through the hammer and body: the vibrations flow from controller to wristband to backpack when charging, and in reverse when releasing the lighting (Fig. 2).

The cross-device haptic effects were designed using an iterative process with frequent feedback from colleagues. The intensity and timing of vibrations were carefully selected to best match audio-visuals and design intent, such as producing a sensation of flow. The vibration intensity of the backpack was kept well below maximum (30% for *Hammer* release, 12% elsewhere) to better match the lower-intensity vibrations of the controllers and wristbands, and to prevent masking [11]. The vibration pulses of the wearables were produced from sound files of low-frequency noise, while those of the controllers were produced through the XR Interaction Toolkit.

The timing and duration of the haptic effects was confirmed by measurements with an accelerometer. As expected, the vibrations patterns did not match perfectly those specified in software, likely due to communication latencies and device particularities. The controllers behaved reproducibly, but produced vibrations that could be as much as 500 ms shorter than requested. The wristbands were less consistent, but deviated from specifications by no more than 40 ms. The backpack generally complied with specifications but produced some effects as much as 400 ms longer than expected.

For comparison, single-device haptic effects were also created to match cross-device vibration sequences. These effects used only controller vibrations, simulating the feedback available in typical VR environments. Like their cross-device counterparts, these effects were designed to match the audio-visuals and design intent.

4 User Experiment

A user experiment was designed to compare our cross-device haptics with the feedback used in conventional VR environments. The cross-device haptics mode (*CDH*) produced vibrations through the controllers, the wristbands, and the backpack, while the single-device haptics mode (*SDH*) relied only on the controllers.

4.1 Experimental Protocol

The experiment lasted less than 40 min. The experiment was approved by our Research Ethics Board and participants provided informed consent. They were fitted with the equipment (headset, headphones, controllers, wristbands, backpack) and instructed to use the controllers. To avoid biases related to weight and encumbrance, all devices were worn throughout the experiment.

The participants interacted with the three activities in sequence, each once per mode (*SDH*, *CDH*), for a total of 6 experiences. The experiences were limited to 1 min, during which participant were free to use the weapon provided as many times as they wished. The order of activities and modes were counterbalanced. A participant could for example experience the activities in the order *Pistols*, *Bow & Arrow* and *Hammer*, each with mode *SDH* first and mode *CDH* second.

After each experience, participants removed the headphones and headset to fill out questionnaires on a tablet. The questionnaires were created for the experiment and were partially based on Kim and Schneider's Haptic Experience model [13]. A first questionnaire (Q1-7) was administered after each experience to confirm feedback perception (Q1) and gather impressions in the mode used (Q2-7):

- Q1: What devices did you feel vibrating during the experiment?
- Q2: Did you perceive a sequence in the vibrations you felt?
- Q3: The vibrations you felt were natural.
- Q4: The vibrations you felt provided you with information.
- Q5: The vibrations you felt seemed disturbing.
- Q6: The vibrations you felt seemed to agree with what you saw.
- Q7: The vibrations you felt seemed pleasant.

The participants check marked devices in a list for Q1. They answered on a Likert scale from 1 (simultaneous vibration of all devices) to 5 (easy differentiation of different vibrations) for Q2, and from 1 (strongly disagree) to 7 (strongly agree) for Q3-7.

A second questionnaire (Q8-12) was administered after each each pair of experiences for an activity to compare modes:

- Q8: Did you notice any difference between the interaction modes?
- Q9: Which interaction mode did you prefer?
- Q10: Which interaction mode did you find most realistic?
- Q11: Which interaction mode did you feel most in control of?
- Q12: Which interaction mode did you have the most fun with?

Participants answered on a Likert scale from 1 (no significant difference) to 5 (clearly noticeable difference) for Q8, and from 1 (first mode) to 7 (second mode) for Q9-12.

The experiment ended with a semi-structured interview designed to gather impressions and feedback of participants. The experiment was conducted in French. The questionnaires and interview quotes have been translated for this paper and are available in French as Supplementary Materials.

4.2 Results

24 participants (5 female, 15 male, 23.2 mean age; 4 didn't provide demographic information) took part in the experiment. All were French-speaking and most were engineering students. Prior VR experience was not required. Two additional participants were discarded due to technical problems.

4.2.1 Quantitative results. Q1 asked which devices were felt to have vibrated in the different activities and modes (Table 1). Vibrations were generally detected when present with rates ranging from 62.5% to 95.8% (mean of 72.6%). Vibrations were however sometimes falsely detected at the wristbands (34.7%) and backpack (16.6%) in *SDH*, and in the backpack (12.5%) for a *CDH* activity where it was not present (*Pistols*).

