MASTER THESIS

Weight Perception in VR: A Novel Haptic VR Controller with Adaptive Trigger Button Resistance

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Declaration of Authorship

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Abstract

It is challenging to simulate physical properties of virtual objects in virtual reality (VR). Current standard VR controllers and software-based approaches cannot render the appropriate haptic stimuli to the hand and are therefore limited in providing a realistic haptic sensation. This thesis explores adaptive trigger button resistance as a novel interaction technique to resemble a perception of virtual weight in VR. We iteratively implemented two haptic VR controllers with different spring mechanisms for a dynamic adjustment of the resistance. Thus, users need to adapt their index finger force to grasp virtual objects of different virtual weights. Two psychophysical user studies evaluated the impact of both controllers. The results showed that the adaptive trigger button resistance enabled participants to experience different virtual weights. The evaluation also identified participants who did not notice the change in the haptic stimuli. This demonstrated a new perspective on the haptic perception of spring tension in VR.

Acknowledgements

With the help of many people, the idea of adaptive trigger button resistance was turned into this master thesis and two haptic VR controllers.

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Finally, I wish to thank all people who participated in the user studies and provided valuable feedback for the haptic VR controllers.

Table of Content

List of Abbreviations

2AFC	Two-alternative forced choice
C/D	Control/Display
CE	Constant error
DC	Direct current
EMS	Electrical muscle stimulation
HCI	Human-computer interaction
HMD	Head-mounted display
JND	Just noticeable difference
MCU	Microcontroller unit
PF	Psychometric function
PSE	Point of subjective equality
RL	Real life
VE	Virtual environment
VR	Virtual reality

1 Introduction

VR systems offer users a countless variety of applications. By using a head-mounted display (HMD) the computer-generated world becomes visible and users are enabled to explore endless virtual environments (VE) within the boundaries of a few square meters. To resemble a realistic and coherent experience, sensory input for various modalities like vision and touch is required [14]. Gallace and Spence describe the sense of touch as *"the one that contributes most to making things "real" to us"* [19]. Interacting with virtual objects in VR helps users to accept the VE as "real", i.e. gaining the feeling of being present [65]. However, the interaction does not provide users with the realistic haptic sensation. Current standard VR controllers lack the ability to render appropriate haptic stimuli to simulate physical properties of virtual objects. Grabbing a *virtual chocolate bar* haptically feels the same as lifting just a small piece of it. This identical sensation results in a discrepancy between what users expect from the real world and what users experience in virtual worlds. Haptic characteristics such as weight get lost in translation between the computer-generated world and the sensory system. This missing haptic component in VR experiences opens new challenges for VR input techniques to render physical properties of virtual objects.

1.1 Motivation and Research Goal

Conveying physicality of virtual objects to enable a more realistic sensation for VR users has been an area of active research in human-computer interaction (HCI). The weight of a physical object in real life (RL) is always present during an interaction which makes it an important aspect for realistic object perception in VR. Approaches that depend on current standard VR controllers are limited in providing a haptic sensation for weight since they cannot render forces to the hand. The development of novel haptic VR controllers overcomes those hardware limitations and allows the design of innovative input techniques that incorporate customized haptic stimuli. Various researchers have proposed different implementations, outlined in chapter 2, to stimulate users' haptic senses while holding virtual objects. While these first approaches have shown promising effects, they rely on complex systems making mass production and easy access for consumers inaccessible.

The goal of this thesis is the implementation of a novel haptic VR controller that renders haptic feedback for the perception of weight in VR. The approach aims to incorporate and enhance familiar input techniques to enable a quick and easy introduction to future standard VR controllers.

1.2 Adaptive Trigger Button Resistance

To grab and lift objects in RL humans use their hands and receive haptic stimulation during the interaction based on the object's weight. Gaining insights into the sensory system and the involved physical stimuli can yield helpful information on how to simulate this action in VR and for giving users a sense of weight. The following example and Figure 1 illustrate this clearly.

Look around and pick up an object that you reach from where you are sitting. This could be for example a full glass of water. Focus on the level of pressure that you apply with your fingers to keep the object lifted. Become aware of the kinesthetic forces acting on your fingertips. Put it down and choose another object of considerable different weight. Lift it, focus again on the pressure at your fingertips and compare it to the first object. For the empty glass, the pressure is substantially lower, barely squeezing the skin at the fingertips. The intensity of the grip strength decreases with the lower weight of the empty glass.

FIGURE 1 Two glasses with different weights. The intensity of the grip strength decreases with the empty glass on the right side. Here, the skin at the fingertips and palm is barely squeezed.

The mental model behind this scenario is explained by the current understanding in psychology. The human brain scales fingertip forces accordingly to its weight prediction of an object, incorporating visual cues and previous experiences. Touching an object supplies additional tactile information which leads to an update of the previous estimation [46, 56]. The consequence is a direct relation between the perceived weight and the exerted force by the fingers. In other words, finger forces are adapted according to an object's weight.

For grabbing a virtual object with a standard VR controller, the trigger button is typically used as an input technique. Pulling the trigger requires the manual force of the index finger to overcome the trigger button resistance and grab the object. Adjusting the trigger button resistance according to a virtual object's weight and therefor inducing adaptive finger forces would allow to transfer the above described mental model to the one-finger interaction with the trigger button. An illustration of the intended effect is shown in Figure 2.

FIGURE 2 Illustration of three levels of trigger button resistances simulating different weights of virtual objects. The resistance increases from left to right, marked by yellow, orange and red.

1.3 Research Questions

The technical implementation of the concept enables dynamically adjustable haptic feedback for virtual objects of different weights. Based on the understanding of how fingertip forces link to the brain's perception of weight, it can be hypothesized that higher resistances inducing higher fingertip forces translate to the impression of heavier virtual objects, smaller resistances inducing smaller fingertip forces translate to lighter virtual objects.

The main objective of this work is to investigate if the trigger button resistance can resemble a perception of virtual weight in VR. To answer this main objective, we formulated the following three research questions.

RESEARCH QUESTION I

Do different trigger button resistances influence the perception of virtual weight in VR?

RESEARCH QUESTION II

Do smaller trigger button resistances induce a perception of lighter objects and higher trigger button resistances a perception of heavier objects?

RESEARCH QUESTION III

How can the intensity of the trigger button be quantified and mapped to convey distinguishable virtual weights?

To investigate these questions, a first prototype of a haptic VR controller and a revised version named Triggermuscle were built. Both implement a dynamic adjustment of the trigger button resistance. Two user studies evaluated their effect on the perception of virtual weight and the benefits and limitations of this novel approach.

2 Related Work

Conveying physicality in VE has been an interest in the field of HCI since decades [10]. The aim is to achieve a better and more natural interaction by providing haptic sensations for shapes, surface textures, weight or compliance. With the increased interest in VR interactions, provoked through the release of different consumer VR systems, a more realistic experience is additionally emphasized to improve the sense of presence in VR. Resembling the perception of physical characteristics involves various sensory modalities and requires multimodal sensory input from the technology.

However, the current hardware limitations of standard VR settings lack the ability to provide users with a rich haptic sensation. During an interaction with a physical object in RL two main sensory information are provided: tactile and kinesthetic information [10]. Tactile information occurs during touch and is often substituted with vibrations in current consumer VR controllers as the ones from HTC Vive or Oculus Touch do [53]. The required actuators are small, lightweight and easy to integrate into handheld devices. Kinesthetic information such as the pull of gravity or inertia is experienced during a manipulation of an object in RL. These cannot be rendered by the controllers since they rely on directional forces which are difficult to implement due to the absence of external forces in a handheld device.

To address the need for haptic stimulation in VR and to overcome the described hardware limitations a diverse range of techniques was proposed in academic research. They mainly focus on the visual and haptic sense and the interaction between both. This chapter outlines the proposed techniques for conveying physicality of virtual objects.

2.1 Physical Probs

Using physical probs offers the ability to easily provide realistic haptic feedback. Virtual objects within a VE are mapped to physical replications in RL at the same position. Touching or lifting a virtual object results in performing the same action with the respective physical prop. This provides users with a realistic and comprehensive sensation since both the visual and haptic sensory information match [29]. Augmenting the VE with these physical counterparts has shown to increase presence [30] while the shape of the prop has a higher influence on the illusion than the materials [70]. To make physical probs more dynamic and adjustable for different virtual shapes in VR, robotic assembly systems were proposed [90]. However, providing a counterpart in RL for every task in VR involving contact with a virtual object is impossible. Changes within the VE need to be replicated in the physical clone which is time consuming.

2.2 Pseudo-haptics

Another interaction technique to simulate haptic properties is pseudo-haptics [44]. Pseudo-haptics combine visual feedback with passive haptic feedback to create a haptic illusion. The effect relies mainly on the software side by rendering different visual information and introducing conflicts between the visual and haptic sense. Because of the often observed visual dominance in VR, its modification influences the haptic perception of a virtual object.

The effect was first observed by Lécuyer et al. in 2002 where participants successfully discriminated the stiffness between a virtual spring and a real spring [44]. Springs with different degrees of stiffness were visually rendered on a computer screen. Passive haptic feedback was provided by an isometric input device that was unable to produce force feedback. However, in combination with the displayed compression of the virtual springs the subjective perception of the passive haptic feedback changed as well.

Since then the phenomenon was widely investigated [60] and successfully applied to various haptic properties of virtual objects such as texture [42, 43]. A haptic illusion of weight was induced by manipulating the control/display (C/D) ratio to virtual objects [12] and body movements of a self-avatar [32] or by visualizing the gravitational pull through a virtual rubber band between the virtual object and visual cursor [54]. An impression of shape was gained by touching a real object with the pointing finger and visually seeing a different virtual shape [2]. Displacing the virtual representation of users' hands created the perception of virtual forces applied to their hand although no force was rendered [61].

However, these approaches were all applied to a desktop setup where users' movements were translated onto a computer screen. This indirect interaction cannot be compared to the interaction in VR where users directly handle virtual objects. In recent years, various researchers introduced pseudo-haptics to the VR setting. Its benefits were demonstrated for a more realistic perception of texture roughness and hardness through 3D-printed hair structures [11]. The manipulation of the C/D ratio between users' hand movements and the rendered position in VR also induced an impression of weight [64]. During the experiment participants lifted two identical wooden boxes. An increase (decrease) in the offset for heavier (lighter) virtual boxes resulted in an amplification (compression) of users' actual hand movements. This affected the subjective perception of the boxes' weight. The effect is illustrated by Samad et al. in Figure 3. Others demonstrated the combination of pseudo-haptics with a standard VR setup. The impact on the perception of weight by controlling the C/D ratio of hand movement was also achieved using a standard VR controller [63]. Another approach utilized the controller in combination with vibration and visual feedback to communicate kinesthetic feedback [62].

FIGURE 3 Illustration of applying pseudo-haptics for weight perception in VR. The manipulation of the offset between the rendered hand position and the actual hand movement lead to an impression of different weights [64].

Pseudo-haptics in combination with the idea of physical probs have also proven to induce a haptic sensation. The technique of haptic retargeting allows the mapping of multiple virtual objects to the same physical prob. Reusing the same prob overcomes the previously described challenges to provide an endless number of counterparts to map all possible virtual objects. The technique was introduced by Kohli [38] in which the visual information dominates the proprioception. Warping the VE induces a subconscious adaption of users' hand movements. This redirects their hand back to the same physical prob while visually touching objects at different virtual locations. Since then, the technique was further explored and it was demonstrated that users adapt quickly to the mismatch between visual and proprioceptive information [22, 23]. It was used for a semi-automated system to enhance haptic perception of military training systems [37] and Azmandian at al. applied the effect to provide haptic feedback for multiple virtual cubes by one single physical cube [1]. Participants successfully stacked the virtual cubes in VR but always grabbed the identical physical prob in RL during the task. Another approach predicted users' targeted touch locating based on the gaze to redirect the hands to an appropriate spot on the passive prob [7].

The techniques of pseudo-haptics and haptic retargeting allow an easy integration of haptic sensations and avoid the complexity and costs for haptic devices. Nonetheless, the effect is limited in providing a rich haptic sensation since there are no distinguishable haptic stimuli applied.

2.3 Haptic Devices

Haptic devices allow a much more versatile application but require at the same time complex systems with various motors and sensors. They aim to render appropriate sensory input to resemble a realistic sensation of physicality of virtual object. Designing those devices relies on the understanding of the human haptic system. Extended research in human haptic perception in RL reveals the complexity of the sensory information during the interaction with a physical object and demonstrates the challenges for the technology [6, 10, 22]. Based on the interaction task different sensory processes involve various subsystems such as the mechanical, sensory, motor and cognitive system [10]. For example, to successfully perceive the shape of an object with the finger pad the human hand performs a complex mechanical behavior. The ability of the skin to register compliance and friction collaborates with the sensory and motor capabilities of the hand. Merging all sensory information enables the hand to glide over a shape without losing physical contact but to control the applied pressure at the same time to avoid any damage to the object.

Despite this wide range of involved sensory information, focusing on the key inputs for the sensory system can simplify the technical implementation and might still provide an appropriate haptic feedback. This consideration finds its application in many proposed haptic devices. They offer a wide range of haptic functionalities by rendering e.g. vibrations or kinesthetic forces. Various types of haptic devices exist. Grounded devices [50] for desktop settings offer the advantage of rendering external forces. However, they considerably limit the range of motions.

2.3.1 Wearable Haptic Devices

Wearable haptic devices such as exoskeleton gloves overcome those restrictions and allow users to freely move around within a defined tracking space. They provide a more natural and direct interaction by tracking finger and hand postures and translating them into the VE. A wide variety of proposed devices render force feedback to the fingertips and palm to simulate a sense of touch [3, 5, 23] or additionally provide tactile feedback [39]. *FlexiFingers* utilizes passive haptics to create a sense of stiffness for virtual objects [2].

A different implementation for wearable haptics utilizes electrical muscle stimulation (EMS) that induces actuation of users' muscles to render tactile feedback. Based on the interaction with the virtual object the electric stimuli are applied to the respective area of the body. Lopes et al. rendered EMS at users' arms to prevent them from passing through virtual walls allowing users to perceive the solidness [48]. They also simulated the weight of a grasped virtual object by inducing a downward movement of users' arms. In combination with a magnetic actuator tapping the skin EMS provided a haptic sensation for virtual forces applied to users [47]. Others used an additional mechanical stimulation and influenced the sensation of friction and roughness [87].

To produce a sense of weight *GravityGrabber* generates a deformation of finger pads at the index finger and thumb [51]. Another device induces skin deformation to scale inertial forces which are perceived when moving objects through space [74]. *Grabity* renders different haptic feedback to simulate grip forces and a sensation of weight [8]. The device is mounted on the thumb, index and middle finger and renders kinesthetic forces during a grasp motion by constraining the movement of the fingers. In addition, asymmetric vibrations of voice coil actuators stretch the skin at the fingertips to convey a pull of gravity.

Nonetheless, since wearable haptic devices track the movement of users' arms, hands or fingers by placing the structure on the body these setups can sometimes feel cumbersome or uncomfortable.

2.3.2 Handheld Haptic Devices

This disadvantage is overcome by handheld haptic devices. These can be easily and quickly grabbed by users and do not physically restrict their movements. In recent years, the development of handheld haptic devices has received considerable attention. Various systems were proposed that render haptic feedback to enable a more realistic perception of virtual objects in VR. For example, *CapstanCrunch* allows to feel rigid and compliant objects and *TORC* creates a haptic sensation for texture and compliance. The proposed VR controllers *NormalTouch* and *TextureTouch* render shape and texture through haptic feedback at users' index fingers[4]. Tilting a platform at the finger pad created a sensation for shape and actuated pins resembled different surface textures. Further examples are explained more in detail in the following paragraphs and shown in Figure 4.

CLAW is a handheld device that integrates multiple haptic technologies [9]. A combination of a servo and force sensor renders kinesthetic forces at the index finger during grasping and touching. This allows to haptically experience the shape and stiffness of virtual objects. An additional voice coil actuator produces vibrations for different surface textures. The controller is shown in Figure 4(A). Another proposed device for surface properties is the *Haptic Revolver* [84] which is shown in Figure 4(E). It renders haptic feedback at the index finger pad through exchangeable haptic wheels. When users touch a surface within the VE the wheel is moved with a servo towards users' index fingers to create haptic contact. Shapes and shear forces that occur during gliding along a surface are rendered by rotating the wheel with a direct current (DC) motor. The haptic wheels are customizable and can provide various textures and shapes. Attaching active electronic components such as buttons, switches and joysticks allow the appropriate haptic feedback for the respective virtual counterpart. The perception of shapes is enabled by the VR controller *Drag:on* [89]. It changes its shape to render dynamic passive haptic feedback through drag and weight shift. The mechanism has two attached hand fans that open or close with two servos as shown in Figure 4(B). This adjusts the surface area of the fans and changes the noticeable air flow resistance when moved through space. Users perceive based on the modified inertia different scales of shapes of e.g. virtual signs. This also resembles different virtual materials e.g. a wooden or metallic shovel or virtual gas flow. Another device that enables shape perception through inertia is *Transcalibur* [69]. The controller has two "arms", each with an attached weight. This is shown in Figure 4(C). To change the 2D shape of the controller both arms are rotated and the weights are shifted along the length. This results in different weight distributions of the handheld device. Moving the controller through space makes the inertia noticeable for users and creates a haptic shape illusion for the currently held

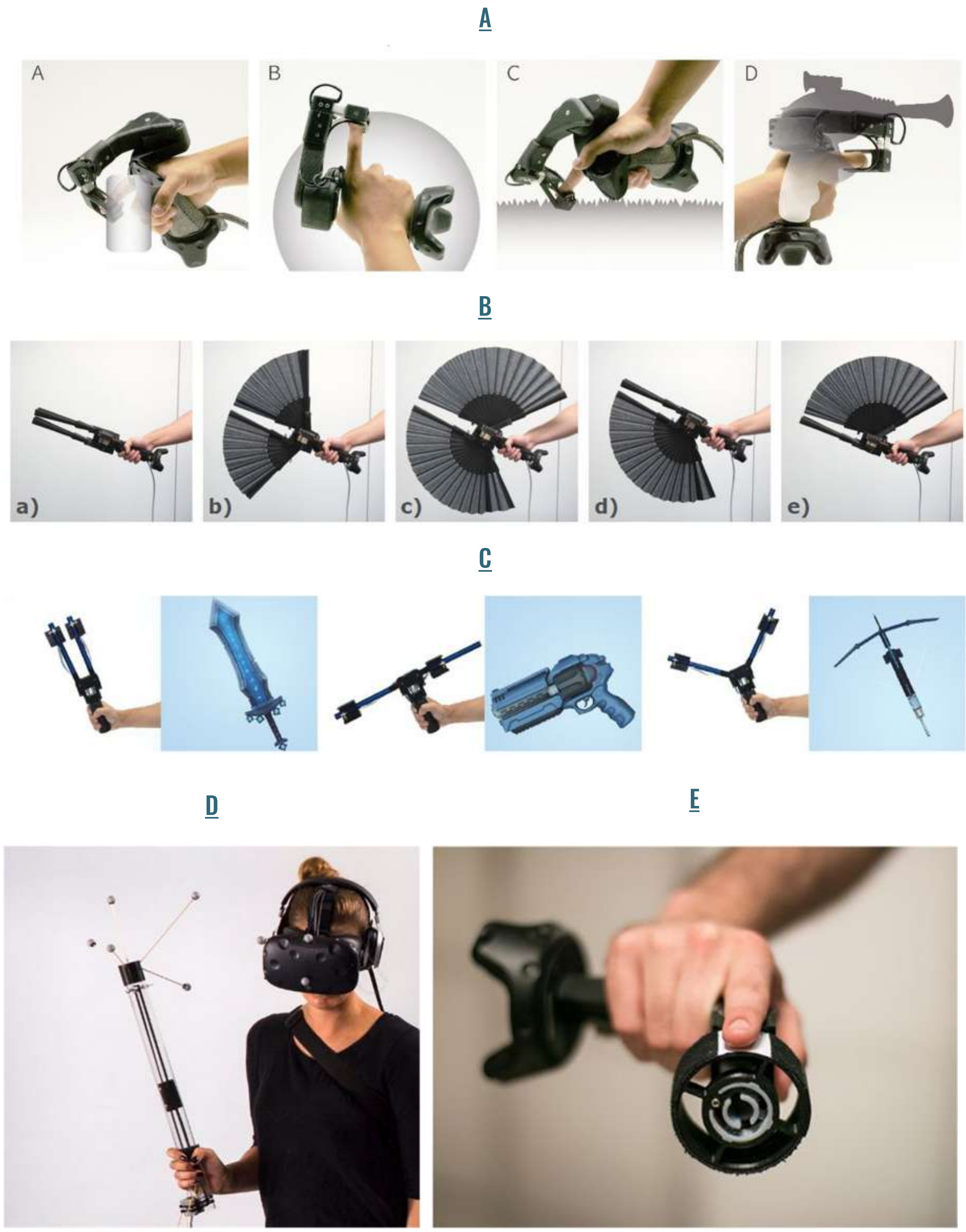


FIGURE 4 **(A)** The multifunctional VR controller CLAW renders kinesthetic forces and vibrations during grasping and touching [9]. **(B)** Shape-shifting VR controller Drag:on adjusts air flow resistance when moved through space [89]. **(C)** Transcalibur creates a perception of shape by rotating two arms and shifting weights [69]. **(D)** Shifty changes its weight distribution and provides dynamic passive haptic feedback [88], figure modified by the author. **(E)** Haptic Revolver enables perception of touch, shapes, shear forces and textures through exchangeable haptic wheels [84].

virtual object. A similar concept is implemented by *ShapeSense* [45] with movable surface elements that increase or decrease the surface area. *Shifty* enhances the perception of virtual objects by changing its weight distribution [88]. An internal weight is moved along the device's length, shown in Figure 4(D), and allows a more realistic perception of objects changing their thickness or length. Picking up a virtual object, the perceived weight is resembled in combination with visual feedback that balances the time of shifting the internal weight.

