Investigating Haptic Devices in IVR Systems

A scoping review of haptic devices and their relation to immersion and presence in IVR systems

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Master Thesis

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July 5th, 2023

Enschede, The Netherlands

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Acknowledgments

This master's thesis was the last step I needed to take in order to graduate from the masters' course in communication science at the University of Twente. The scoping review allowed me to explore immersive virtual reality and haptic technology in great detail and contribute to this complex and evolving academic field. I would like to express gratitude to my two supervisors for the motivating and reassuring feedback. First, I would like to thank Dr. Mirjam Galetzka for her expertise, helpful advice, patience, and feedback throughout this assignment. Secondly, I want to thank Dr. Joyce Karreman for her insightful comments and suggestions as a second supervisor.

Additionally, I would like to thank my family, partner, and friends for their support and help throughout my entire studies.

Abstract

Aim: This master thesis aimed to investigate the role of haptic devices in Immersive Virtual Reality (IVR) systems, while specifically focusing on their relation to the mental responses of immersion and presence. The IVR research landscape saw immense growth during the past decade, particularly since the Oculus Rift and other head mounted devices (HMDs) became available on the market. Haptic devices such as finger sensors, joysticks, hand gloves, and full body suits were integrated in IVR systems to elicit cognitive responses by influencing human senses and touch. **Method**: The thesis followed a scoping review methodology aligned with the principles of the JBI scoping review methodology and used the PRISMA-ScR checklist. Sources of evidence were collected from Web of Science, Scopus as well as IEEE Xplore. The final corpus consisted of 44 conference sources and 25 journal articles. The Covidence screening tool was utilized to screen sources and perform intercoder reliability testing. Sources were organized into five groups and the analysis outlined three specific areas of application: Learning, Leisure and culture, and Design and Evaluation. **Results**: The results, presented in the form of narrative summaries and tables, outlined that haptics essentially had a positive impact on users' immersion and presence in IVR systems. **Conclusion**: Overall, this thesis highlighted the positive effect of haptic devices on users' feeling of immersion and presence in IVR systems, in fields such as medical skills training. This thesis is among the few scoping reviews in the field of IVR, and the first, to summarize and disseminate research findings in the field of haptic devices in IVR while focusing on the immersion and presence.

Keywords: Immersive Virtual Reality (IVR), scoping review, haptics, immersion, presence, UX

Table of Contents

Introduction

Virtual reality is one of the technological advancements defining the Fourth Industrial Revolution (4IR) together with artificial intelligence (AI), big data, machine learning, mobile technology, the Internet of Things, geo-tagging, speech recognition, and biometrics (Budhwar et al., 2022). In their paper, Rubio-Tamayo et al. (2017) described immersive and interactive Virtual Reality (VR) as a new turning point in how we engage with our surroundings and how we adopt novel approaches to our relationship with reality. Furthermore, the authors claimed that VR is not just a novel form of ICT but a new research field that could improve our understanding of human interactions in the physical world and comprehension of multidirectional cues. More effective immersive experiences within VR will be made possible by developing new user interfaces (such as brain-computer interfaces) and gaining deep knowledge of the human senses (Rubio-Tamayo et al., 2017).

Joysticks, body costumes, and hand gloves are devices that contribute to the immersive experience through senses and touch. Moreover, scholars argue that research in VR haptics currently offers various potential approaches, which allow many possibilities, but yet increase the complexity of outlining a framework where haptics, other technologies, and approaches apply to the domain of VR research (Rubio-Tamayo et al., 2017). Additionally, Sim et al. (2021) advised implementing haptic systems together with motion-tracking gloves to improve immersive interactions. Gibbs et al. (2022) argued that although haptics are still not well established, they are still progressively introduced to enhance the user's sense of 'reality'. The authors informed that vibrating feedback is becoming part of mainstream VR consumer devices and thus emphasized the urgent need to investigate how haptic and visual feedback impact the sense of presence.

Immersive technologies such as augmented reality (AR) and virtual reality (VR) are increasingly pervasive in our daily lives, however, despite the received scholarly attention, there is still no common understanding of what immersive technology is and what the research designs, methods, and settings applied in the field (Suh & Prophet, 2018). Furthermore, most studies investigated a single or narrow aspect of immersive technology, while very few scholars explored the different effects of diverse technological stimuli on several aspects of user performance (Suh & Prophet, 2018). Hence, the authors argue that "it would be meaningful to develop and conceptualize immersive system features and explore their influence on user experience and performance in a systematic way" (p. 87). Moreover, Radhakrishnan et al. (2021) urged future studies in the IVR field to investigate haptic integration across various sectors and to further explore parameters such as immersion, memory, and presence.

Therefore, in accordance with scholars' recommendations, this thesis aims to contribute to the body of literature investigating broader aspects of IVR technology by conducting a scoping review on IVR haptic devices. To determine what role haptic devices, have on users' feelings of immersion and presence across different domains, the following research question is introduced:

RQ1: *"What is the role of haptic devices on users' feeling of presence and immersion in IVR systems within different areas of application?"*

To answer this question, a systematic scoping review with a final corpus of 69 sources was performed by following the adjusted JBI guidelines and PrismaScR checklist. In the next section of this article, the relevant theoretical concepts supporting this thesis are discussed.