Q2-7 evaluated the user experience of each activity in modes *CDH* and *SDH*. Non-parametric Wilcoxon tests were performed since responses did not follow a normal distribution. As shown in Fig. 3, the results were generally positive with both modes scoring high on being natural (Q3), informative (Q4), a match for visuals (Q6) and pleasant (Q7), and low on being disturbing (Q5). For most questions, participants scored both modes similarly, with no statistically significant differences. In Q2, however, participants

Table 1: Detection rate (%) of vibrations with false positives in *italics*.

	Pistols		**Bow & Arrow**		**Hammer**	
	CDH	SDH	CDH	SDH	CDH	SDH
Controllers	62.5	91.7	75.0	75.0	83.3	95.8
Wristbands	75.0	*41.7*	62.5	*37.5*	70.8	*25.0*
Backpack	*12.5*	*8.3*	91.7	*20.8*	87.5	*20.8*

better perceived a sequence with *CDH* than *SDH* for *Bow & Arrow* ($z = -2.42$, $p = 0.0154$) and *Hammer* ($z = -2.77$, $p = 0.0055$). In Q5, however, participants found *CDH* more disturbing than *SDH* for *Pistols* ($z = -2.33$, $p = 0.0197$) and *Hammer* ($z = -2.11$, $p = 0.035$).

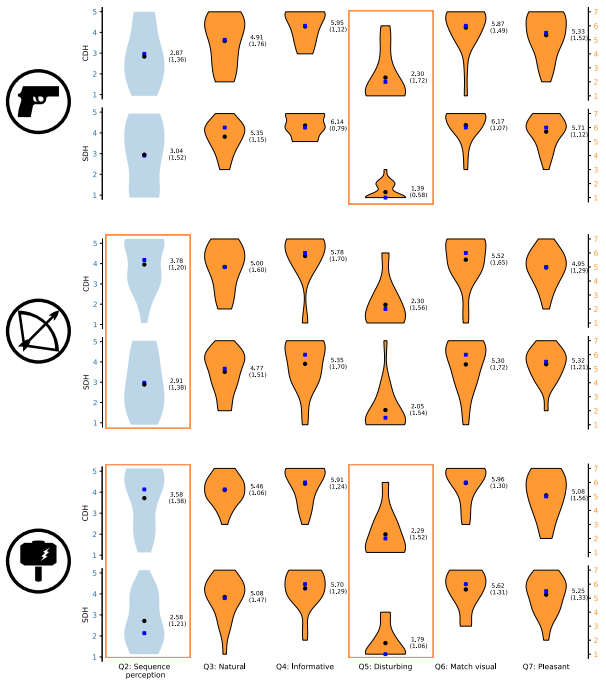


Figure 3: Response distribution for Q2-7 across activities and modes. Means and medians are represented respectively with a black circle and blue square. The mean and standard deviation are indicated in text. Statistically significant differences are marked with a box.

Q8-12 directly compared *CDH* and *SDH* for each activities (Fig. 4). Q9-12 were re-encoded with low and high values favoring *CDH* (1) and *SDH* (7), respectively. Q8 suggests that differences between modes were perceptible, with means from 3.83 to 4.29 (max of 5). Other measures (favorite mode, Q9; realism, Q10; sense of control, Q11; fun, Q12) seem to slightly favor *CDH*, but means were close to neutral, from 3.03 to 3.88. One-sample Student's t tests indicate for most questions that the difference with the neutral value (4 for Q9-Q12, 3 for Q8) was not significant. The exception, Q10, indicates that *CDH* was more realistic for the *Hammer* ($mean = 3.0417$, $sd = 1.97$, $t = -2.3872$, $p = 0.02558$).

4.2.2 Qualitative results. The experiment ended with a semi-structured interview. A thematic analysis was performed and responses were sorted according to different themes, such as whether *CDH* and *SDH* were appreciated for the different activities. Overall, most participants indicated that they appreciated the cross-device haptic feedback for at least some of the activities.

For *Pistols*, 17/24 participants found *CDH* consistent with their actions, with several quotes suggesting an appreciation for cross-device haptics: *"[Like] arcade, with vibrations mainly on the hands*

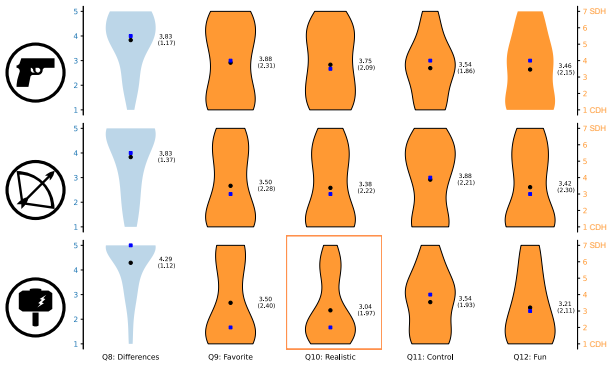


Figure 4: Response distribution for Q8-12 across activities. Means and medians are represented respectively with a black circle and blue square. The mean and standard deviation are indicated in text. Statistically significant differences are marked with a box.