2.4 Commercial Haptic Devices

An extended number of haptic devices has also been introduced by the industry [83]. More recent examples, shown in Figure 5, are often developed for providing haptic sensations in VR training or haptic prototyping. *SenseGlove* provides force feedback and tactile feedback [68]. *TESLASUIT GLOVE* was recently announced as an addition to the full-body haptic feedback TESLASUIT providing users with sense of touch and texture [79]. *HaptX Gloves* provide a haptic sensation for a wide variety of physical properties such as weight, size, shape and texture [26]. Their design incorporates a silicon-based textile *"microfluidic skin"* with multiple actuators that push against users' skin resembling touch contact. The *Reactive Grip* motion controller from Tactical Haptics resembles touch contact with virtual objects through actuated sliding plates [25].

A B C D

FIGURE 5 Haptic devices introduced by the industry. All figures are screenshots from the referenced company websites. **(A)** SenseGlove [68] **(B)** HaptX Glove [26] **(C)** TESLASUIT GLOVE [79] **(D)** Reactive Grip motion controller [25].

A particular interest for this thesis are the announced game controllers with haptic feedback from Sony and Microsoft. The limited available information about the *DualShock 5* controller for Sony's PlayStation 5 mentions *"adaptive triggers"* as part of the haptic feedback [20]. More details are known about Microsoft's upcoming Xbox One game controller with a force feedback trigger button. In their filed patent from June 2017 and published in December 2018 [18] different technical implementations of a trigger button with *"user-perceived resistance"* are schematically illustrated including a rack gear, force feedback motor or spring. A screenshot from the patent in Figure 6 shows the variant including the spring.

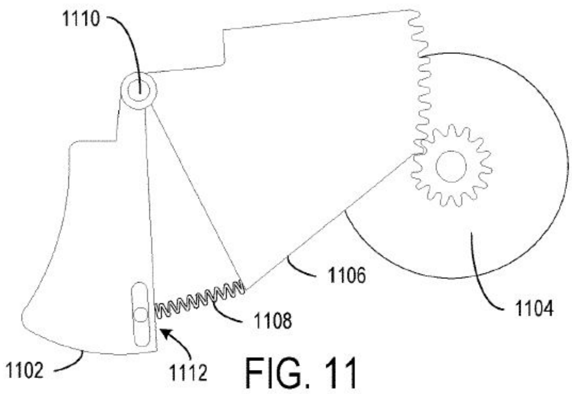


FIG. 11

FIGURE 6 Screenshot from the filed patent by Microsoft for their upcoming Xbox One game controller. This schematic illustrates one of the proposed implementations for a force feedback trigger button including a small spring [18].

3 First Prototype

Based on the previously introduced idea in chapter 1.2, we built a first prototype of a haptic VR controller that allowed dynamic adjustment of the trigger button resistance. Utilizing the trigger button as an established input technique holds the benefit that users are already familiar with the input and do not need to learn a new method.

The typical mechanical implementation of standard trigger buttons utilizes a torsion spring. Pulling the trigger button twists one of the torsion spring's legs around the pivot point, compressing the torsion spring by a few degrees. Its torque exerts a force in the opposite direction, i.e. resisting the finger's pull. Squeezing a safety pin gives a comparable impression of this principle. The second leg of the torsion spring remains fixed during this process and thereby keeping the same spring angles for the released and pulled state of the trigger button.

3.1 Concept

To enable a change in the resistance, a change in the torque must be established before a pull motion. This is achieved by twisting the second leg of the torsion spring and thereby increasing or decreasing the torsion spring's angle. Different angles then lead to a more relaxed or more tensed state. Augmenting the underlying idea, Figure 7 illustrates the basic concept for the adjustable trigger button resistance.

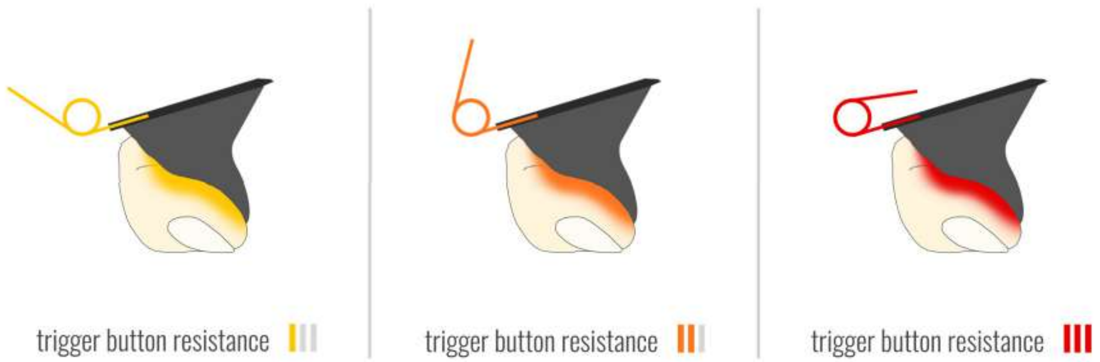


FIGURE 7 A torsion spring with three different angles exerting three different levels of torque. The respective trigger button resistance is a direct result of the torsion spring's modification.

3.2 Construction

The casing of an HTC Vive controller was used to implement the concept described above. It is equipped with a mechanical construction of a trigger button that allows enough room for modifications. Utilizing the case of a standard VR controller for the prototyping process also eliminated the necessary workload of creating a new case for the machinery and ensured a comfortable fit in users' hands. Moreover, it outlines the potential of incorporating the mechanism in other standard VR controllers.

The original construction of the trigger button follows the standard mechanical implementation as described above and can be seen in Figure 8. The released (A) and pulled (B) states of the trigger illustrate the moving part which is controlled by the index finger. Removed from the case, its shape can be identified as well as a rectangular-shaped mounting element (C). A double leg torsion spring ties both together (D) and exerts the default resistance during the pull motion.

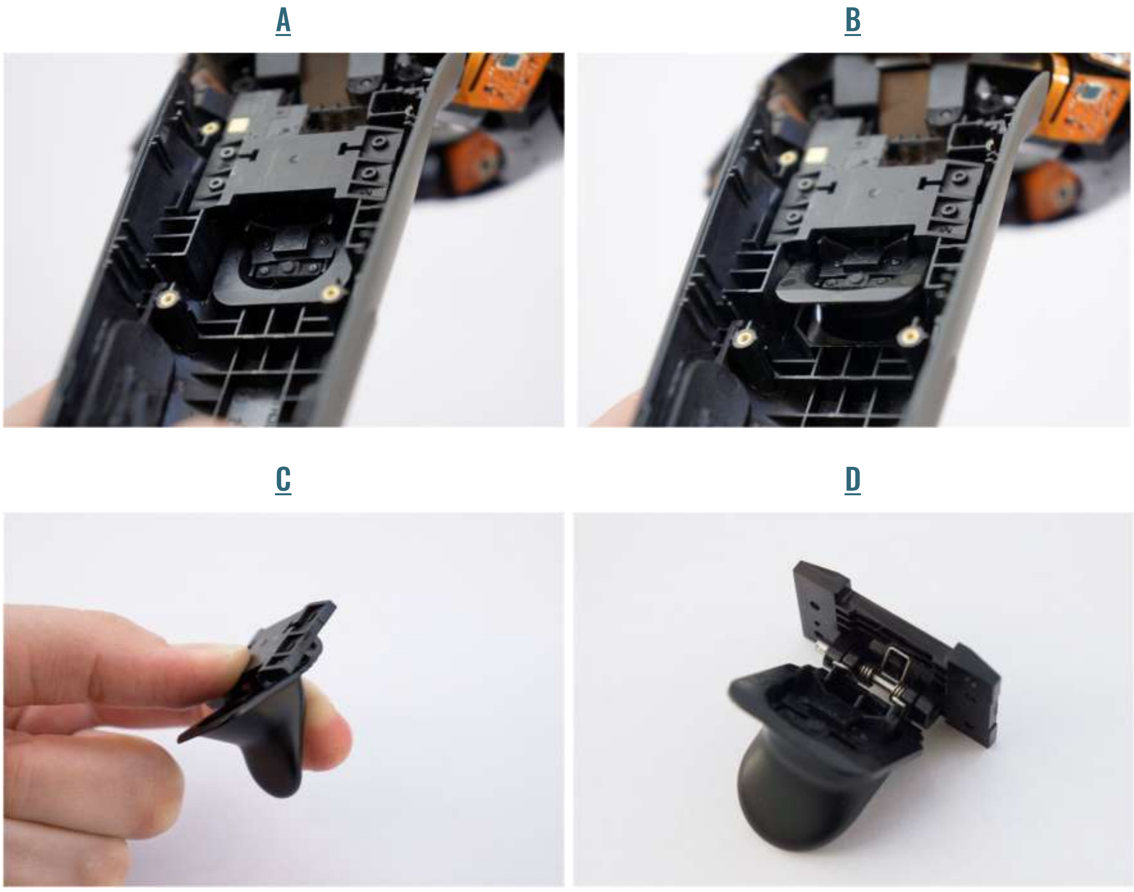


Figure 8 The original trigger button in its **(A)** released state, **(B)** pulled state, **(C)** removed from the controller case and **(D)** a double leg torsion spring inside the trigger button producing consistent resistance.

This type of torsion spring has a small loop in the middle interrupting the coil and two legs on both sides of the coil. This loop leans against the fixed mounting element, keeping the resistance identical for each pull motion. This static construction is illustrated with a simplified torsion spring in Figure 9 (A). Turning this standard trigger button into one with adjustable resistance requires the transformation of the fixed mounting element into a movable element. Its rotation would twist the second torsion spring's leg and change the angle. The concept is shown in Figure 9 (B).

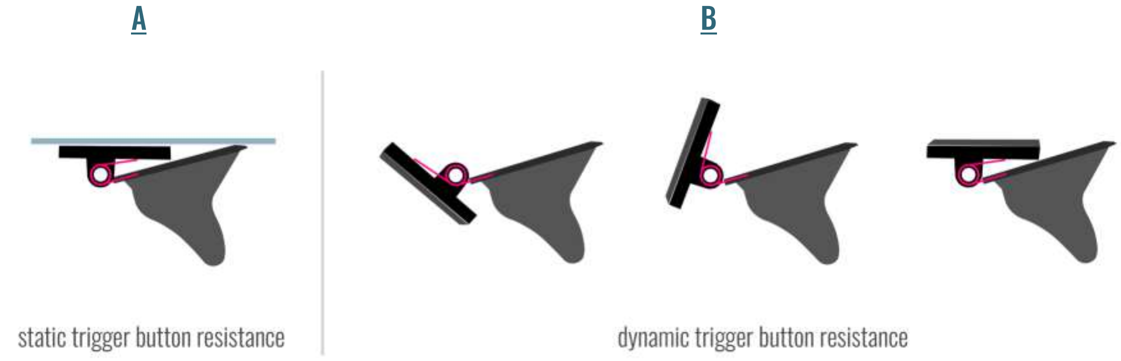


FIGURE 9 **(A)** The trigger button exerts a static resistance. Due to the construction inside the casing, the circuit board (blue) forbids any rotation of the mounting element. **(B)** The rotation of the mounting element allows to twist one leg of the torsion spring. This changes the torsion spring's torque and modifies the trigger button resistance.

Inside the controller's casing, however, two screws on both edges of the static mounting element keep it attached to the frame. Detaching them would detach the whole trigger button. As a solution a gap was cut into the component's center between the screws, leaving both edges attached to the case but creating enough space in between for an additional component. This could then be tilted back and forth rotating around the tension spring's pivot point as shown in Figure 10. (A). The additional component for the prototype was made of brass which provides enough stability for the task. As Figure 10 (B) shows, the shape was grounded into a brass U-profile and cut off later.

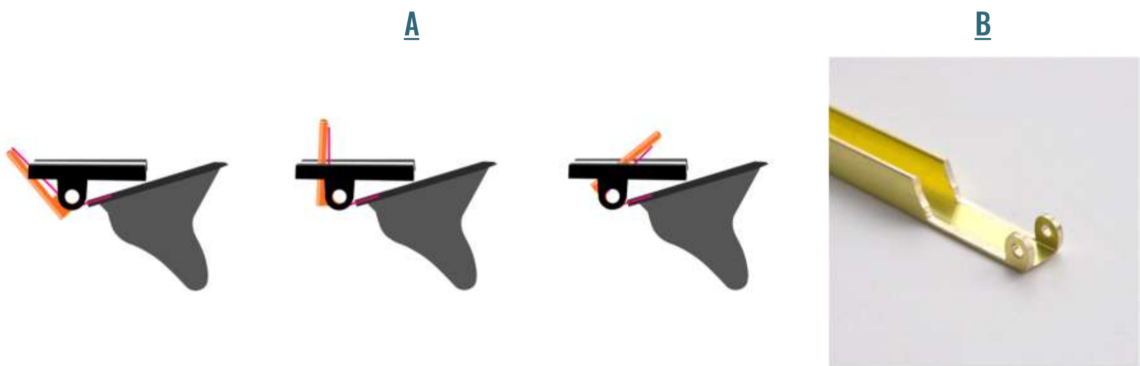


FIGURE 10 **(A)** An additional component (orange) that rotates around the torsion spring's pivot point tilts one spring leg. The fixed mounting element keeps the trigger button attached to the case. **(B)** The additional component grinded into a brass U-profile.

For an automatic tilting, the digital micro servo motor BMS-115HV from Blue Bird was installed [77]. It is a high voltage motor operating on 7.4 V. The technical specifications are listed in Table 1. This motor fulfills all requirements of fast and precise adjustment, enough strength, light-weight and small dimensions to fit inside the case. The specific orientation of the mounting parts of this servo allowed to install it horizontally which ensured a full closure of the upper enclosure part of the case.

Dimensions	23.2 x 10 x 23 mm
Weight	11.3 g
Torque at 7.4 V	540 Nmm
Speed at 7.4 V	0.10 s / 60°

TABLE 1 Technical specifications of the Blue Bird BMS-115HV micro servo [77].

Servos are often used in model building, e.g. to move the steering components of a model airplane. They are therefore available in very small sizes, are light-weight and strong enough to move steering components against the strong airflow during flying. A servo is controlled with angle values, which allows precise adjustment. Other types of motors were also considered, such as DC motors and linear motors. However, DC motors cannot provide precise adjustment, since they only allow to control the rotational speed. Small linear motors can provide enough strength but are moving too slow.

Due to the limited space inside the casing, the servo had to be installed horizontally and a few centimeters away from the tilting element as shown in Figure 11. A perfect frame for its attachment was provided by the original circuit board of the HTC Vive controller. It is thoroughly screwed to the case and can hold the servo in place.

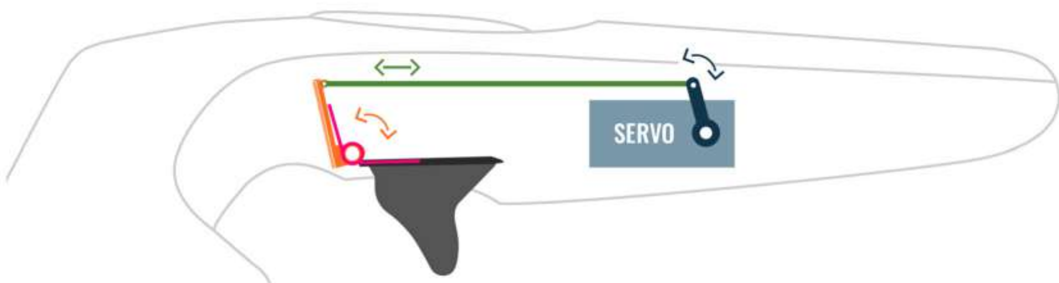


FIGURE 11 Illustration of the mechanism for dynamic trigger button resistance of the first prototype.

Bridging the occurred distance to the tilting element allowed different approaches. Mounting a gearwheel to the servo could move a toothed rack back and forth. Connecting it to the tilting element would allow a conversion of its linear to the rotational movement. The downside of this approach is the intricate installation of a guiding rail for the toothed rack to keep it intertwined with the gearwheel at the servo. An easier solution was to connect both components with a spring steel wire. One end was threaded into the servo horn, the other one into a tiny piece of brass pipe that was soldered onto the upper edge of the tilting element. Figure 11 illustrates the concept, Figure 12 shows the installation inside the casing.

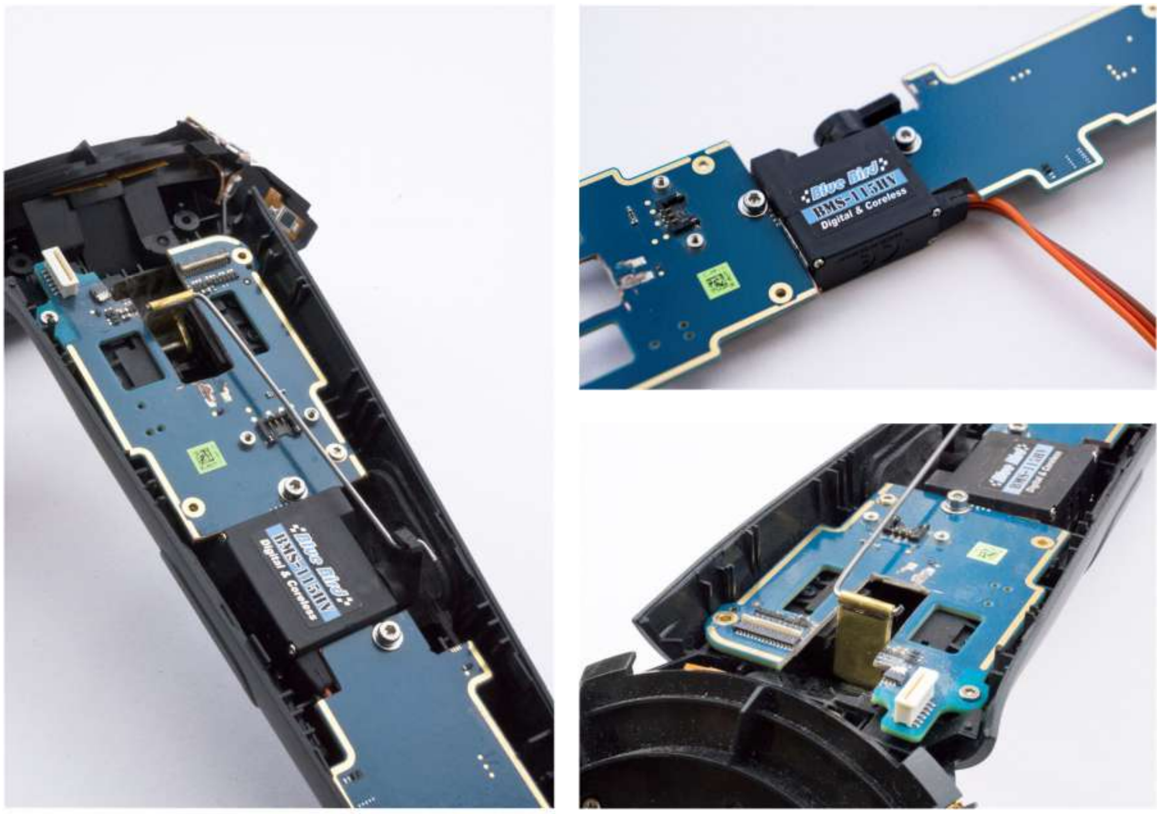


FIGURE 12 Components for the automatic adjustment built into the case. A servo placed in the middle of the original circuit board is connected to the brass tilting element via spring steel wire. The rotation of the servo tilts the brass element.

The maximum rotational angle of the servo in this setup is 100°, allowing the same change in the torsion spring's angle. The original double leg variant, however, has a smaller angle making it too limited for the mechanism. With the additional tilting element on the trigger button, it was also too wide to fit back in. A new torsion spring with a wider angle but smaller dimensions to fit inside was needed.

Various options were investigated regarding size, maximum angle, coil diameter and torque range. Based on these four requirements, the model T-16204R from the factory Gutekunst Federn was the most suitable fit [16]. The diameter of the wire is 0.63 mm and 3 mm of the coil, making it small enough to fit inside the trigger button. The original leg length of 30 mm was shortened to 7 mm which can be seen in Figure 13 (A). The torsion spring has a default angle of 180° and a spring constant of 0.39 Nmm/rad. It exerts a continuous linear torque of up to 29.44 Nmm at a 104° compression angle as shown in the force-displacement diagram in Figure 13 (B).

Installed inside the prototype the torsion spring is preloaded by 50°. This was manually measured with high caution for accuracy. The additional compression of 100° by the servo results in a total compression angle of 150° which surpasses the spring's maximum angle. However, the factory confirmed that the short-term overload of this torsion spring in this proof of concept does not compromise its integrity. The full range of the torque i.e. of the trigger button resistance reaches from 19.27 Nmm to 47.61 Nmm. The values are based on the compression angle set by the servo and the additional 18° compression when the trigger button is pulled. Mentioned resistances in this thesis always include the additional 18°. Since their calculations include hand-measured parameters the values are associated with a small level of uncertainty. The maximum resistance value illustrates an increase by 147%. Research in the discrimination of spring tension showed that humans perceive a difference between 15 and 22% [33]. Informal testing allowed the assumption that the trigger button resistance of the original HTC Vive controller lies in the middle of the prototype's range.

A

B

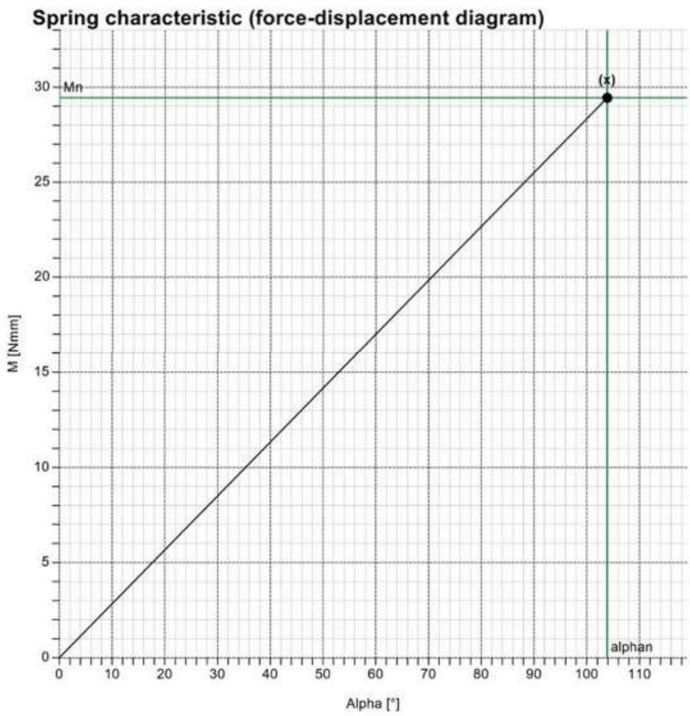


FIGURE 13 **(A)** The torsion spring used for the prototype. **(B)** The force-displacement diagram shows the linear torque range reaching up to 29.44 Nmm at a 104° maximum compression angle. Inside the mechanism, the torsion spring undergoes a higher compression resulting in higher resistance [16].

To dynamically control the servo, the ESP32 microcontroller unit (MCU) was used. It is connected to the servo via three cables (Signal (S), Positive (+) and Negative (–)) and establishes a Bluetooth connection with a PC. An alternative and smaller MCU, ESP8266, was initially tested which could have potentially fit inside the casing. However, this board communicated via WLAN with a delay that was too long for the task of dynamic adjustment when users interact within a VE. The ESP32 is carried in a small bag on the user's back. A cable length of 1.8 m between the casing and the bag ensures a non-restrictive movement.

Both servo and MCU are powered by a 11.1 V lithium polymer (LiPo) battery with three cells each 3.7 V and a battery eliminator circuit (BEC) to keep the necessary power supply of 7.4 V constant. This is particularly important for the servo since the nominal voltage of each cell of the LiPo battery increases to 4.2 V in a fully charged state producing a total voltage of 12.6 V. These fluctuations caused by varying charging levels influences the power supply and might compromise a consistent operation of the servo. Instating the BEC absorbs these fluctuations. Choosing a smaller LiPo battery with two instead of three cells storing a nominal voltage of 7.4 V would have also supplied an appropriate voltage. Due to the described fluctuations and the proximity to the necessary voltage, however, the necessary power supply could not have been guaranteed. Both the battery and BEC are carried in the bag alongside the MCU. All three components are shown in Figure 14 (A).

A B

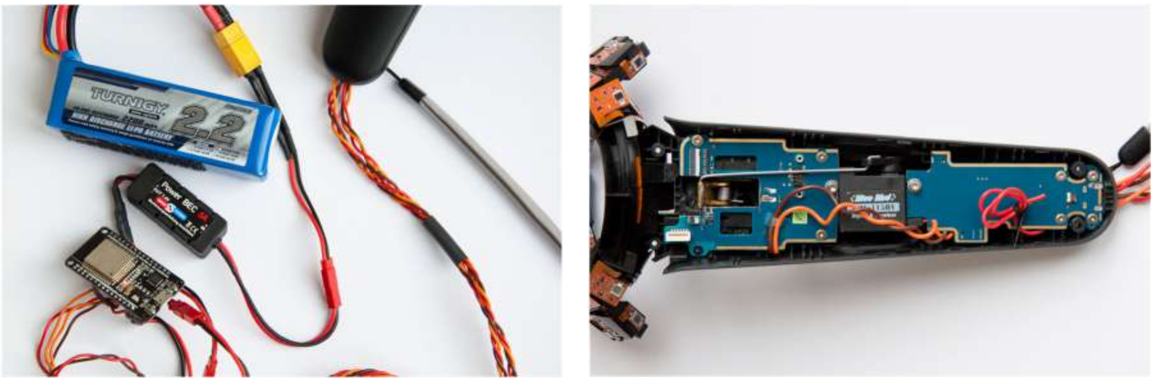


FIGURE 14 (A) Electronical components (LiPo battery, BEC and MCU), that are connected to the prototype's bottom via cable. **(B)** The course of the two cables (brown, orange) inside the casing connecting the mini push button switch on the underside of the circuit board with the MCU.

A crucial aspect for a functioning trigger button is the digital signal when a pull is completed. In case of this prototype it is the indicator for attaching the grabbed virtual object to the virtual controller representation in the VE. For this purpose, the original circuit board has a mini push button switch mounted right above the trigger button. It is pushed when the trigger button is completely pulled. It is also responsible for the familiar final haptic click. To register this crucial signal for the interaction, two cables were soldered onto the exposed poles and connected with the MCU. Their course inside the casing can be seen in Figure 14 (B). The schematic illustration of the overall electric circuit is shown in Figure 15.

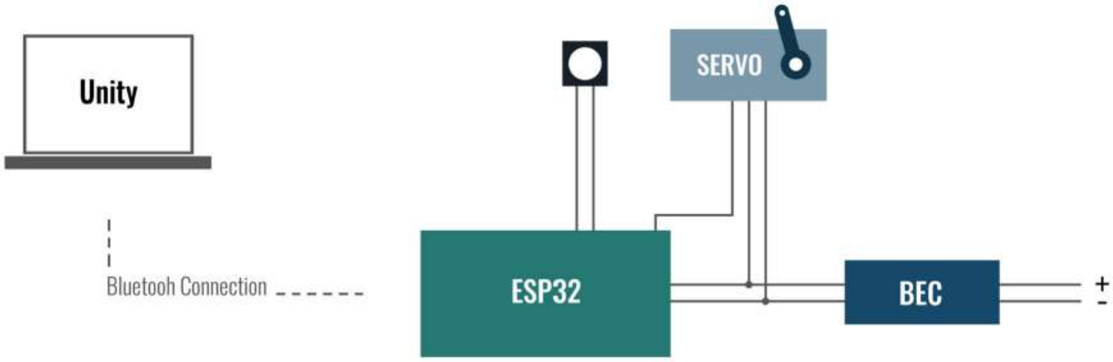


Figure 15 Illustration of the mechanism for dynamic trigger button resistance of the Triggermuscle controller.

The final prototype of the haptic VR controller with a torsion spring mechanism can be seen in Figure 16. A Vive Tracker attached to the controller's top ensures spatial tracking since the original tracking components were removed from the casing. Connected to a solid piece of wood with a threaded nut via a threaded rod, the tracker clings to the casing. The prototype itself weighs 200 g, the same weight as the original HTC Vive controller. The total weight including the tracker (90 g) and its mounting (10 g) is 300 g. The bag carrying the battery (250 g), MCU (10 g) and BEC (22 g) weighs 350 g in total.

Figure 16 The final version of the first prototype with an attached Vive tracker for spatial tracking. The cables are connected to the electrical components inside the bag.

4 User Study I: First Prototype

The first user study investigated the effect on the perception of weight in VR resembled by the adaptive trigger button resistance of the first prototype. Furthermore, it evaluated the benefits and limitations of the taken approach for the technical implementation.

4.1 Study Design

The experiment was conducted in a within-subject design in which each participant performed the same two tasks. The first task explored if participants noticed the change in the trigger button resistance and identified the just noticeable difference (JND). With the second task we investigated the ratio between the resistance intensity and the subjectively perceived virtual weight.

4.1.1 JND Task

In this task participants compared two visually identical boxes and identified the heavier one. Each box had to be moved from its original platform to the one right next to it by pulling the trigger button of the first prototype. Moving a box simulated a natural scenario in which the weight of an object is experienced. The setup in the VE is shown Figure 17.

FIGURE 17 Setup in the VE of the JND task. Both boxes had to be lifted and placed onto the platform right next to it. "HEAVIER"-buttons on the target platforms allowed participants to log in their response.

For managing the trigger button resistances to be tested and determining the JND, this task applied the technique of psychophysical experiments [15, 21]. This area of research focusses on the psychological perception of physical stimuli. Its main objective is to understand the influence of the sensory system on the brain's decision making that manifests in the subjective perception of an objective physical stimulus. Various studies [35, 49, 52, 58] utilize psychophysical testing for the evaluation of haptic interfaces since it allows to quantify the relation between the intensity of the rendered haptic stimulus and its effect on users. Applying this technique for the evaluation of adaptive trigger button resistance gathered data to determine the minimal required change in the resistance to produce a JND in the sensation of VR users.

Psychophysical experiments offer multiple methods for evaluation. This task implements the method of constant stimuli with a two-alternative forced choice (2AFC) paradigm [13, 33]. The method of constant stimuli is considered to obtain the most accurate results [13, 24, 40, 71]. In each trial the same standard stimulus is compared with a member of a set of preselected stimuli. Participants give their response about which stimulus was, in this case, heavier based on their subjective perception. Typically, between five and 20 [13, 71] preselected stimuli values are tested that are equally distributed along the respective physical scale and on either side of the standard stimulus. The maximum value should be chosen to be judged by participants almost always greater as the standard stimulus and the minimal value almost always smaller. During one trial, both standard and comparison stimuli are experienced once and no feedback about the correctness of the response is given.

To explore the full extent of the largest available change in the resistance of the first prototype, the standard resistance was chosen to be at the lower end of the possible stimuli range, similar to [41, 49]. The standard resistance was 19.27 Nmm (0% of the range). Five comparison resistances, listed in Table 2, were linearly spaced with an interval of 25% along the resistance range: 19.27 Nmm (0%), 26.35 Nmm (25%), 33.44 Nmm (50%), 40.52 Nmm (75%), 47.61 Nmm (100%). In this case the 0%-value was expected to be judged lighter than the standard value half as often as heavier. The 100%-value was expected to be judged almost always heavier. Each comparison value was tested ten times each which resulted in a total number of 50 trials, sequenced in a random order. Within one trial the order of standard and comparison stimuli appearance was randomized as well.

Standard Resistance	Comparison Resistances				
19.27 Nmm	19.27 Nmm	26.35 Nmm	33.44 Nmm	40.52 Nmm	47.61 Nmm
0%	0%	25%	50%	75%	100%

Table 2 Trigger button resistances of the first prototype tested in the first user study. The comparison values were linear spaced along the available resistance range. Each trial rendered the standard resistance and one of the comparison resistances.

The decision for the number of five comparison stimuli was based on the resulting total number of trials. Since each value was tested 10 times, a potential fatigue of participants' index fingers had to be considered and prevented.

4.1.2 Ratio Task

The aim of this task was to find a ratio between the resistance intensity and the perceived virtual weight. For this, participants were instructed to fill up a virtual paper plate with strawberries until holding the plate plus strawberries matched their current impression of weight. During each trial one resistance was rendered and three different intensities were tested, 19.27 Nmm (0%), 33.44 Nmm (50%) and 47.61 Nmm (100%). Repeating each value five times participants performed 15 trials in total, sequenced in a random order. Since this task was performed after the JND task, the total number was kept small to prevent index finger fatigue. The virtual setup is shown in Figure 18.

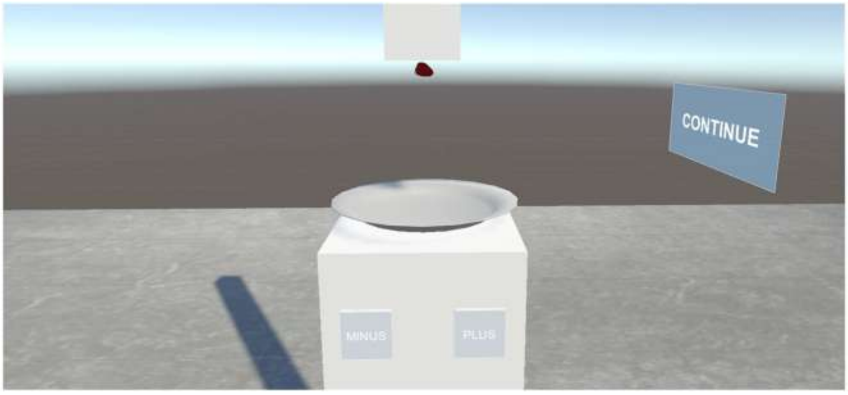


FIGURE 18 Setup in the VE of the ratio task. The plate had to be filled with strawberries until lifting it with the strawberries matched the current weight impression of participants.

Since the ratio task relied on the subjective weight assumption of the virtual strawberry, we did not expect that the absolute amount of selected strawberries would be consistent across participants, but to find a consistent ratio along the intensities of resistance. Therefore, the focus of this task lied on the relative virtual weight i.e. a pattern in the ratio between the different resistances and the absolute number of chosen strawberries. For example, one participant might choose one strawberry for the lowest resistance and seven for the highest. Another participant might select seven strawberries for the lowest and 21 for the highest. The subjective weight assumption about the strawberry is different for both participants but the ratio is the same.

4.1.3 Variables and Measurements

The independent variable in both tasks was the intensity of the trigger button resistance.

The JND task measured the proportion of "heavier"-responses as the dependent variable. The number of correct and false responses were directly obtained from the quantitative data recorded during the performance.

The dependent variable in the ratio task was the number of selected strawberries. In addition, Likert-scale questions (Appendix D) assessed the subjective experience during this task and the raw (non-weighted) NASA TLX [27] rated the task load. The data was of quantitative nature.

Qualitative data was gathered from a demographic questionnaire (Appendix A) and a semi-structured interview. The interview was conducted at the end of each session and guided by a set of predetermined questions (Appendix E). They focused on the subjective impression of virtual weights during the ratio task and observations about the handheld prototype.

4.2 Implementation

The virtual setups for both tasks were implemented in Unity 2018.3 which was also used for pre-generating the randomized orders of resistances values for both tasks.

4.2.1 JND Task

The random orders were produced with a shuffling algorithm. It iterated through an array containing all 50 values (each resistance ten times) and assigned a random position for each member by means of the Unity class Random. The sequences were stored in a file, one line for each order i.e. one line per participant. Based on the inserted participant ID at the beginning of the experiment task the application loaded the respective randomized sequence.

In an iterative process during the task performance that restarted at the beginning of each trial, the standard resistance and the comparison resistance next in line were randomly assigned to the two boxes. When reaching for a box and, thus, the collider of the virtual controller intersected with the one from the box, the respective servo angle for the resistance was sent via Bluetooth to the MCU adjusting the servo. To provide the servo with enough time to adjust before the trigger button got pulled, the default diameter size of the controller's collider was increased by 2.5, provoking an early adjustment.

To ensure that the randomized order within one trial was followed, the second box only appeared after the first box had been placed on its target platform. To guarantee that each resistance was only experienced once, the starting platform disappeared as soon as the box was lifted. This left participants no other choice but placing the box on the remaining target platform. As soon as one box was put down it turned inactive and could not be lifted again. This was communicated by a color change to gray of the box. In case participants dropped a box unintentionally, it was automatically placed on the target platform by the system. After lifting both boxes, on each target platform a "HEAVIER"-button was enabled. The participants touched one button with the controller and were instructed to not pull the trigger button for the selection. The response was recorded and stored in a file containing participant ID, trial number, rendered resistance of each box and the selected box of the respective trial.

Two additional "concealing angles" per trial were sent between lifting the first and second box and after receiving the response. This measure was taken to conceal the two cases in which two identical resistances (both 0%) were compared or in which the last lifted box had the same resistance as the first one of the subsequent trial i.e. no servo adjustment. These cases might carry the risk of influencing participants. The "concealing angles" disguised the scale of the adjustment.

4.2.2 Ratio Task

The appearance order of the resistance intensities was randomized with the same shuffle algorithm as for the JND task and stored in a file. Based on the inserted participant ID at the beginning of the task, the respective sequence was loaded into an array. This was worked through with the increase of the trial number.

In contrast to the JND task, the servo angle was set at the beginning of each trial, not when the collider of the plate was hit by the virtual controller. This was due to the fact, that the plate was lifted multiple times during one trial after adding or removing strawberries to reevaluate the weight impression. Adjusting the servo produces a light vibration as a side effect which appears when the plate was lifted for the first time. However, grasping the plate afterwards would not produce the same effect, since the angle was already set. To avoid this the early adjustment was implemented.

At the beginning of each trial the empty plate had to be lifted to assess its virtual weight. For adding or removing strawberries two virtual buttons ("MINUS" and "PLUS") were provided on the front side of the platform. The virtual buttons were controlled by touching them with the tip of the virtual controller as in the JND task. The trigger button was not pulled. A collision between the respective button collider and the virtual controller either deleted one strawberry from the plate or released a new one from a column hanging right above the plate. Thus, the strawberry would fall onto the plate and ensured that only the plate was lifted with the set resistance. The procedure could be repeated as often as participants liked until they felt confident with the amount of strawberries. At the end of each trial the choice was submitted using a "CONTINUE"-button to the right.

After submission, a "concealing angle" was again sent to conceal the possible case of consecutive identical resistances within the random order.

4.2.3 Bluetooth Connection with MCU

To enable the computer's Bluetooth ability a Bluetooth-USB-Dongle was used. The Bluetooth connection between Unity and the MCU was established with the plugin "Arduino Bluetooth Plugin" version 4.0 by Zaidan [73]. The functionality of the MCU was programmed with the Arduino IDE 1.8.9.

4.3 Experiment

This study was conducted in English over a period of three days. Most participants were expected to speak English, however, the semi-structed interview was hold in the preferred language English or German.

4.3.1 Participants

The experiment was conducted with eight participants (2 females, 6 males) recruited from the university environment. Their average age was 27.00 (SD = 4.10) and the majority (75%) reported previous VR experience.

4.3.2 Procedure

After signing the consent agreement (Appendix B) and completing the demographic questionnaire in Google Forms participants received a short general introduction into the experiment and saw the prototype for the first time. The general research topic about weight perception in VR was mentioned, the trigger button resistance was not.

Prior to both experiment tasks, all participants practiced the lifting interaction in a demo scene with two boxes rendering the same resistances 33.44 Nmm (50%). As previously mentioned in chapter 3.2, informal testing suggested a comparability between this value and the resistance of the original HTC Vive controller. The servo motor was disconnected from the MCU and power supply to avoid any sounds coming from it. To isolate the motion noise of the servo motor during both tasks and avoid potential bias participants wore noise-canceling headphones and listened to neutral music during both tasks. Written instructions for both tasks were provided (Appendix C).

At the beginning of the JND task three unrecorded practice trials guided by visual instructions in the VE were conducted so participants could familiarize themselves with the procedure. During those trials of the JND task it was crucial to avoid resistances that were used during the recorded section to guarantee the exact amount of repetitions of comparison values. Therefore, 40.06 Nmm (70%), 43.03 Nmm (80%), 46.00 Nmm (90%) were used in a randomized order for each participant. Before starting the experiment trials, participants were asked for any unresolved questions.