and a little on the controllers. This adds realism and immersion." (P7); *"[There were] vibrations in the controllers and watches, [which gives us] feedback on what we're doing. You know you've fired the gun, it's more realistic. More disturbing with the stronger vibrations, not pleasant like a massage, matched the game."* (P11); *"Interesting addition, the controller or the wrists were fine, and it doesn't draw attention, more immersive."* (P16). On the other hand, 4/24 participants gave negative feedback, e.g., *"[The wrist is] a sensitive area, I found it odd. Preference for controllers because they're like holding something in your hand"* (P10). 8/24 had difficulty feeling the difference between controller and wristband vibrations, e.g., *"The two sensations blend together"* (P22). 2 found the vibrations weak.

For *Bow & Arrow*, few participants mentioned wristband vibrations. Of those who did, 7 liked it while 4 did not. The benefit most cited was the backpack vibration when drawing an arrow: e.g., *"Vibration that indicates whether I've caught the arrow, natural, good information. For the mode without vibration, [...] I didn't know if it was in the right place, less guided."* (P21). Some appreciated it even though it didn't feel realistic: *"The arrow confirmation vibration gives information but is not necessarily realistic. I don't need my eyes to know what I'm doing"* (P15). 3 participants suggested adding a vibrations while pulling the bowstring.

For *Hammer*, 6 participants liked *CDH* a lot, while 5 didn't. P20 was destabilized: *"A lot of information and vibrations, not reproducible in real life, so a little disturbed, but more fun with several devices than with just the controllers"*. For P8, it was *"weird and uncomfortable but immersive"*. P11 *"preferred with strong vibrations, goes well with lightning, powerful. You'd expect it to be stronger than the bow, went well with the game, so not unpleasant"*. P14 liked that vibrations were consistent and well incorporated in the game: *"I like the vibrations when I don't notice it."*

5 Discussion

All quantitative results, except disturbance, slightly favored *CDH* over *SDH*, but few statistically significant differences were found. Participants, however, did notice the difference between modes (Q8,

interviews) and most appreciated *CDH* for at least some activities in the interviews.

Few comparable results are available in prior work. Harmonious Haptics [9] and Duet [2] did not evaluate their proposed cross-device haptics between a watch and mobile device. Vi-Bros primarily evaluated the detection of cross-device navigation cues, but received positive subjective feedback on the concept [14]. Other works on vibrotactile arrays focus on tactile illusions, without subjective evaluation in a specific application context (e.g., [10, 12]). Our results, however, are in line with prior work that has shown an improvement in the user experience of game-like VR scenarios with haptics, e.g. with ultrasounds projected on the mouth [17].

6 Limitations

Several limitations of this work should be addressed in future work. Aggregate results may have been affected by diverging individual preferences for *CDH* or *SDH*. Experience with virtual reality may have influenced these individual preferences but was not collected in our demographic survey. The discrepancy between questionnaires, which have not been validated, and interviews also suggests a need for better questionnaires to capture the haptic experience [1].

The evaluation focused exclusively on the subjective experience of shooting activities: *Pistols*, *Bow & Arrow* and *Hammer*. Cross-device haptics may perform differently in other scenarios, such as surgical simulation or industrial training. Similarly, the impact of cross-device haptics on objective performance measures, such as aiming accuracy, is unknown.

Improvements to cross-device haptic effects are also likely possible. While largely appreciated in *Pistols* and *Hammer*, the effects were often criticized or missed in *Bow & Arrow*, for which feedback while pulling the bowstring was also suggested. Many also could not differentiate the vibrations of the wristbands and controllers (Q1, interviews), which suggests a need to personalize vibration intensities. Similarly, several participants found the feedback intense or weak, suggesting a need for personalization. While our goal was to investigate the design space with off-the-shelf devices, improvements to actuation and latencies could also allow more expressive cross-device haptic effects, such as tactile illusions [12].

Finally, participants removed the headset to answer questionnaires after each brief experience. This choice may have decreased presence and immersion and distracted from the haptic experiences. Better results could be obtained with a longer exposure to haptic experiences and the integration of the questionnaire in VR.

7 Conclusion

This work explored the use of cross-device haptic effects to enhance the user experience in VR. Three exemplar activities (*Pistols*, *Bow & Arrow*, *Hammer*) were developed to showcase the added value of cross-device haptics coordinating vibrations on off-the-shelf wearable haptic devices (wristbands, backpack) with those of VR controllers. A user study (N=24) was conducted to compare the user experience of the three activities with cross-device haptics or more conventional single-device haptics on the VR controllers alone. While questionnaire responses are largely inconclusive, discussions with participants suggest an appreciation for cross-device haptics for at least some VR activities. Further work will be necessary to refine haptic experience measurement tools, cross-device haptic effects, and exemplar activities demonstrating their value.

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