The procedure of the ratio task was also practiced in three trials guided by visual instructions with a randomized order of the resistance values 19.27 Nmm (0%), 33.44 Nmm (50%), 47.61 Nmm (100%).

After finishing the second task, the NASA TLX was filled out with pen and paper, the Likert-scale questions in Google Forms and the interview was conducted. One session took around 45 min.

4.3.3 Modification of Experiment Tasks

On the second day, our observations, a preliminary evaluation of both tasks and interview answers showed that all eight participants did not notice the change in the trigger button resistance. Participants often reported their developed techniques to assess the virtual weight during the tasks which were independent from the trigger button resistance. They searched for visual cues e.g. letting the boxes fall to identify a difference in the falling speed or grabbing the plate at different positions in the ratio task to observe its behavior. They also stated to use the vibration, a side effect of the servo's adjustment, as an indicator for the virtual weight and they felt *"something moving"* inside the casing.

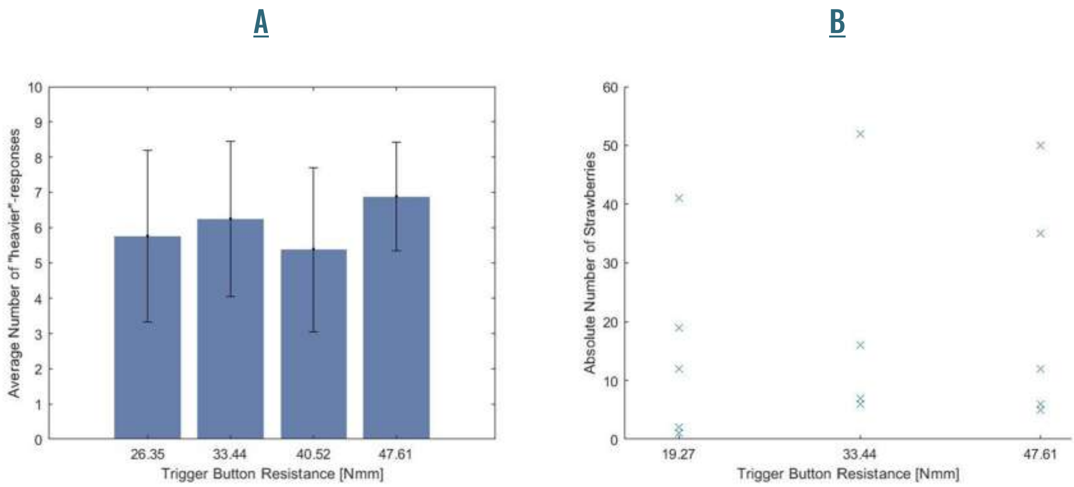


FIGURE 19 **(A)** Average number of "heavier"-responses recorded during the JND task. The maximum possible value is ten due to the total amount of ten trials per intensity level. **(B)** Scatter plot showing the recorded data of one participant from the ratio task.

Figure 19 (A) shows the average amount of how often the four highest trigger button resistances were identified as heavier. The results in ascending order of resistance intensity were 5.75 (SD = 2.43), 6.25 (SD = 2.19), 5.38 (SD = 2.33) and 6.88 (SD = 1.55). It was expected that the number of "heavier"-responses demonstrate an increase with the increase in the resistance intensity. Based on the ten repetitions per intensity level and the selection criteria for the highest resistance, the respective value was expected to reach an average amount close to ten. However, the recorded data did not correspond to the expected perception and no intensity level exceeded a percentage proportion of 75%. This threshold is considered to mark the absolute stimulus value that is perceived equally as the standard stimulus in a 2AFC task in psychophysical testing. The data suggested that the change in the trigger button resistance had no influence on the perceived virtual weight.

The data recorded during the ratio task indicated a randomness for each resistance intensity. The recorded data of one participant is shown in Figure 19 (B) as a representative example for the outcome.

We therefore decided to change the experiment tasks before completing the experiment as originally planned. Based on the described observations, we assumed the visual modality was dominating participants' attention. We simplified the visual input, intending to enable participants' attention to engage more with the haptic feedback at their index finger. The ratio task was removed without replacement.

4.3.3.1 JND Color Task

The modified JND task eliminated the procedure of lifting physical objects that could be examined for visual cues. The new task, referred to in the following as the JND color task, involved a big virtual wall of which the color could be changed by pulling the trigger button. In each trial two colors, magenta and green, had to be activated one after another. The color that felt heavier to activate had to be identified by participants. The chosen colors are known to be distinguishable by people with normal sight and colorblindness [34].

An activated color appeared for as long as the trigger button was pulled and disappeared as soon as the trigger button was released. A few seconds after the first color, a "PRESS" sign appeared informing participants that they can pull the trigger button for the second time. At the end of each trial, two virtual interface buttons in the respective colors appeared and allowed the submission of participants' decisions.

Due to the short-term changes, participants received the instructions for the task only on paper (Appendix G) and not in the VE. However, the three practice trials remained. Due to the cancelling of the ratio task, the interview (Appendix H) was conducted righter after the JND color task. The total duration of the modified experiment was around 20 min. The modified consent agreement is shown in Appendix F.

4.3.3.2 Participants of JND Color Task

The modified experiment was conducted with nine participants who were all recruited from the university environment. One participant misunderstood the task which was confirmed during the post-task interview. This dataset was not included in the analysis.

The remaining eight participants consisted of 2 females and 6 males with an average age of 28.00 (SD = 9.22). The majority was studying (6), two of them in a program not related to the field of computer science. Two persons were employed (2).

All but one participant stated previous VR experience. The level of experience ranged from "less than three times in total" (1), "at least once in three months" (3), "at least once a month" (1), "at least once a week" (1) and "never" (2). Five of them knew the HTC Vive system. Other mentioned familiar VR systems were Google Cardboard (3) and Oculus Rift (3). Two participants used VR as developers, one in the scope of *"studying"*, another one for *"taking part in experiment"*. Five people had previous experience with other game controllers from Xbox (2), PlayStation (4) and Nintendo (2). Their usage frequency ranged from "less than three times in total" (1), "at least once in three months" (3) to "at least once a week" (1).

4.4 Results of Modified Experiment

To get a first overview into how the change in the trigger button resistance influenced the perception, the average amounts of "heavier"-responses for each intensity level were plotted. Figure 20 illustrates the resulting values of 7.00 (SD = 2.00), 7.88 (SD = 2.17), 8.00 (SD = 2.56) and 7.88 (SD = 2.80) for all eight participants. However, when evaluating the "heavier"-responses for the smallest intensity level none of the assessments could be counted as heavier since the resistance was equal to the standard stimulus. Initially this comparison pair was expected to be judged lighter than the standard value half as often as heavier. This discrepancy between the comparison of two identical stimuli and the requested discrimination of the heavier stimulus was a mistake in the study design. To overcome this issue the respective trials were excluded from the analysis.

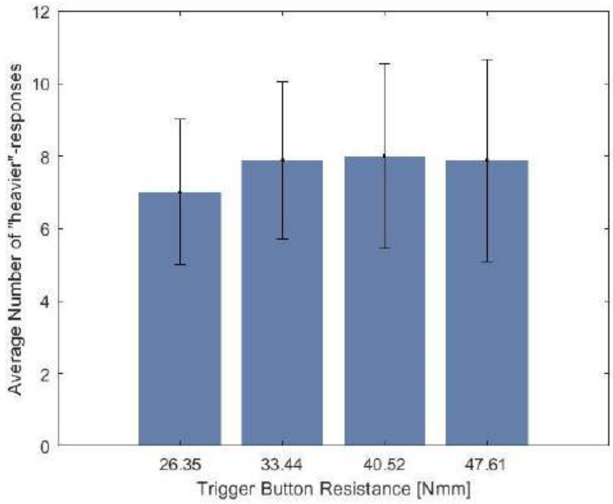


FIGURE 20 Average number of "heavier"-responses for each tested level of trigger button resistance. The maximum possible value is ten due to the total amount of ten trials per resistance level.

4.4.1 Fitting the Psychometric Functions

To achieve deeper insights into subjective perceptions and to determine the JND, a psychometric function (PF) was sampled for each participant. The function estimates the probability of a "heavier"-response over the range of resistances based on the experimental data. The analysis is explained in the following section.

The MATLAB toolbox psignifit 4 by Schütt and Wichmann was used [81] for fitting the PFs in combination with the MATLAB version R2019a. The current version 4 is based on the Bayesian approach which is suited for datasets with a small number of trials [66, 80]. The underlying model in version 4 uses a beta-binomial distribution and extends the standard binomial model of classical PF estimation. It is more robust against overdispersion in the data and more accurate than the previous version 2.5 [66]. The analysis procedure followed the Psignifit Wiki [86] and the accompanying explanations in [66].

Each dataset was fitted using a cumulative Gaussian function which is the default setting of the toolbox. It has the shape of a sigmoid and is identified by a characteristic s-shape. Since the experiment was conducted in a 2AFC discrimination task with a 50% probability for a "heavier"-response, the PF was fitted between 0.5 and 1.0 [36]. It describes, therefore, the proportion of "heavier"-responses above the guessing rate. The absolute resistance value that is perceived identical to the standard resistance is called the point of subjective equality (PSE) or threshold. It marks the midpoint between the minimum and maximum of the function. In the case of the 2AFC method it is marked by 0.75 on the y-axis.

An essential part of underlaying Bayesian statistics is the definition of the prior. In psignifit 4, the default setting for the prior assumes *"that the threshold is within the range of the data and with decreasing probability up to half the range above or below the measured data."* [85]. Therefore, the toolbox expects a set of data that covers the whole PF with at least one trial above and below the threshold.

The data from the experiment, however, did not meet this requirement for every participant. The removal of the trials rendering the smallest comparison stimulus resulted in three datasets missing a trial below threshold as shown in Figure 21. The blue dots mark the trials of the four remaining comparison resistances and the solid vertical line marks the absolute resistance level of the threshold.

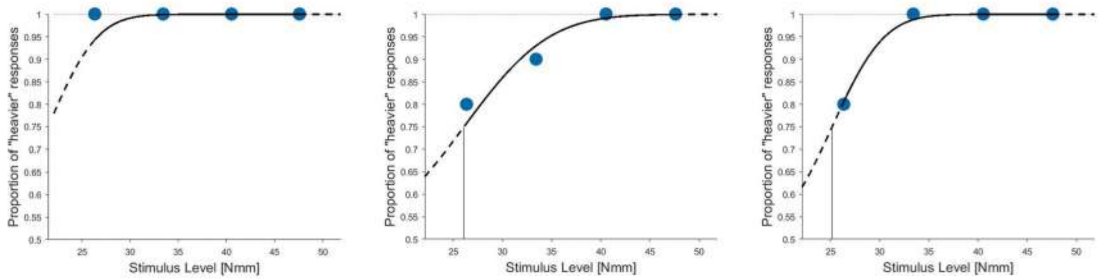


FIGURE 21 Three datasets without a trial below threshold. The x-axis shows the stimulus level [Nmm], the y-axis the proportion of "heavier"-responses.

Taking a look on the marginal plot for the threshold of one of the three participants in Figure 22 (A) also shows how the prior (dashed grey line) decreases within the lower resistance range with posterior probability below 26.35 Nmm. In other words, the prior influences the outcome and makes the threshold below 26.35 Nmm less likely. However, since the recorded data clearly misses a trial that performed below threshold, we assume that the threshold must be below 26.35 Nmm.

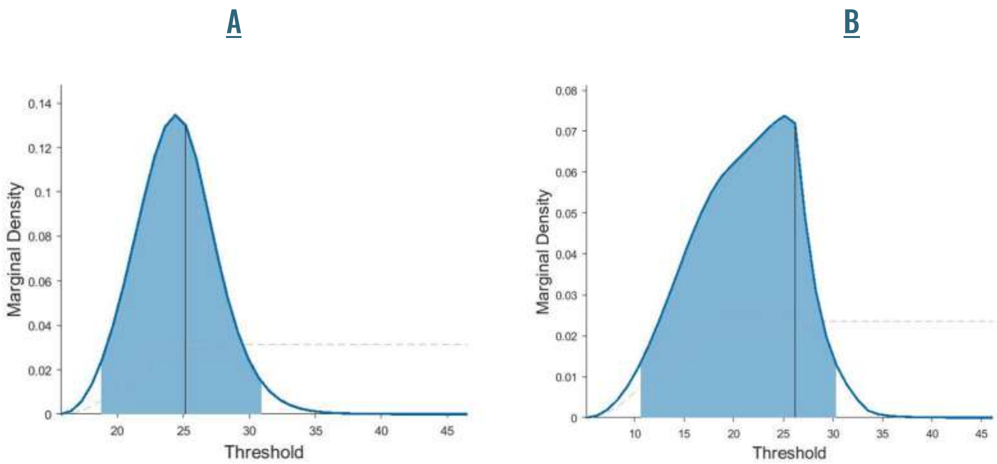


FIGURE 22 (A) Marginal plot of one participant who performed below threshold. The default prior of psignifit 4, marked as the dashed grey line, decreases within the stimuli range of the posterior probability. **(B)** Marginal plot after the adjustment of the prior.

To adjust the prior, psignifit allows users to specify another stimuli range for which one believes matches the assumptions of the toolbox' prior. For the experimental data the upper limit should remain at 47.61 Nmm since the requirement of recording at least one trial above the threshold is fulfilled. However, the lower limit should be shifted from 26.35 Nmm to 19.27 Nmm which is the value of the standard stimulus. Defining the range limit [19.27, 47.61] now expresses our assumptions that the threshold lies in the range between the highest and lowest resistance values used in the experiment. A look at the new marginal plot in Figure 22 (B) shows that the prior stays constantly within the defined stimuli range. The outcome for the threshold is now dominated by the data. With the adjusted prior setting the data of all eight participants was fitted. The results are shown in Figure 23.

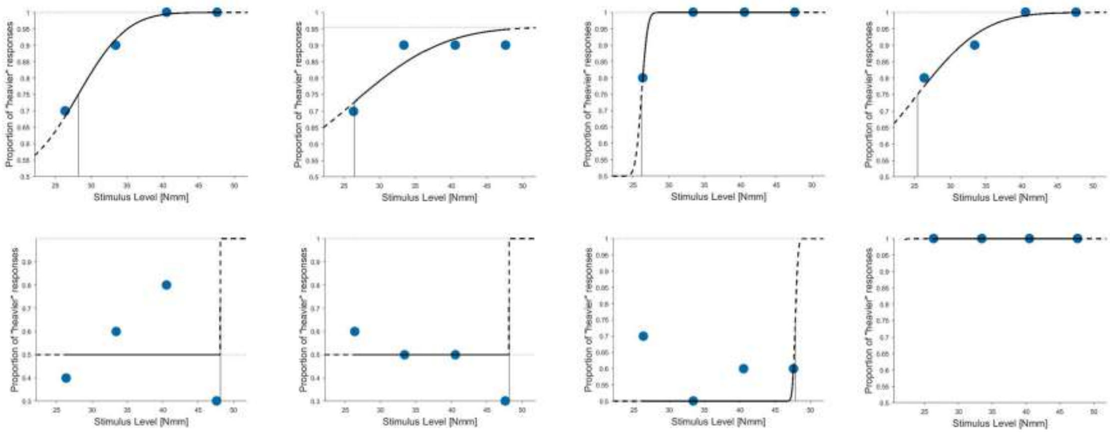


FIGURE 23 PFs of all eight participants with adjusted prior. The x-axis shows the stimulus level [Nmm], the y-axis the proportion of "heavier"-responses.

A first visual evaluation reveals that the last four PFs (second row) do not show the expected s-shape. The corresponding participants of the first three plots stated in the post-task interview that they did not notice the change in the trigger button resistance. The fourth plot belongs to a participant who presumed the prototype to be a haptic controller after reading the general study information. The respective produced data shows no incorrect responses.

To quantify the goodness of fit, the deviance was calculated for all participants. It assesses the proximity to the underlaying model and asymptotically converges to 1.0 for one stimulus block for binomial data. *"A typical cut off of 2.0 [..] is often informally regarded as a still "well behaved" dataset."* according to Schütt et al. [66]. For the whole PF the deviance converges to the total number of tested stimuli, in this case four. The results are shown in Table 3 (A).

	A	B			
	Deviance	JND (Nmm)	WF (%)	PSE (Nmm)	CE (Nmm)
	0.16	3.62	12.83	28.19	8.92
	0.71	3.29	12.43	26.47	7.20
	0.00				
	0.38	4.79	18.85	25.42	6.15
	6.31				
	2.05				
	2.05				
	0.00				
Mean	1.46	3.90	14.70	26.69	7.42
SD	2.13	0.79	3.60	1.40	1.40

TABLE 3 Table rows are in the identical order as the PFs in Figure 23. **(A)** Deviance values of all eight participants. Higher values indicate a higher discrepancy between the underlaying model and the fitted dataset. **(B)** JND, WF, PSE and CE of the remaining participants to assess the precision and accuracy of the sensory system.

Three datasets show a deviance value above 2. This indicates a higher discrepancy between the PF and the underlaying model and suggests that the perception was not influenced by the resistance intensity. The fitting process of two other datasets produced a deviance of 0. Both participants performed perfectly for at least three out of four resistance intensities and did not provide information about their sensory perception near the threshold. All five datasets were excluded from further quantitative analysis due to the described factors.

To measure the precision of the sensory systems of the remaining participants, the JND was determined as well as the PSE and constant error (CE) to assess the accuracy. The CE is the difference between the standard stimulus and the PSE. The JND is defined as the absolute resistance difference between the 25% and 75% points of the PF and is calculated with the resistance values of the respective percentage: (0.75 – 0.25) / 2 [31, 49, 59, 67]. To compare the results of the JND across psychophysical experiments the Weber Fraction (WF) was additionally determined [21]. The WF is named after the German physiologist Weber who discovered that increases in the intensity of a stimulus were *"a constant fraction of the stimulus intensity"*. In other words, the higher the stimulus, the larger the required difference must be to be noticed. This relation applies to various sense modalities and is known as Weber's law.

The results are listed in Table 3 (B). The average JND was 3.90 Nmm (SD = 0.79) resulting in an average WF of 14.70% (SD = 3.60). This level of sensory precision is in line with the reported 15-22% WF in the literature of spring tension discrimination. The average PSE of 26.69 Nmm resulting in an average CE of 7.42 Nmm (SD = 1.40) shows a similar accuracy across all considered participants.

4.4.2 Interview Outcome

After completing the task, all participants reported their subjective impression in the audio-recorded interview. Five participants chose to do their interview in English, three chose German.

The qualitative content analysis of the responses was done by the following procedure: transcription of audio files, categorization of these statements based on the objectives of the questions, comparison of the statements and merging overlapping or identical statements.

4.4.2.1 Trigger Button Resistance

One of the main goals of the interview was to determine if participants self-reported the change in the trigger button resistance and five stated they did. Two of them were excluded from the JND evaluation because of the reasons above. The five participants described their experience as *"the trigger was harder to press"*, *"Der Gegendruck der Taste ist unterschiedlich stark"* [the strength of the trigger button resistance varies], *"Widerstand des Tasters [war] unterschiedlich groß"* [the intensity of the resistance varied] and *"harder to pull"*. One stated that *"I could not convince myself that the trigger would be the same amount of pressure all the time. It really felt like the pressure that I needed was different to pull the trigger"*.

Two described the range of the resistance as *"ganz wabbelig"* [very wobbly] *to "deutlicher Widerstand"* [clear resistance] and as *"a little bit"* to *"much heavier"*. One said that sometimes the difference was obvious and he could immediately decide. Two participants also stated that they did not always feel the difference and that it was sometimes "hard to tell" and that they had to guess. One said it sometimes felt equal and one mentioned he did not feel the difference during the training trials and estimated he started to notice the difference after 5 trials. He also reported that *"you don't feel [the small differences] if you don't actually know how to look for them"*. Two participant who did not notice the change in the resistance stated that they decided based on their general feeling.

4.4.2.2 Controller Vibration

A very prominent point in the interview answers was the vibration of the controller. It was mentioned by all participants as the aspect noticed first about the device.

Four said they connected the vibration to a change in the device and three of them assumed it would change the intensity of the trigger button resistance. Two participants also reported they could feel something changing in the controller and one stated it might have biased his decision. However, the implemented "concealing angles" prohibited a clear pattern of adjustment motion and an assumption about the scale of adjustment

Three participants described that they noticed distinct kinds of vibrations. One described them as sometimes *"stronger"* and *"lighter"*. One participant compared the intensity of the vibration as a light vibration mode of a mobile phone but *"deutlich weniger"* [much less] and another one described them as *"little vibration"*. One participant stated that he liked the vibration overall but that he still *"felt"* the vibration in his hand by the time of the interview. He suggested that longer usage might be uncomfortable.

An unexpected focus regarding the time of appearance of the vibration was reported. Three participants stated that they felt the vibration after activating the first color and after selecting one color at the end of each trial and another one recalled experiencing *"two peaks"*. One participant particularly mentioned he did not feel a vibration after activating the second color. Another one stated that since he felt a vibration after selecting the green colored square, he always selected the green color. One participant stated he felt the vibration from time to time. Each participant who did not notice the change reported details about the appearance of the vibration. Only one of the five participants who noticed the change mentioned something similar.

4.4.2.3 Limitations

No one reported any system errors. However, one participant mentioned he once pulled the trigger button before he saw the respective sign, another one also reported he pulled the trigger button too fast.

One participant noted that it was sometimes hard to feel because he was really fast on pulling the trigger button and that he did not necessarily feel the subtle changes. He stated, *"that is something I got used to, I got more careful when pulling the trigger"*. Another one also recalled that, first he did not understand that he could hold the trigger button for a longer moment and only saw a color for a split second.

One of the participants who did not notice then change in the resistance assumed it was a system error that the vibration was only after activating the first color and making the color choice and not after activating the second color as well.

Although noise-cancelling headphones were used during the task, four participants reported that they heard noise from the controller. One described it as buzzing, another one as a small sound. One participant portraited it as a short and longer constant sound

4.5 Discussion

The analysis of the JND Color task showed an improvement in the perception of the adaptive trigger button resistance compared to the original task. With the removal of lifting virtual physical objects most participants noticed the change and were able to distinguish different intensities. We assume that the simplified visual input enabled a shift in the sensory attention of participants and allowed them to become aware of the haptic input. It is conceivable that the visual input dominated the haptic perception in the two initial experiment tasks. Previous research in pseudo-haptics showed that the visual dominance in human perception [57] occurs in combination with the haptic sense [28]. This effect is beneficial for e.g. the haptic retargeting technique mentioned in chapter 2.2. However, in our case is might have distracted from the haptic stimuli.

The findings demonstrate a big variety in the influence of the trigger button resistance. More than half of the participants noticed different intensities and described a clear distinction between smaller and higher resistances. Some of them reported an initial or occasional uncertainty that might be attributed to the comparisons of highly similar resistances which is intended by the method. However, two participants detected the differences almost perfectly suggesting that the tested stimuli range was too wide for them. One of them immediately asked after reading the instructions if a force feedback controller was evaluated which might have steered his attention towards the controller. Other participants struggled to identify a difference which was confirmed by their self-reports during the interview. We assume that the resistance range was too small for them to be distinguishable in combination with the visual input in VR. This is an unexpected observation since the WF of spring tension discrimination is clearly fulfilled by the controller's resistance range. However, this value was obtained from experiments in which participants were aware of the resistance change. It also leads to the consideration if the servo's vibration might be a distraction as well.

The vibration was mentioned by all participants and some of them associated it with a setting change inside the casing. Further details about its appearance were reported by those who did not notice the resistance change and only one who did notice the change. This could lead to the assumption that the vibration was more likely to be further explored in case of the absence of another noticeable changing factor. Nonetheless, informal testing showed that a light vibration but no variations during the servo's adjustment were noticeable. This is supported by one participant who stated that he based his decision purely on the vibration. This dataset did not show an influence of the intensity of the resistance.

One possible explanation for the prominence of the vibration in participants' attentions might be the proximity of the servo to the holding hand. Due to the construction of the mechanism the position of the servo inside the casing was in the center of users' hand grips. Another cause might be the implementation of additional "concealing angles" to conceal the scale of the servo's adjustment. This resulted in a slightly longer adjustment time since the servo had to set two angles, the "concealing angle" and the one for the next resistance value.

The results demonstrate a new perspective on the haptic discrimination of spring tension in VR. However, at this point no assumptions can be made about the influence on the perceived virtual weight. The obtained results justify further development of the adaptive trigger button resistance to continue the investigation of the effect. Improvements of the implemented technology are expected to provide a better understanding about the wide variety of subjective perceptions.

4.5.1 Implications for Further Development

The evaluation of the first prototype revealed two key limitations of the construction that lead to implications for further development.

To investigate if the tested stimuli range is too small for some users to be perceived in VR a wider range needs to be achieved. This enables the rendering of higher intensities of haptic stimuli and larger differences in the resistance. Furthermore, the vibrations caused by the servo adjustment need to be reduced to limit the potential distraction. Other possibilities for actuation need to be explored that could replace the servo.

5 Second Prototype: Triggermuscle

To overcome the limitations of the first prototype a second haptic VR controller was developed named *Triggermuscle*. It applied a different approach for the technical implementation of adaptive trigger button resistance. This enabled a substantial increase in the resistance range compared to the first prototype.

5.1 Concept

The revised concept utilizes a tension spring, which allows a wider manipulation of the exerted force due to the technical specifications of the spring type. The concept is illustrated in Figure 24. Pulling the trigger button provokes a stretch of the connected tension spring. Thus, the exerted force is perceived at the index finger as the resistance of the trigger button. Increasing the spring's length before a pull motion increases the level of tension. As a result, a higher finger force is required to overcome the respective trigger button resistance.

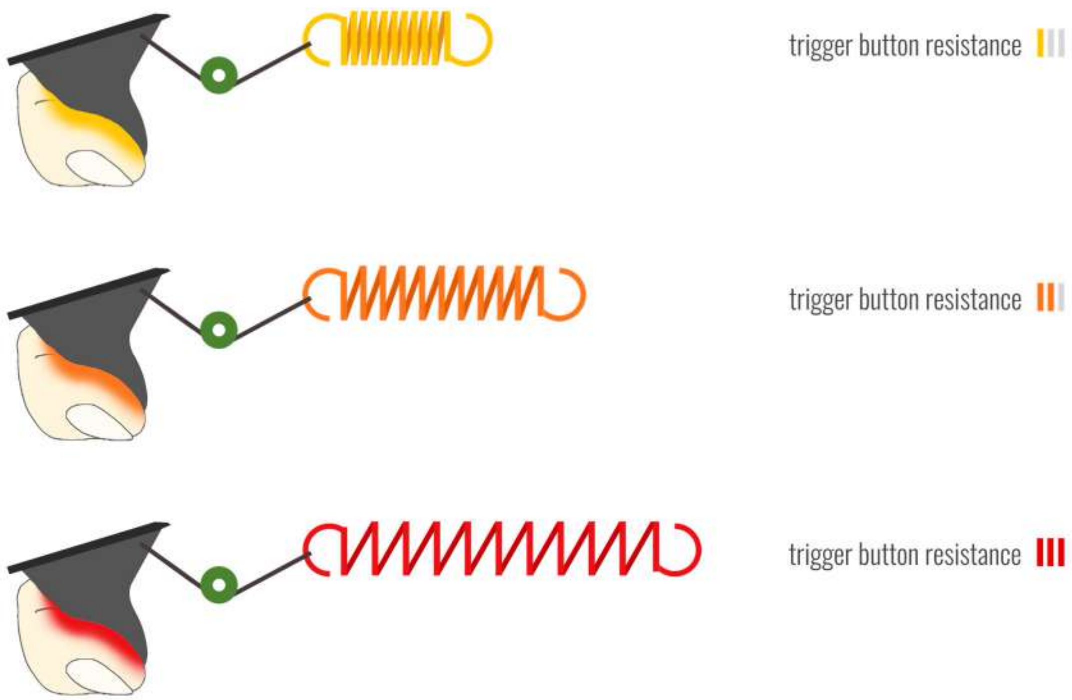


FIGURE 24 A tension spring with three different lengths exerting three different levels of force. The respective trigger button resistance is a direct result of the tension spring's modification.

To avoid the vibration caused by the servo actuating the spring various other approaches were explored. The alternatives utilized different permanent magnets and electromagnets and combinations among them. The trigger button resistance was rendered by the magnetic force in this approach. However, experimental tests showed various disadvantages. While two electromagnets, facing each other and small enough to fit inside the casing, enabled an easy control over the intensity of their repulsion force, the produced maximum force was not nearly strong enough to resist the pull of the index finger. A different idea utilizing the attraction force between an electromagnet and an iron plate revealed a high force intensity. But as soon as both components lost direct contact no attraction force could be registered. A third combination replaced the iron plate with a neodymium magnet to overcome this spatial gap with no attraction force. This resulted in a high attraction force towards the iron core of the electromagnet which locked both components permanently together.

A more promising result was achieved with the combination of two neodymium magnets. Increasing or decreasing the distance adjusted the repulsion force and allowed a high maximum force intensity. However, several limitations regarding the technical implementation were observed. Moving one magnet back and forth required a motor which introduces vibrations again. It also required a strong guidance system that could keep up with the repulsion forces between both magnets. Likewise, a strong attachment to the trigger button was needed to keep the second magnet in place. Tasks that were too complex to implement inside the casing. Another disadvantage concerned the accuracy of the mechanism. The magnetic force decreases fast with increasing distance [75] as shown in Figure 25. Moving the neodymium magnet for 2.5 mm already divides the magnetic force in half. The necessary precision was considered as too challenging.

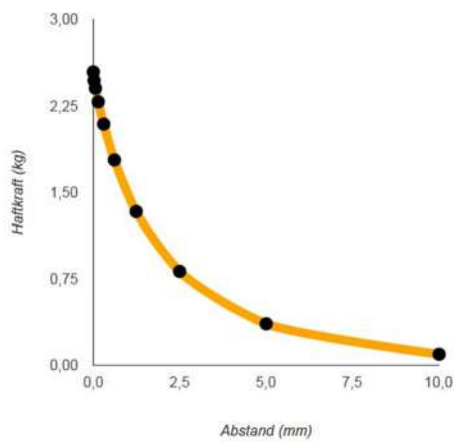


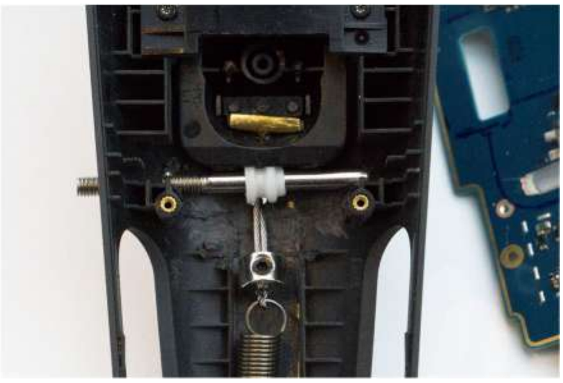
FIGURE 25 The force displacement diagram of two neodymium magnets. It shows the rapid decrease of attraction force in kg with a relatively small increase of distance in mm. The behavior of the repulsion force is identical [75].

5.2 Construction

The mechanism for the revised concept was again built into the casing of an HTC Vive controller. It allowed enough space for the necessary components and provided flexibility for a different servo integration to address the concerns regarding the vibrations.

To achieve the key aspect of the concept i.e. the translation of the spring tension into the resistance of the trigger button both components were connected via a thin wire rope. Despite its small diameter of 1 mm the wire rope is strong enough to handle the forces and inelastic to ensure accurate translation. It was attached to the trigger button with a small self-built anchor that had the shape of a “T”. The crossbar hooked into the trigger button and the “leg” was threaded through a small hole drilled into the button’s shell. The structure is shown in Figure 26 (A). The crossbar was formed with a tiny piece of brass pipe that already found its application in the first prototype for the built tilting element. Here, it was cut in half to create a smaller half shell and pierced at the center. One end of the wire rope was threaded through this hole and glued to the inside of the shell. A simpler approach by tying a knot did not work due to multiple reasons. The wire rope was not flexible enough to form a small and tight knot. In addition, the dimensions inside the trigger button did not provide enough space to accommodate the knot.

A



B

FIGURE 26 (A) The ”T”-anchor hooks into the trigger button. The crossbar is the small brass-colored bar. The movement of the connected wire rope is restricted by a pulley made from plastic to avoid friction between both elements. **(B)** The upper tension spring is connected to the wire rope with an adjusting ring. The lower tension spring shows the first approach using an additional ringbolt.

To connect the other end of the wire rope to the tension spring a different approach was taken. The wire rope was threaded through the spring’s loop and locked in place by an adjusting ring. An adjusting ring has a second hole that allows a threaded screw to reach inside of it. Tightening the screw squeezes both sections of the wire rope and ensures a secure grip. This implementation is applied to the upper spring in Figure 26 (B). The lower spring shows the initial attachment incorporating an additional ringbolt. However, applying this at both ends of the tension spring increased the size by over 10 mm and occupied valuable space inside the casing. Later testing of pulling the trigger button revealed a friction between the casing’s bottom and the adjusting ring. As a solution, the bottom half of the ring was grinded into a flat shape. An additional piece of rubber glued to the casing’s bottom absorbed the remaining friction.

Pulling the trigger button in this state only moved the closer end of the tension spring up and down. To translate the rotational pull movement into the linear stretch of the tension spring, the course of the connecting wire rope was restricted by a small pulley made from plastic. The pulley was hold in place by a long screw connecting both sides of the casing which is shown in Figure 26 (A). This construction was strong enough to withstand the acting forces. The first approach for controlling the wire rope used a small ringbolt screwed through the bottom of the casing. This provided a loop to thread the wire rope. However, tests demonstrated that pulling the trigger button created a noticeable friction between the wire rope and the loop. It also allowed too much wiggle room and was therefore revised.

The dynamic adjustment of the tension spring was established with a servo. Previous research for different motor types during the first prototyping process identified the servo as the most accurate choice. However, to keep the exposure to vibrations during the adjustment as small as possible, the installation into the casing took multiple measures.

Since the mechanism of the first prototype positioned the servo at the center of the handle, it was right in the center of the user's hand grip. To reduce noticeable vibrations as much as possible by increasing the distance to users' hands it was placed at the upper end of the casing. The original trackpad of the HTC Vive controller provided a suitable environment for the installation. This component also yielded further advantages regarding the absorption of vibrations. Since the trackpad provides users with a soft haptic experience during usage, it is not firmly attached to the casing. The flexibility is established by a small piece of foam on one side and two thin plastic "legs" on the other. These "legs" which can be seen in the background of Figure 27 (A) bend when the user's thumb applies force on the trackpad. This loose connection between the component and casing suggested some degree of absorption.

Dimensions	23 x 12 x 25.4 mm
Weight	16 g
Torque at 6.0 V	380 Nmm
Speed at 6.0 V	0.13 s / 60°

Table 4 Technical specifications of the Blue Bird BMS-210DMH micro servo [78].

For actuating the tension spring in this mechanism, the digital micro servo Blue Bird BMS-210DMH was used [78]. Its small dimensions, low weight and high torque qualified this model for the application. The technical specifications are listed in Table 4.

To attach the servo to the trackpad a rectangular hole in the servo's dimension was created. Since the space inside the casing at this location was very limited, the motor was inserted upside down leaving the "body" outside. Figure 27 (A) shows the setup with a cardboard placeholder for the trackpad, Figure 27 (B) shows the bottom side of the setup revealing the servo horn.

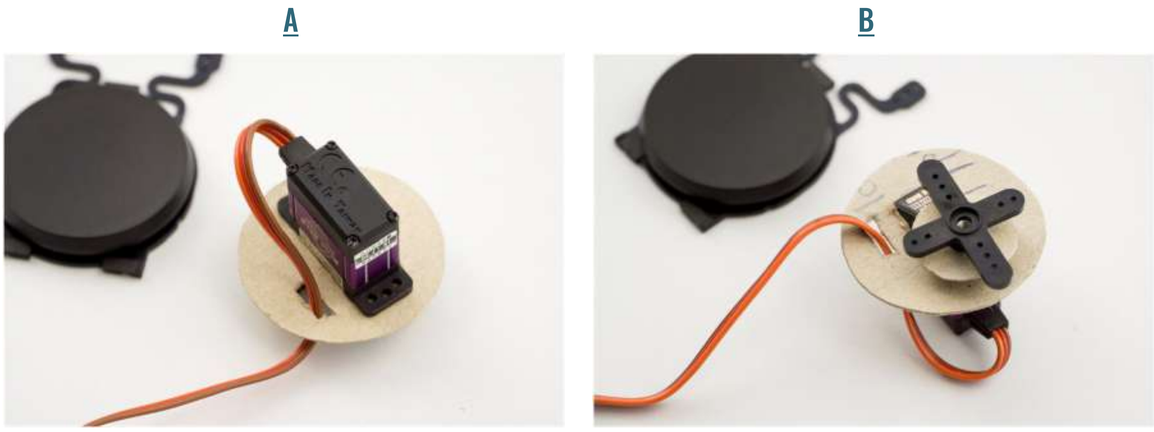


FIGURE 27 (A) The servo is placed upside down and inserted into a cardboard placeholder for the trackpad. **(B)** Perspective of the bottom side of the construction revealing the servo horn.

To bridge the distance between the servo and the tension spring a longer section of wire rope was used. The resulting mechanism is illustrated in Figure 28. Changing the servo's angle rotates an attached pulley. This winds the wire rope and pulls one end of the tension spring. A smaller pully mounted into the original circuit board at the end of the casing restricts the path of the wire rope. The implementation and relevant components are shown in Figure 29.

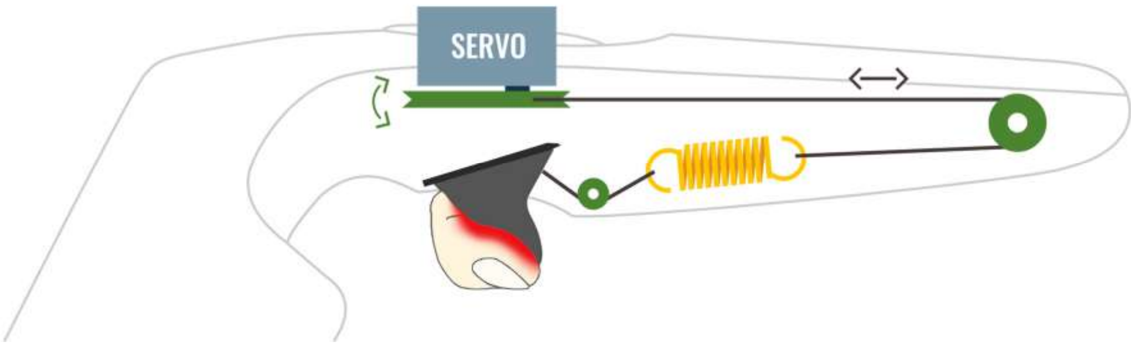


FIGURE 28 Illustration of the mechanism for dynamic trigger button resistance of the Triggermuscle controller.

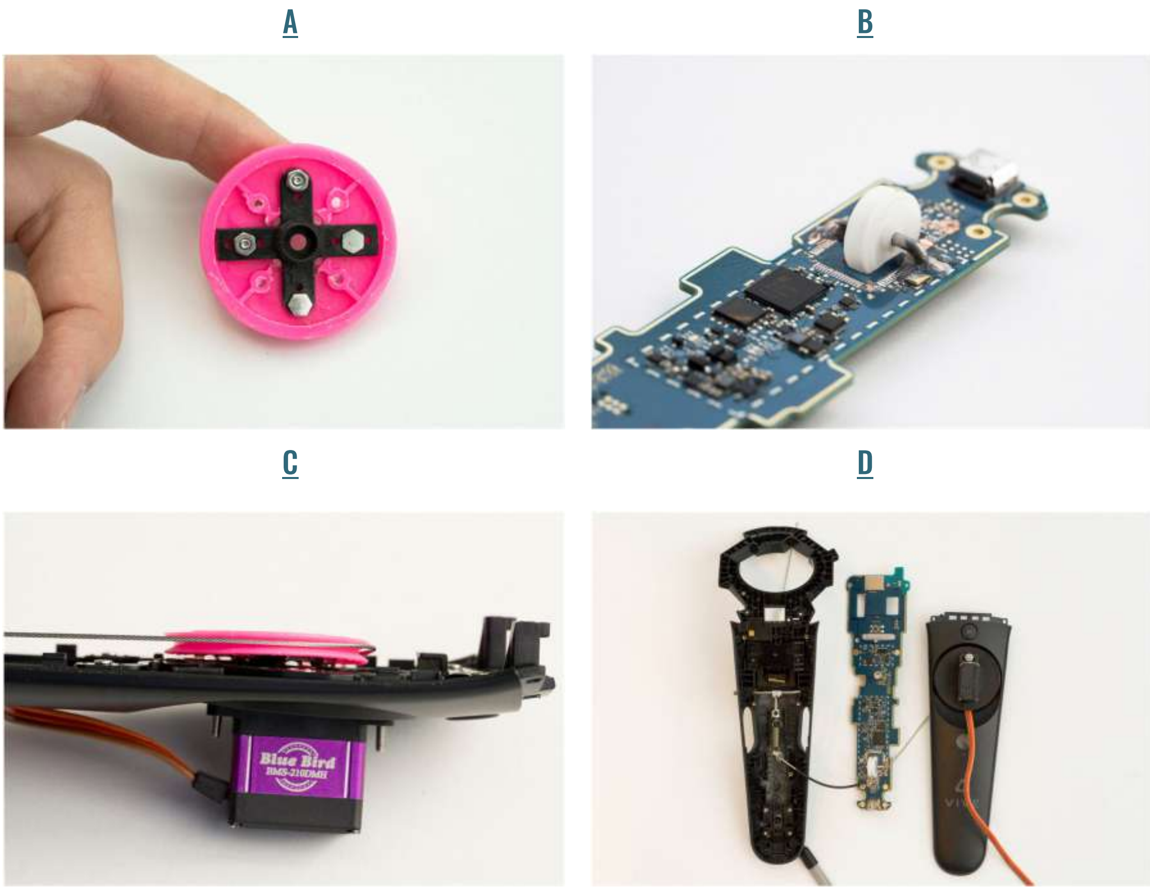


FIGURE 29 **(A)** A pulley made from plastic is attached to the servo horn. **(B)** A smaller pulley is mounted into the original circuit board to restrict the path of the wire rope. **(C)** Installation of the winding mechanism. **(D)** Disassembled controller revealing all connected parts of the mechanism. The wire rope was additionally wrapped with a shrinking tube to avoid friction between the pulley and the material of the rope.

The final tension spring was selected at the end of the construction process since the requirements were dictated by the dimension of the finished controller. The various considered options are shown in Figure 30 (A) and the chosen model is marked with a blue arrow. The best fit was the spring tension Z-057LI from the factory Gutekunst Federn [17]. It provided the largest range of force within the available space while still exerting small forces at the lower range limit. The spring model has a minimum length of 19.80 mm, including loops on both sides, and allows a maximum extension up to 46.50 mm. With a spring constant of 0.59 N/mm and the adjustable length of 26.70 mm the exerted force ranges from 1.33 N to 17.15 N. The respective force-displacement diagram is shown in Figure 30 (B). Installed inside the casing and including the additional 5 mm stretch caused by the trigger button pull, the effective trigger button resistance of the Triggermuscle controller ranges from 4.29 N to 16.36 N. This enables an increase of the minimum value by 281%. In contrast, the first prototype allowed an increase of 147%. The Triggermuscle controller, therefore, exceeds the previously tested range of trigger button resistance by 134%.

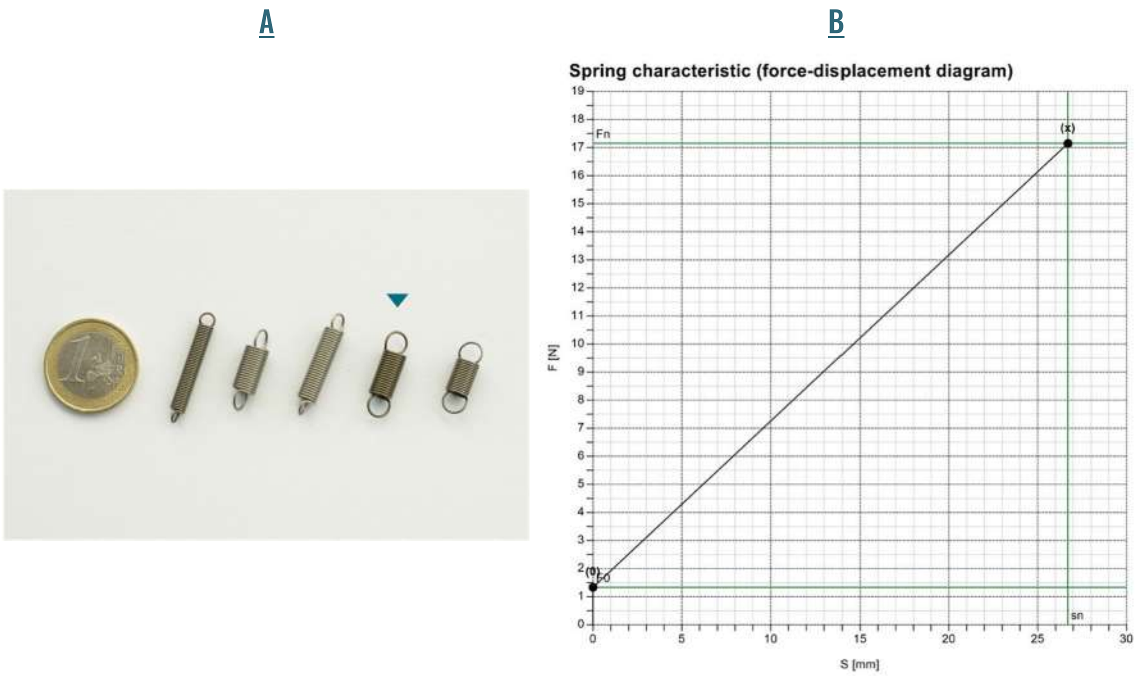


FIGURE 30 **(A)** Considered tension springs. The second last model marked with a blue arrow was used for the Triggermuscle controller. **(B)** The force-displacement diagram of the tension spring shows the linear force range reaching up to 17.15 N at the maximum stretch of 26.77 mm. Due to the space conditions inside the casing, the maximum force of the controller was 16.36 N [17].

Note that the unit for the tension spring force [N] differs from the unit of the torsion spring torque [Nmm]. Nonetheless, converting the values of the first prototype allowed to assess the comparability of both ranges. The converted torque values reach from 2.75 N to 6.8 N. and are illustrated in Figure 31 next to the range of the Triggermuscle controller.

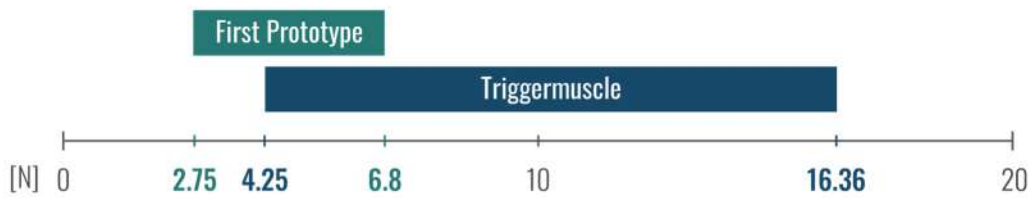


FIGURE 31 Ranges of the trigger button resistance of both controllers. The torque values [Nmm] of the first prototype were converted into [N] for the purpose of comparability.

The electronic engineering was kept identical to the first prototype, except for the BEC which is responsible to keep the power supply constant. This component was replaced by a variant suitable for the required 6 V of the servo. The finished Triggermuscle controller is shown in Figure 32. It has a total weight of 180g which is close to the 200 g of the original HTC Vive controller. With the attached Vive tracker (90 g) and its mounting (10 g) the total weight reaches 290 g. As an additional measure to conceal the servo's adjustment a commercially available silicone sleeve for HTC Vive controllers was wrapped around the handle. The bag carrying the battery (250 g), MCU (10 g) and BEC (22 g) weighs 350 g.

FIGURE 32 The finished haptic VR controller Triggermuscle.

6 User Study II: Triggermuscle

The user study described in this chapter evaluated the revised technical implementation of adaptive trigger button resistance in the Triggermuscle controller. The main objective was to explore if the increased range of resistance leads to a higher rate of users noticing the intensity change. In addition, we investigated if different intensities of trigger button resistances resemble a perception of virtual weight.

6.1 Study Design

The experiment had a within-subject design and implemented the initial JND task of the first user study described in chapter 4.1.1. The value of the standard resistance was 4.29 N (0% of the range). The five comparison values were 4.46 N (2%), 4.79 N (5%), 6.09 N (19%), 8.67 N (46%), 13.82 N (100%), as listed in Table 5. The initial maximum value of 16.36 N was restricted to 13.82 N due to a servo malfunction during testing. This still allows to increase the standard stimulus by 222%. Nevertheless, 59% less than the initial value of 281%.

Standard Resistance	Comparison Resistances				
4.29 N	4.46 N	4.79 N	6.09 N	8.67 N	13.82 N
0%	2%	5%	19%	46%	100%

Table 5 Trigger button resistances of the Triggermuscle controller chosen for the second user study. Each trial rendered the standard resistance and one of the comparison resistances. The comparison values were presented ten times each resulting in a total number of 50 trials.

The selection process for the five comparison values was influenced by the observed variety in the subjective perception in the first user study ranging from influenced perceptions to non-influenced perceptions. To ensure at least one trial below threshold, the 2%-value presented the smallest possible resistance that differed from the standard value and could be set with the servo. In expectation of some participants performing a consistently successful discriminations as in the first user study, the lower half of the available resistance range was covered by three values (5%, 19%, 46%) spaced with an interval of 15% and 30%. The disparity of 1% in the actual percentage values was caused by the resolution of the servo angles. The 100%-value was expected to be judged almost always heavier in virtually all cases, even by participants who might struggle with smaller intensity changes.

6.2 Implementation

For the most part, the implementation was kept identical to the description in chapter 4.2.1. Nonetheless, a few changes were made to address previously identified limitations.

The evaluation of the interview responses of the first user study suggested that the vibrations caused by the servo's adjustment were perceived more than anticipated. In response to this, the "concealing angles" were eliminated to remove the artificial additional adjustments. One of the initial reasons for their introduction was to conceal comparisons of two identical resistances. These cases, however, did not occur in this study since the smallest comparison value differed from the standard value and provoked a servo adjustment. The second reason for the elimination was that the vibrations of the different mechanism of the Triggermuscle controller where more subtle than the ones produced by the first prototype. This was verified by informal testing indicating that decisions based on the vibrations produce a dataset that does not show a relation to the resistance intensity.

Another measure was taken to prevent a misunderstanding of the servo's adjustment as an indicator. In the first study, reaching for the box and therefore intersecting the colliders of the virtual controller and the one from the box provoked the angle change. To remove the vibration of the adjustment from the moment when participants focus on the box and initiate the grabbing action, the adjustment was performed independently. The angles were set at the beginning of each trial and between placing the first box and lifting the second box.

6.3 Experiment

The experiment was conducted over a period of four days in German and English. Participants chose their preferred language.

6.3.1 Participants

21 participants were recruited from the university environment. They comprised of 5 females and 16 males with an average age of 22.67 (SD = 2.78). A large proportion of students (13) and doctoral students (2) studied computer science or a related field, others (6) were from non-related fields.

Most participants (19) stated previous VR experience, however, ten of them with an experience "less than three times in total". The remaining 9 people ranged between "at least once in three months" (4), "at least once a month" (1), "at least once a week" (2) and "once a day" (2). They stated to be familiar with HTC Vive/HTC Vive Pro (11), Oculus Rift/Oculus Quest (9), PlayStation VR (5), Google Cardboard (5) and Samsung Gear VR (4). Their purpose for VR usage showed a large variety. Nine played games, three used it additionally for developing, one for developing and research and three only for developing. Two participants mentioned to watch movies/videos and one additionally for games.

14 participants also reported previous experiences with other game controllers. Xbox (8) was mentioned the most, closely followed by PlayStation (7) and Nintendo (7). The level of frequency using other game controllers ranged from “less than three times in total” (1), “at least once in three months” (3), “at least once a month” (3), “at least once a week” (4) and “daily” (3).

6.3.2 Procedure

At the beginning of the experiment the consent agreement (Appendix I) and demographic questionnaire in Google Forms (Appendix A) were filled out and general information about the research topic was given. The trigger button resistance was not mentioned.

The instructions for the experiment task were provided in written form on paper (Appendix J) and as visual guidance during three practice trials in VR. This allowed participants to familiarize themselves with the procedure. The resistances during the practice trials were rendered with a value of 7.29 N (25%), 7.72 N (29%) and 8.15 N (32%) which did not appear during the experiment trials. The values were distributed around the lower third of the range to ensure an unbiased starting position for the psychophysical testing. We assumed that higher values might affect participants beforehand since we considered higher resistances from the controller as easily noticeable.

After the task completion, the semi-structed interview was held (Appendix K).

6.4 Results

All participants completed the experiment successfully and produced valid data. The average number of “heavier”-responses per resistance intensity is shown in Figure 33. The maximum value is ten based on the total amount of ten trials per intensity level. The resulting values were 6.86 (SD = 2.06), 6.67 (SD = 2.50), 7.86 (SD = 2.13), 7.76 (SD = 2.36) and 7.86 (SD = 2.83).

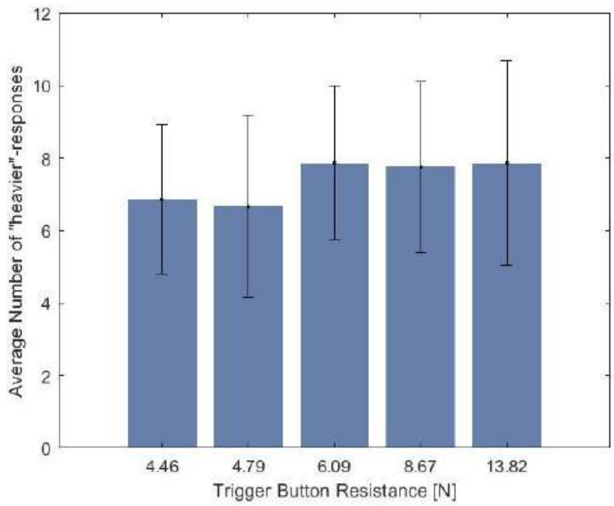


FIGURE 33 Average number of "heavier"-responses for each tested resistance intensity. The maximum possible value is ten due to the total amount of ten trials per intensity level.

6.4.1 Fitting the PFs

Fitting the PFs for all 21 participants revealed five datasets without a recorded trial below threshold (75% in this 2AFC task). Since the MATLAB toolbox's requirements for datasets covering the whole PF were not met, the fitting process considers the threshold to be "*with decreasing probability up to half the range [...] below the measured data*" [85]. However, the threshold is clearly expected to be below the recorded trials. To fix this, the prior was adjusted by changing the lower limit for the resistance range to match the standard resistance, as previously done in the first user study in chapter 4.4.1. We defined [4.29, 13.82] as the new range which expresses our belief that the threshold lies between the standard resistance and the maximum resistance of the tested range. All fitted PFs are listed in Figure 34.

A first visual inspection reveals a large variety in the PFs regarding the expected s-shape. Some indicate a high proportion of "heavier"-responses for most comparison values, others indicate no connection to the level of intensity.

To quantify the goodness of fit the deviance was calculated. It describes the degree of how well the data fits the underlaying model and asymptotically converges to 1.0 for one stimulus block for binomial data. *"A typical cut off of 2.0 [..] is often informally regarded as a still "well behaved" dataset."* [66]. For the whole PF the deviance converges to the total number of tested stimuli, in this case five. The results are listed in Table 6 (A) and lead to the exclusion of 17 participants from further quantitative analysis. The demonstrated perceptions can be divided into three behavioral patterns.

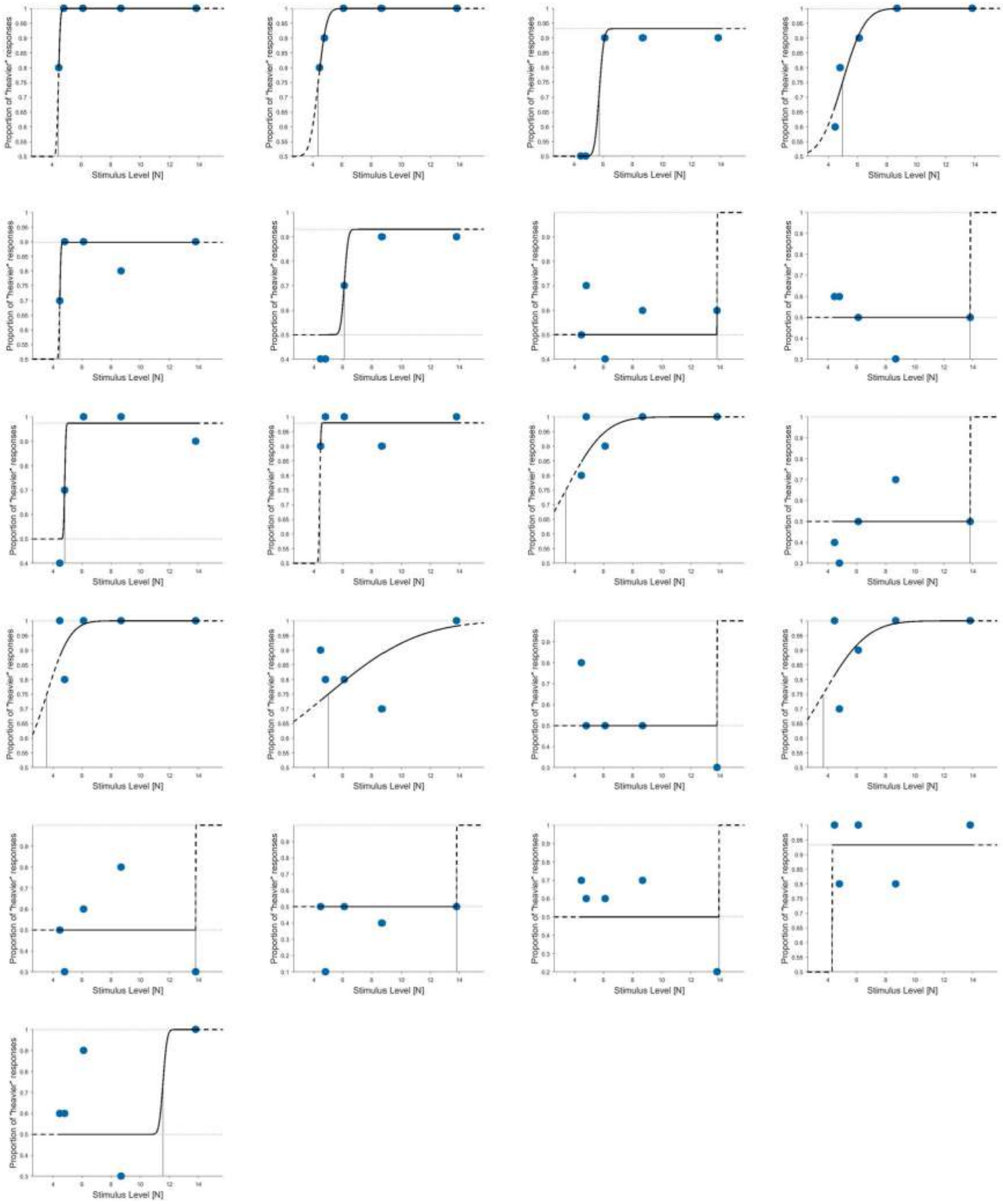


FIGURE 34 PFs of all 21 participants with adjusted prior. The x-axis shows the stimulus level [N], the y-axis the proportion of "heavier"-responses.

The first group consisted of seven datasets that showed a deviance above 2.0 with an average percentage of 50.3% (SD = 5.50) for the "heavier"-responses. This value is equal to the guess rate which indicated no influence of the resistance intensity on the sensory system. Since in our case each comparison stimulus was higher than the standard stimulus, the proportion of "heavier"-responses can also be associated with the success rate. Thus, this group is referred to as "low performers" in the following. The second group included seven participants with an average success rate of 94.30% (SD = 1.80), five showing a deviance above 2.0, two a value of 0 and 0.02. These participants did not produce data about their sensory perception near the threshold. They are referred to as “high performers” in the following. The third group is defined by three datasets without specific characteristic in the success rate but a deviance above 2.0.

	A	B			
	Deviance	JND (N)	WF (%)	PSE (N)	CE (N)
	0.00				
	0.02				
	0.27	0.13	2.23	5.72	1.43
	0.57	0.81	16.27	4.96	0.67
	0.84	0.06	1.25	4.46	0.17
	1.07	0.13	2.14	6.11	1.82
	2.45				
	2.45				
	2.73				
	2.89				
	3.34				
	3.69				
	4.11				
	4.90				
	5.50				
	5.57				
	7.55				
	7.76				
	7.95				
	7.97				
	9.81				
Mean	3.88	0.28	5.47	5.31	1.02
SD	3.01	0.35	7.21	0.74	0.74

Table 6 Table rows are in the identical order as the PFs in Figure 34. **(A)** Deviance values of all 21 participants. Higher values indicate a higher discrepancy between the underlaying model and the fitted dataset. **(B)** JND, WF, PSE and CE of the remaining participants to assess the precision and accuracy of the sensory system.

It is important to mention that the method of psychophysical testing does not aim for a high number of correct responses. It rather requires a decreasing range of correct responses between 100% and 50% (in our 2AFC case) which allows an understanding about the discrimination sensitivity of the sensory system. Excluding many datasets does not provide a direct indication for a successful or unsuccessful perception of virtual weight.

The results of further quantitative analysis are shown in Table 6 (B). The sensory precision of the remaining four participants was determined by an average JND of 0.28 N (SD = 0.35). This resulted in an average WF of 5.47% (SD = 7.21) which is below the reported WF of 15 to 22% in the literature of spring tension discrimination. Nonetheless, the low average is caused by three out of the four datasets showing a value of equal or below 2.23%. Only one dataset produced a WF of 16.27% that is in line with the literature. The CE reveals an average accuracy of 1.02 N (SD = 0.74).

6.4.2 Interview Outcomes

After the experiment task a semi-structured interview was hold. Since most participants were German, 18 interviews were conducted in German, three in English. The analysis of the responses was done by the following procedure: transcription of audio files, iterative categorization of statements, comparison of statements and summarizing overlapping or identical statements.

18 participants stated that they experienced different weights during the task. Two were unable to decide since it was *"hard to tell"* (P9) and one of them stated he *"knew it didn't make a difference"* (P5). One participant reported he noticed differences but did not perceive them as weight (P14). All three participants stated they only perceived some vibrations but did not mention the change in the trigger button resistance.

6.4.2.1 Experiencing Different Weights

Multiple strategies were reported by all participants for distinguishing different weights. To gain a better overview most of the responses were grouped based on the indicator involved in the decision making, the remaining responses were individually evaluated. Furthermore, the statements were cross-referenced with the respective quantitative results to set them into context. This was noted as "high performers" (strong influence by level of intensity but not included in JND calculation because of deviance value above 2.0), "JND performers" (included in JND calculation), "high deviance performers" (deviance above 2.0 but success rate above guess rate) and "low performers" (responses equal to guess rate and deviance above 2.0).

The first established group of mentioned indicators contained five participants who focused only on the trigger button resistance, two participants additionally included vibrations (P6, P4). This resulted in a total number of seven participants stating that they noticed the adaptive trigger button resistance. A group of six participants incorporated only vibrations into their decisions and a group of four participants relied on a combination of two perceived indicators that did not include the trigger button resistance. Furthermore, one participant mentioned only visual input (P1) and the responses of three participants could not be assigned to one of the established groups.

Participants who only mentioned the trigger button resistance reported a changing pressure resistance (P18) ("JND performer") and stated that the trigger button was heavier to press for heavier boxes (P17) ("JND performer"). Grabbing a box felt *"schwerer oder weniger schwer"* [heavier or less heavy] or sometimes equal (P18) ("JND performer") and it was sometimes *"total einfach [...] zu entscheiden"* [very easy [...] to decide] (P6) ("high performer"). Furthermore, pulling the trigger button was described as *"schmerzhafter"* [more painful] and it took *„viel länger"* [much longer] to grab the heavier box (P15) ("high deviance performer"). One participant felt it was *"anstrengender"* [more demanding] and felt more tension in his arm (P17) ("JND performer"). One participant stated he initially asked himself *"Wie passiert das?"* [How does this happen?] before identifying the trigger button as the cause for his sense of weight. However, he stated that he stopped being aware of the change after some time since he felt so immersed into the world (P8) ("high deviance performer"). Another participant also revealed that it took him a moment to realize that the button was lighter and heavier to press. He first assumed the vibration was supposed to be the indicator, but it did not provide him with an impression of lighter or heavier boxes (P18) ("JND performer"). Three people from this group mentioned vibrations as a perceived side effect when being asked about the controller or vibrations specifically (P13, P15, P17) two of them were associated with "JND performers" one with "high deviance performer". However, they did not mention vibrations when they explained how they distinguished weights. One participant stated that he did not notice any vibrations (P8) ("high deviance performer").

Two people explained they additionally included vibrations into their decision. One participant felt it was part of the heaviness and did not find it distracting (P4) ("high performer"). The other person focused sometimes on light vibrations when he was unsure about the weight (P6) ("high performer").

Analyzing the reported decision processes that were based only on vibrations revealed two participants who identified heavier boxes when they felt vibrations and lighter boxes when they felt no vibrations (P3, P7) (both "high performers"). However, one of them stated he did not actually perceive the vibrations as the weight of the box (P3). One person stated he experienced different intensities of the vibration and the difference was sometimes *"sehr groß [...] und sehr gering"* [very big and very small] (P12) ("high performer"). Another participant explained it was easier for him to distinguish when he experienced only subtle vibrations since this felt as a bigger difference in weight (P14) ("high performer"). Two participants provided more details regarding the vibration's appearance. One person described different versions of how the vibration ended and multiple rounds with no vibration (P5) ("JND performer"). Another one felt vibrations when he dropped the box and when he pushed the "HEAVIER"-button to submit his answer (P21) ("low performer"). He also mentioned he felt the vibration even before he dropped the box which was disturbing for him.

One participant assessed the weight of the virtual boxes only based on visual input ("low performer") (P1). He reported he was unsure in the beginning and tried to find a pattern. He thought it was related to how the boxes moved when they fall on the platform. In case the box did not move it felt lighter for him, in case the box was shaking a felt heavier. Grabbing the box also made a difference but he could not identify the reason. He also stated to notice vibrations but could not identify variations in them.

A combination of two indicators which did not include the trigger button resistance were used by four participants. Three of them incorporated vibrations together with visual observations ("low performers") (P2, P10, P19). The behavior of the boxes when they fell on the platform was mentioned as well as vibrations that sometimes appeared and sometimes not. One participant stated he focused on the vibration and perceived a sound when he experienced more vibrations (P9) ("low performer"). To prevent any influence of the sound of the servo's adjustment all participants were noise-cancelling headphones with neutral music during the experiment task.

Three participants demonstrated strategies that did not overlap with others. One participant was unable to identify the reason for his decision and described that it sometimes felt *"deutlich schwerer"* [much heavier] and *"deutlich leichter"* [much lighter] (P16) ("high performer"). One participant reported that it felt *"generell schwerer"* [heavier in general] when grabbing the box and described that it felt as if the weight was illustrated by the controller (P11) ("high deviance performer"). He mentioned a resistance, but specifically said that it was not the trigger button. One participant occasionally noticed a tug when he let the box fall which let him to the impression that the box was falling heavily on the platform (P20) ("low performer").

6.4.2.2 Associations of Box Content

During the interview participants were asked if they had spontaneous associations for the content of the boxes during the task. Nine did not, but twelve reported their imaginations. For them light boxes felt empty and were associated with feathers, heavy boxes felt solid and as if they were filled with sand, stones, gravel, brick or a book. One participant stated he imagined the boxes empty but made from different materials.

6.4.2.3 Realism of Rendered Virtual Weight

To gain insights into how realistic the Triggermuscle controller renders virtual weight participants were asked to rank their experience from one to six. However, since only seven participants stated they noticed the change in the trigger button resistance, it was unclear if the remaining assessments were related to the haptic feedback. Because of that, we decided to only evaluate the qualitative comments that were sometimes additionally provided.

Multiple participants who noticed the trigger button resistance stated that the light boxes felt more realistic than the heavier ones since the virtual boxes seemed too small and the cardboard too weak to hold the imagined weight. One mentioned it felt more realistic towards the end. Two participants stated that it was fun to use.

Participants who reported other indicators for their decision described their assessment as partly realistic and partly not realistic (P1). One expected the boxes to feel lighter because of their small size (P20). Two people did not find the weight realistic in general since they did not feel anything when lifting the box (P9) and one of them mentioned he would have preferred to feel the gravity of the weight when picking the box up (P21).

6.4.2.4 Additional Comments

One participant mentioned that the trigger button was sometimes “sehr schwer” [very hard] to pull but he did not recognize it as an indicator for the weight (P1) (“low performers”). Another person questioned how long the button was in use, since he dropped a box a couple of times because he had not pulled hard enough. He did not mention the resistance for his decision process (“high performers”) (P3). One participant mentioned it sometimes felt as if the handle was increasing its volume but only considered vibrations for his decision (“JND performers”) (P5).

Eight participants stated that they sometimes heard a background sound or humming. Some of them associated it with a change in the controller. One participant mentioned that he would have appreciated if the controller switched the settings when grabbing a box and not after finishing a trial (P13). This implementation was changed for the purpose of the second user study based on the concerns risen in the first user study that a setting change in the moment of grabbing a box might draw the attention to the vibrations.

6.5 Discussion

The evaluation of the Triggermuscle controller showed that the revised technical implementation with a larger resistance range improved the perception of adaptive trigger button resistance. In total, thirteen out of 21 datasets suggested an influence of the level of intensity. In contrast, participants using the first prototype with the smaller resistance range showed no influence performing the identical JND task. The total number of 13 consists of seven “high performers”, four “JND performers” and two additional participants showing an average success rate of 80% and 84%. These two were initially excluded from further quantitative analysis because of their high deviance values for their respective fitted PF. However, their average success rates were above the threshold of 75% in 2AFC tasks. We therefor included them for the part of the discussion. Based on the subjective perceptions of all 13 participants, an increase by 222% of the resistance ensured a 97% probability that users of the Triggermuscle controller perceived the virtual box as heavier. A change in the resistance of 42% still provided a 92% chance to recognize the heavier box.

Most participants stated that they experienced different virtual weights using the Triggermuscle controller and described similar estimates for the absolute weight. Light boxes were imagined being empty, heavy boxes felt as if they were filled with sand or stones. Nonetheless, some participants also mentioned that the virtual cardboard boxes seemed too small and fragile to realistically hold the heavy weight they experienced. Because of that, we assume participants might have been influenced by the visual appearance of the boxes. It is reasonable to imagine that the boxes reach their highest plausible weight when being filled with heavy materials that fit inside the dimensions like sand or stones. However, we consider the adaptive trigger button resistance more as a weight metaphor conveying relative virtual weights. To test this assumption further investigation is needed.

A large variety in the quantitative analysis of the subjective perception was observed ranging from no influence to high influence. This also occurred in the first user study with the modified JND task. The same effect reappeared in the self-reports demonstrating two scenarios of consciously noticing and not noticing the change in the trigger button resistance. This raises the question why these two extremes occur and why many participants did and did not sense the change in the haptic feedback.

Cross-referencing the quantitative data with the self-reports identified that the recorded influenced behavior of the sensory system did not always corresponded to the subjective statements.

Datasets showing an influence belonged to statements mentioning the change in the trigger button resistance, vibrations and a combination of both. Participants who stated to only rely on the trigger button resistance fulfilled the expectations for a decrease in the sensory perception caused by a decrease in the stimulus level the most, three of them qualified for the JND calculation. The best performance was shown by participants reporting the resistance change plus vibration and vibration only. This suggests that the vibration had an impact on the sensory system and lead to a higher discrimination rate. However, five participants of the non-influenced datasets also stated that they incorporated vibrations into their decision and they produced average success rates closely around the guess rate. One possible explanation might be that the sensory systems of the "high performers" perceived the change in the trigger button resistance but the participants did not consciously notice the haptic feedback. This theory is supported by three reported observations which indicate that the sensory system might have registered the resistance change. One participant was unable to identify a reason for his sense of weight and was therefore not focusing on a specific factor. Two others additionally commented observations outside the context of distinguishing weights about the trigger button or a noticeable volume increase of the handle. The self-reports corresponding with a high performance also lead to the assumption that the vibrations might have an additional impact on the sensory system next to the trigger button resistance. “High performers” recorded an average success rate of 90% (SD = 1.0) for the smallest increase in the resistance of 2%. We consider that these participants might have a higher sensitivity towards vibrations and might have been impacted by the small servo adjustment for the small resistance change. Tan et al. describe vibrations as *“one of the most noticeable disturbances in a force reflecting device”* and refer to the high sensitivity towards vibrations [76]. Studies showed a WF of vibrotactile frequency ranging from 3-30% and vibrotactile amplitude produced a WF of 13-16% [33]. This wide range in the subjective perception of vibrotactile frequency might also explain why one participant reported that he did not notice any vibrations, others described them as a side effect and others fully focused on them as an indicator for the virtual weight. In an approach to quantify participants’ exposure to the vibrations we took preliminary measurements. For this, a smartphone (One Plus 5) was attached to the Triggermuscle controller with a clamp and the smartphone application “vibration analysis” [55] was used for measurements. All servo adjustments tested in the JND task were rendered, however, no vibrations were registered using this setup. To clarify the vibration exposure of the Triggermuscle controller further investigations with more sensitive measuring devices are required. Overall the influence of the vibrations on the perception of virtual weight in this study remains unclear.

For answering the remaining question why the sensory systems of eight participants did not show an influence of the level of trigger button resistance, literature proposes multiple theoretical explanations.

Selective attention describes the ability of humans to control the processing of multiple sensory stimuli [72]. Being exposed to many different sensations at the same time is overwhelming or distracting. This mechanism is helpful to focus only on the relevant information that is required e.g. for achieving a task. Extended research showed that humans sometimes direct their attention towards one individual modality and mask others. Regarding the integration of multiple senses, selective attention influences e.g. which stimulus is perceived first during simultaneous exposure. For example, Vogels demonstrated that a visual stimulus was perceived earlier than the haptic one when participants directed their attention towards the visual modality and vice versa [82].

This mechanism of selecting and directing attention might have contributed to the failed perception of the change in the trigger button resistance of some participants. The first servo adjustment appeared even before participants pulled the trigger button for the first time i.e. before they were exposed to the resistance. The vibration might have been a distraction causing a shift in the attention right at the beginning of the task away from the haptic sensation at the tip of the index finger. As a result, the respective incoming information from the index finger might have been judged as irrelevant for the task and was therefore not processed. Since participants were unaware of the change in the trigger button resistance, some might have never become aware because of the vibration. This could also be an explanation why one participant did not recognize his own observations of a trigger button that was sometimes hard to pull as a haptic input for the virtual weight. Overall it is clear that there is no simplistic explanation for the absence of the influence of the trigger button resistance in the sensory perception of some participants.

7 Conclusion

Designing haptic feedback to provide users with a sense of weight in VR is a challenging area in HCI. Various proposed haptic devices often rely on complex systems making them inaccessible for the consumer market. Approaches utilizing current standard VR controllers cannot render forces to the hand and are therefore limited in providing a comprehensive haptic sensation. This thesis addressed the need for a handheld device to simulate virtual weight by augmenting a standard VR controller with adjustable haptic feedback. We introduced adaptive resistances to the trigger button to render different haptic stimuli for different virtual weights. In an iterative process, two prototypes for a haptic VR controller implemented the dynamic adjustment of the resistance via a spring mechanism. The main objective of this work was to investigate if the trigger button resistance can resemble a perception of virtual weight in VR.

The evaluation in two psychophysical user studies showed that participants perceived different virtual weights using the revised haptic VR controller Triggermuscle which renders a larger range of resistance. We therefor confirm the first research question, if different trigger button resistances influence the perception of virtual weight in VR. Since participants also successfully identified heavier virtual objects, we confirm the second question regarding the relation between smaller resistances for lighter virtual weights and higher resistances for heavier virtual weights. Nonetheless, the results demonstrated a wide variety in the subjective perception of the intensity of the resistance. Some participants easily distinguished smaller changes while others did not show any influence of the intensity level. The influence of the vibrations, a side effect of the adjustment mechanism remains unclear. We therefor partially answered the third research question of how can the intensity of the trigger button be quantified and mapped to convey distinguishable virtual weights. Nonetheless, self-reports about the experienced absolute weight showed comparability between statements for lower resistances and respectively for higher resistances. While these reported impressions indicated a possible influence of the visual appearance of the virtual boxes used in the experiment task, they suggested the possibility of using visual input for mapping the level of intensity and the perceived absolute virtual weight.

7.1 Future Work

Continuing the research for weight perception in VR using the Triggermuscle controller proposes multiple directions.

To overcome the shortcomings of the user studies outlined above, we propose to clarify the impact of the vibration exposure on the perception of the adaptive trigger button resistance.

A quantified assessment can help to gain a better understanding about the simultaneous processing of multiple stimuli (force feedback and vibration) by the haptic modality.

Furthermore, additional user studies allow to investigate the role of attention by informing participants about the provided haptic feedback. Other approaches e.g. placing a virtual curtain between users and the virtual object or adding a virtual representation of users' hands focus on the impact of visual input. Mapping virtual objects with a wide range of sizes and materials can reveal the potential of combining the haptic feedback with visual information. This can clarify if the adaptive trigger button resistance can be used as a weight metaphor for conveying relative virtual weights. In addition, providing visual input for other physical properties such as stiffness examines the scope of the applications.

So far, the trigger button resistance was changed before the pull motion. Adjusting the resistance while users keep the trigger button pressed might provide the opportunity to simulate changes in virtual objects.

Lastly, following the development of the proposed game controllers by Sony and Microsoft for their game consoles offers further insights into the application of adaptive trigger buttons.

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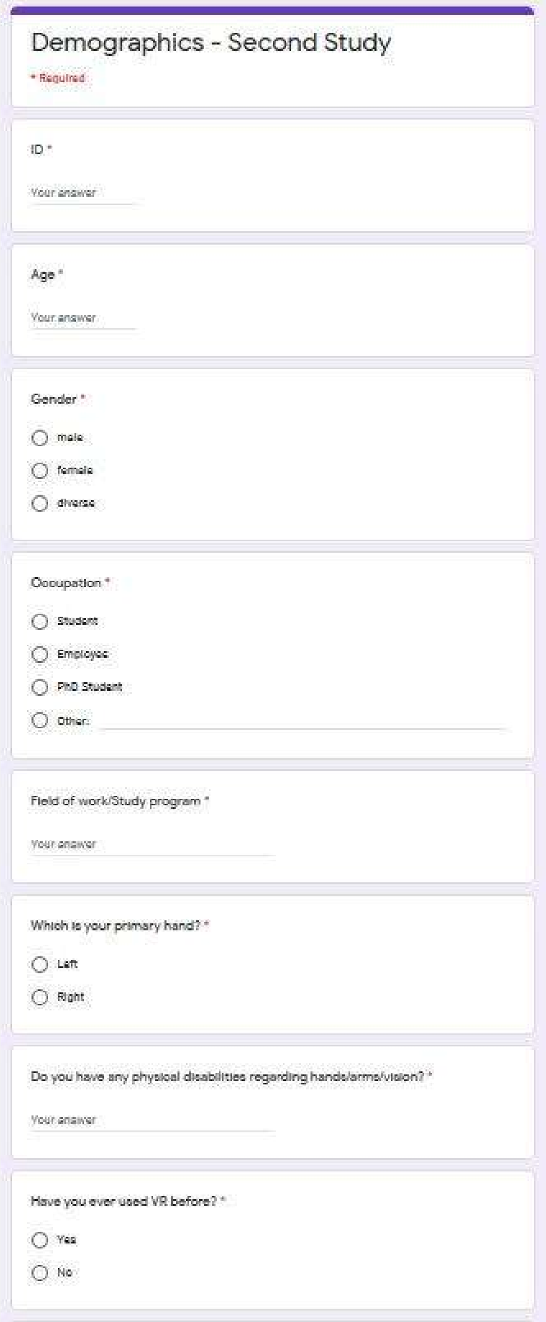
9 Appendix

A **digital copy** of this master thesis and a **demo video** for Triggermuscle are available at

-> **http://bit.ly/masterthesisrepo**

Appendix A Demographic Questions for all User Studies



Demographics - Second Study

* Required

ID *

Your answer

Age *

Your answer

Gender *

- ◯ male
- ◯ female
- ◯ diverse

Occupation *

- ◯ Student
- ◯ Employee
- ◯ PhD Student
- ◯ Other:

Field of work/Study program *

Your answer

Which is your primary hand? *

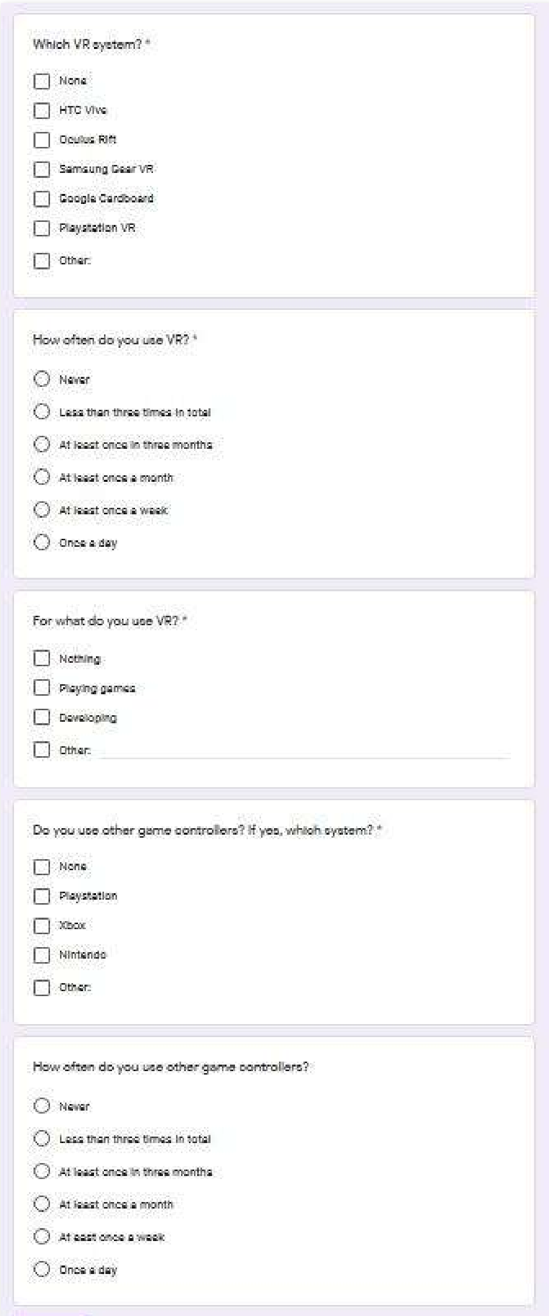
- ◯ Left
- ◯ Right

Do you have any physical disabilities regarding hands/arms/vision? *

Your answer

Have you ever used VR before? *

- ◯ Yes
- ◯ No



Which VR system? *

- ☐ None
- ☐ HTC Vive
- ☐ Oculus Rift
- ☐ Samsung Gear VR
- ☐ Google Cardboard
- ☐ Playstation VR
- ☐ Other:

How often do you use VR? *

- ◯ Never
- ◯ Less than three times in total
- ◯ At least once in three months
- ◯ At least once a month
- ◯ At least once a week
- ◯ Once a day

For what do you use VR? *

- ☐ Nothing
- ☐ Playing games
- ☐ Developing
- ☐ Other:

Do you use other game controllers? If yes, which system? *

- ☐ None
- ☐ Playstation
- ☐ Xbox
- ☐ Nintendo
- ☐ Other:

How often do you use other game controllers?

- ◯ Never
- ◯ Less than three times in total
- ◯ At least once in three months
- ◯ At least once a month
- ◯ At east once a week
- ◯ Once a day

Appendix B User Study I: Consent Agreement

ID______

Study: Weight in VR **Organization**: University of Bremen **Conductor**: Carolin Stellmacher

Description: You are invited to participate in a research study that investigates weight in virtual reality (VR). You will be asked to perform two tasks within VR, followed by answering a questionnaire. At the end a short interview will be conducted which will be recorded. The exact procedure of the experiment will be explained to you at the beginning of the session.
Please read this form carefully and ask any questions you may have before agreeing to take part in this study.

Duration: Your participation will take approximately 1 hour.

Procedure: If you agree to this study, you will be asked to:

- Perform two tasks in VR
- Fill out questionnaires before and after
- Answer a few interview questions and being recorded
- Wear the VR equipment and noise-cancelling headphones

Purpose: The study investigates weight in VR using a new approach and is part of the conductor's master thesis.

Risks: To avoid any risks, the conscious use of the VR equipment is suggested. Being in VR may cause discomfort, which can be, among other things, experienced as headache, nausea or dizziness. Furthermore the experience may cause fatigue. In such case the experiment will be paused or stopped.

Benefits: This study serves as a pre-study for the conductor's master thesis and will gather data relevant for its further development. Your participation also benefits public research about weight in VR which could result in the improvement of interaction within a virtual environment.

Rights: Your participation in this study is voluntary. You may refuse to participate or cancel the study at any time. You have the right to not answer any questions asked or withdraw from answering completely. If you have problems or concerns at any time during the study, you may report them to the conductor.

Consent: With your signature below, you will certify that you have read this document carefully and agree to:

[ ] Participate in this research experiment under the conditions described above.

[ ] Being recorded on audio during the interview for the purpose of anonymized analysis.

Date, Signature: ______________________________

Appendix C User Study I: Participant Instructions

First Task

1. In the first task you are asked to compare the weight of two boxes and choose the heavier one. You must always choose one box. The procedure will be repeated multiple times and will go as follows: You grab the first box, then grab the second box and choose the heavier one. During this task you will be wearing noise-cancelling headphones.

2. Before starting the actual experiment, you will go through a short training phase in VR which will be guided by visual instructions within the virtual environment. In case of questions, say anything and the conductor will remove the headphones for the moment of communication. You'll also get the chance to clear things up after the training phase.

3. You will then perform the experiment task. At the end the conductor will relieve you from the equipment.

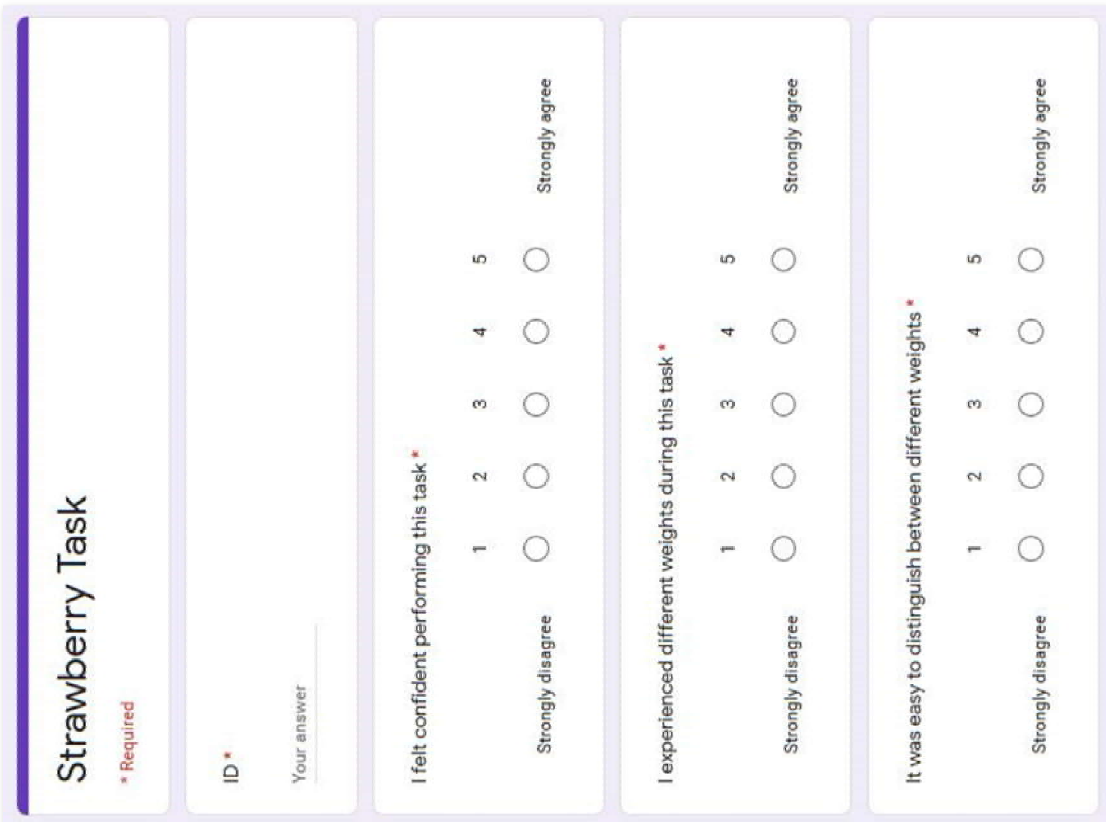
Second Task

1. For the second task you are asked to fill up a paper plate with as many strawberries as you think until lifting the plate feels realistic to you. The procedure will be repeated multiple times and you will be wearing noise-cancelling headphones.

2. A short training phase is conducted in VR to familiarize you with the exact procedure. Visual instructions will explain the process. As in the previous training phase, say anything in case of a question and the headphones will be removed for a moment.

3. After clearing up any possible questions, the experiment task starts. At the end the conductor will relieve you from the equipment.

Appendix D User Study I: Likert-Scale for Ratio Task



Strawberry Task

* Required

ID *

Your answer

I felt confident performing this task *

Strongly disagree 1 2 3 4 5 Strongly agree

I experienced different weights during this task *

Strongly disagree 1 2 3 4 5 Strongly agree

It was easy to distinguish between different weights *

Strongly disagree 1 2 3 4 5 Strongly agree

I felt confident in choosing the respective amount of strawberries *

Strongly disagree 1 2 3 4 5 Strongly agree

My hand got tired towards the end of this task *

Strongly disagree 1 2 3 4 5 Strongly agree

My performance was influenced by my hand being tired *

Strongly disagree 1 2 3 4 5 Strongly agree

I experienced discomfort like headache, nausea or dizziness during this task *

Strongly disagree 1 2 3 4 5 Strongly agree

Discomfort like headache, nausea or dizziness influenced my ability to perform this task *

Strongly disagree 1 2 3 4 5 Strongly agree

Appendix E User Study I: Interview Questions

ENGLISCH

- Did you notice different weights during the strawberry task?
  - How many different weights did you notice in this task?
  - Can you describe how you were able to distinguish between weights?
  - Was it easier for you to distinguish between weights towards the end of this task than it was at the beginning?
- Did you notice anything about the controller while holding it?
- Did you feel any vibrations on the controller?

- Did you notice any system errors during the first or second task?
- Is there anything else you'd like to share about the experiment?

DEUTSCH

- Hast du verschiedene Gewichte in der Erdbeer-Aufgabe bemerkt?
  - Wieviele verschieden Gewichte hast du in dieser Aufgabe bemerkt?
  - Kannst du beschreiben, wie du zwischen den Gewichten unterscheiden konntest?
  - War es zum Ende hin der Aufgabe leichter Gewichte zu unterscheiden als am Anfang?
- Ist dir etwas am Controller aufgefallen während du ihn in der Hand hieltest?
- Hast du irgendwelche Vibrationen am Controller bemerkt?

- Sind dir während der ersten und zweiten Aufgabe Systemfehler aufgefallen?
- Gibt es noch etwas anderes, dass du gerne über das Experiment sagen möchtest?

Appendix F User Study I with Modified Task: Consent Agreement

ID______

Study: Evaluation of a prototype for a controller in VR **Organization**: University of Bremen
Conductor: Carolin Stellmacher

Description: You are invited to participate in a research study that evaluates a prototype for a virtual reality (VR) controller. You will be asked to perform one task in VR, followed by a short interview. The interview part will be recorded. The exact procedure of the experiment will be explained to you at the beginning of the session.
Please read this form carefully and ask any questions you may have before agreeing to take part in this study.

Duration: Your participation will take approximately 30 mins.

Procedure: If you agree to this study, you will be asked to:

- Perform one task in VR
- Answer a few interview questions and being recorded
- Wear the VR equipment and noise-cancelling headphones

Purpose: The study evaluates the usage of the controller prototype in VR and is part of the conductor's master thesis.

Risks: To avoid any risks, the conscious use of the VR equipment is suggested. Being in VR may cause discomfort, which can be, among other things, experienced as headache, nausea or dizziness. Furthermore the experience may cause fatigue. In such case the experiment will be paused or stopped.

Benefits: This study serves as a pre-study for the conductor's master thesis and will gather data relevant for its further development. Your participation also benefits public research about controllers for VR applications which could result in the improvement of interaction within a virtual environment.

Rights: Your participation in this study is voluntary. You may refuse to participate or cancel the study at any time. You have the right to not answer any questions asked or withdraw from answering completely. If you have problems or concerns at any time during the study, you may report them to the conductor.

Consent: With your signature below, you will certify that you have read this document carefully and agree to:

[ ] Participate in this research experiment under the conditions described above.

[ ] Being recorded on audio during the interview for the purpose of anonymized analysis.

Date, Signature: ______________________________

Appendix G User Study I with Modified Task: Participant Instructions

Experiment Task

1. You are asked to activate two colors, one after another, by pressing the trigger button and choose which one felt heavier to activate. You must always choose one color. During the task you will be wearing noise-cancelling headphones. The procedure will be repeated multiple times and will go as follows:

2. You will see a big wall in front of you. When the “PRESS” sign appears, press the trigger button until you see the first color on the wall. Then release it again.
   After a few seconds the “PRESS” sign reappears and you are allowed to press the button a second time until you see the second color. Release it again.

3. Now you will see two squares in the corresponding colors. Choose the color that felt heavier when activating by pushing through the respective square with the tip of your controller.

4. You will practice the procedure in the first three rounds which will be marked with a big “TRAINING” sign. In case you have a question, just say something and the conductor will release you from the headphones for the moment of communication. After three rounds the “TRAINING” sign disappears and the experiment part starts.

5. When the task is completed an “END” sign is shown.

Appendix H User Study I with Modified Task: Interview Questions

ENGLISCH

- Did you notice anything about the controller while holding it?
- Did you feel any vibrations on the controller?
- Did you feel a difference between activating the two colors?

- Did you notice any system errors?
- Is there anything else you'd like to share about the experiment?

DEUTSCH

- Ist dir etwas am Controller aufgefallen während du ihn in der Hand hieltest?
- Hast du irgendwelche Vibrationen am Controller bemerkt?
- Hast du einen Unterschied gefühlt zwischen dem Aktivieren beide Farben?

- Sind dir Systemfehler aufgefallen?
- Gibt es noch etwas anderes, dass du gerne über das Experiment sagen möchtest?

Appendix I User Study II: Consent Agreements

ID______

Studie: Gewicht in VR **Einrichtung**: Universität Bremen **Leiterin**: Carolin Stellmacher

Beschreibung: Du bist zu einer Forschungsstudie eingeladen, die Gewicht in der Virtuellen Realität (VR) untersucht. Du wirst aufgefordert eine Aufgabe in VR durchzuführen, an dessen Anschluss ein kurzes Interview über dein Erlebtes folgt. Während des Interviews wird der Ton aufgenommen. Der genaue Ablauf der Aufgabe wird dir zum Anfang des Experiments erklärt.
Bitte ließ dieses Formular sorgfältig durch und stelle auftretende Fragen, bevor du der Teilnahme an dieser Studie zustimmst.

Dauer: Deine Teilnahme wird etwa 30 Minuten dauern.

Verfahren: Wenn du mit der Studie einverstanden bist, wirst du aufgefordert:

- Einen demographischen Fragebogen auszufüllen
- Eine Aufgabe in VR zu performen
- Ein paar Interviewfragen zu beantworten und dabei aufgenommen zu werden
- Die VR Ausrüstung und rauschunterdrückende Kopfhörer zu tragen

Zweck: Diese Studie nutzt einen neuen Ansatz um Gewicht in VR zu untersuchen und ist Bestandteil der Masterarbeit der Leiterin.

Risiken: Um etwaige Risiken zu vermeiden, wird ein vorsichtiger Umgang mit der VR Ausrüstung empfohlen. Das Aufhalten in VR kann Unwohlsein verursachen, was unter anderem als Kopfschmerzen, Übelkeit, Schwindelgefühl oder Erschöpfung wahrgenommen werden kann. In diesem Falle wird das Experiment pausiert oder abgebrochen. Außerdem kann die Erfahrung Erschöpfung deiner dominanten Hand auslösen.

Vorteile: Diese Studie dient als Folgestudie für die Masterarbeit der Leiterin und wird für die weitere Entwicklung relevante Daten sammeln. Deine Teilnahme kommt ebenfalls der öffentlichen Forschung über Gewicht in VR zugute, was zu einer Verbesserung der Wahrnehmung von Objekten in einer virtuellen Umgebung führen kann.

Rechte: Deine Teilnahme an der Studie ist freiwillig. Du kannst jederzeit deine Teilnahme verweigern oder abbrechen. Du hast das Recht gestellte Fragen nicht zu beantworten oder von der Beantwortung komplett zurückzutreten. Solltest du zu irgendeinem Zeitpunkt Probleme oder Sorgen haben, kannst du dich jederzeit an die Leiterin wenden.

Einverständnis: Mit deiner Unterschrift bestätigst du, dieses Dokument sorgfältig gelesen zu haben und folgendem zustimmst:

[ ] In dem Forschungexperiment zu den oben beschriebenen Umständen teilzunehmen

[ ] Einer Audioaufnahme während des Interviews für den Zweck der anonymisierten Analyse

Date, Signature: ______________________________

ID______

Study: Weight in VR **Organization**: University of Bremen **Conductor**: Carolin Stellmacher

Description: You are invited to participate in a research study that investigates weight in virtual reality (VR). You will be asked to perform one task in VR, followed by a short interview about your experience which will be recorded. The exact procedure of the task will be explained to you at the beginning of the session.
Please read this form carefully and ask any questions you may have before agreeing to take part in this study.

Duration: Your participation will take approximately 30 minutes.

Procedure: If you agree to this study, you will be asked to:

- Fill a demographic questionnaire
- Perform one task in VR
- Answer a few interview questions and being recorded
- Wear the VR equipment and noise-cancelling headphones

Purpose: This study investigates weight in VR using a new approach and is part of the conductor's master thesis.

Risks: To avoid any risks, the conscious use of the VR equipment is suggested. Being in VR may cause discomfort, which can be, among other things, experienced as headache, nausea, dizziness or fatigue. In such case the experiment will be paused or stopped. Furthermore the experience may cause fatigue of your dominant hand.

Benefits: This study serves as a follow-up study for the conductor's master thesis and will gather data relevant for its further development. Your participation also benefits public research about weight in VR which could result in the improvement of object perception in a virtual environment.

Rights: Your participation in this study is voluntary. You may refuse to participate or cancel the study at any time. You have the right to not answer any questions asked or withdraw from answering completely. If you have problems or concerns at any time during the study, you may report them to the conductor.

Consent: With your signature below, you will certify that you have read this document carefully and agree to:

[ ] Participate in this research experiment under the conditions described above.

[ ] Being recorded on audio during the interview for the purpose of anonymized analysis.

Date, Signature: ______________________________

Appendix J User Study II: Participants Instructions

Aufgabe in VR

1. Du wirst gebeten zwei Boxen anzuheben, deren Inhalt unbekannt ist und die schwerere Box auszuwählen. Der genaue Ablauf ist wie folgt:

    - Hebe die erste Box
    - Hebe die zweite Box
    - Wähle die schwerere Box

    Du musst immer eine Box wählen. Der Ablauf wiederholt sich viele Male und du wirst rauschunterdrückende Kopfhörer tragen.

2. Du wirst die Vorgehensweise in einer kurzen Übungsphase kennenlernen, die von visuellen Anweisungen geleitet ist. Solltest du Fragen haben, kannst du einfach etwas sagen und die Leiterin entfernt die Kopfhörer für den Moment der Kommunikation. Am Ende der Übungsphase wirst du ebenfalls die Gelegenheit haben, eventuelle Unklarheiten zu klären.

3. Nach Abschluss der Übungsphase und Klärung aller Fragen beginnt die Aufgabe des Experiments. Am Ende wird die Leiterin dich von der Ausrüstung befreien.

Task in VR

1. You are asked to lift two boxes whose contents are unknown and choose the heavier one. The exact procedure will go as follows:

    - Lift the first box
    - Lift the second box
    - Choose the heavier box

    You must always choose one box. The routine will be repeated many times and you will be wearing noise-cancelling headphones.

2. You will practice the procedure in a short training phase in VR which will be guided by visual instructions. In case of questions, say anything and the conductor will remove the headphones for the moment of communication. You'll also get the chance to clear things up after the training phase.

3. After finishing the training phase and clarifying potential questions, you will then perform the experiment task. At the end the conductor will relieve you from the equipment.

Appendix K User Study II: Interview Questions

ENGLISCH

1. Did you experience different weights during the task?
2. How could you distinguish between the weights?
3. What different contents would you imagine in the boxes with the weights you experienced?
4. If I give you the statement: "The weight of the boxes felt realistic"
    i. How much would you agree with that on a scale from 1 to 6 (where 6 is total agreement)?

5. Did you notice anything about the controller while holding it?
6. Did you feel any vibrations on the controller?

7. Did you notice any system errors during the task?
8. Is there anything else you'd like to share about the experiment?

DEUTSCH

1. Hast du unterschiedliche Gewichte während der Aufgabe wahrgenommen?
2. Wie hast du zwischen den Gewichten unterschieden?
3. Was für unterschiedliche Inhalte würdest du dir in den Boxen vorstellen basierend auf den erlebten Gewichten?
4. Wenn ich dir die Aussage gebe "Das Gewicht der Boxen fühlte sich realistisch an"
    a. Wie weit würdest du dem zustimmen auf einer Skala von 1 bis 6, wenn 6 volle Zustimmung und 1 gar nicht bedeutet?

5. Ist dir etwas am Controller aufgefallen während du ihn in der Hand hieltest?
6. Hast du irgendwelche Vibrationen am Controller bemerkt?

7. Sind dir während der ersten und zweiten Aufgabe Systemfehler aufgefallen?
8. Gibt es noch etwas anderes, dass du gerne über das Experiment sagen möchtest?

Appendix L User Study II: Promotional Poster