Theoretical Background

Defining IVR

In general, VR is regarded as the computer-generated simulation of a 3D environment that looks remarkably real to the person experiencing it by using special electronic equipment. In their article, Xie et al. (2021) reported that Oculus Quest 2, which was released in 2020 has become the fastest-selling VR headset. ‘Virtual reality’, ‘immersive multimedia’, and ‘computer-simulated reality’ are all terms used to describe an environment that mimics physical presence in imaginative or real-world locations within which the user can interact (Velev & Zlateva, 2017). Similarly, Onyesolu and Eze (2011) stated that VR is characterized as a highly interactive, computer-based multimedia environment where the user participates in a virtual world. The goal of IVR is to fully immerse the user inside the computer-generated world, providing the impression to the user that he/she has “stepped inside” the synthetic environment (Furht, 2008).

More specifically, Onyesolu and Eze (2011) distinguish three main categories of VR: (a) Non-Immersive VR Systems, (b) Semi-Immersive VR Systems, and (c) Immersive (Fully Immersive) VR systems. This thesis focuses on fully immersive virtual reality (IVR) because it is regarded as the most straightforward way to experience this unique setting. In this case, in addition to tracking and haptic devices, the user also either wears a head-mounted display (HMD) or uses a head-coupled display to observe the virtual environment. The vision of IVR systems this research plan follows is represented by the visualizations of people using IVR systems as shown in Figure 1.

Figure 1

Examples of users using Immersive VR

Haptic devices

More specifically, this thesis focuses on exploring how haptic devices influence users' cognitive responses to IVR systems. Haptic systems, also known as haptics, are elements of immersive virtual reality systems that interact with the user's sense of touch (Dargar et al., 2015). Haptics could be divided into two categories: tactile perception and kinesthetic perception. Tactile perception includes pressure, vibration, and texture, which are perceived by the human body via receptors in our skin, while kinesthetic perception is focused on forces and movements (Dargar et al., 2015). When interacting with Virtual environments (VEs) via a haptic interface, the human user physically manipulates the interface to convey desired motor actions, which, in turn, displays tactual sensory information by stimulating the users' tactile and kinesthetic sensory systems appropriately (Srinivasan & Basdogan, 1997). Regarding haptic exploration modes, active and passive haptics have been outlined (Rodríguez et al., 2019). During active exploration, the user is in control of his actions, while in passive mode the haptic device is in motor control. In addition, in their paper Pacchierotti et al. (2017) state that cutaneous cues are more informative than kinesthetic cues in regard to surface curvature discrimination and fine manipulation.

Defining Immersion

A literature review performed by Suh & Prophet (2018) revealed that immersion is a key construct that demonstrates users' cognitive reaction when using immersive technology. Traditionally, the term "immersion" has been used to describe users' mental state when they are deeply engaged in an immersive environment. Nevertheless, Huang et al., (2010) discovered that academics studying immersive technologies, often conceptualize immersion in different ways by focusing on either mental or physical sub-dimensions. To illustrate, Witmer and Singer (1998) view immersion as a subjective psychological state where an individual is “perceiving oneself to be enveloped by, included in, and interacting with an environment that provides a continuous stream of stimuli and experiences.” (p. 227). Conversely, other scholars argue that immersion is a systemically objective characteristic of a VR system (Slater et al., 1996; Bowman & McMahan, 2007). In their paper, Jung and Lindeman (2021) discussed these contradictory definitions of immersion and argued for the necessity of a clear reference point in the research community.

Additionally, Mulders et al. (2020) state that immersion is an aspect that adds to the impact of VR by bridging the technical features of a 3D environment, the sense of presence, and the learning affordances of a task. Furthermore, scholars argue that immersion is vital for the successful development of experiences within VR environments and also makes the distinction between mental and physical immersion (Mulders et al., 2020). The visual, auditory, or haptic components provide a physical sense of immersion in the environment when changing in response to the user's movements. Mulders et al. (2020) also state that when more sensory inputs are available in VE the user is eased into visualizing and feeling involved in his surroundings. On the other hand, mental immersion relates to the suspense of being deeply engaged in a VR world. Similarly, Jung and Lindeman (2021) mentioned the subdivision of immersion into perceptual immersion and psychological immersion. Moreover, researchers have identified the following five characteristics of immersion: “inclusiveness (diversion of focus from the real world), extensiveness (extent of sensory input), surroundingness (extent of panoramic display), vividness (richness of features) and proprioceptive matching (alignment of perceptual means with the virtual interface)” (p.212, Mulders et al., 2020).

In attempts to gain a deeper understanding of immersion in the context of gaming a qualitative study concluded that immersion is used to describe the degree of involvement with a computer game (Jennett, 2008). Additionally, this study managed to outline three distinct levels of immersion: engagement (learning how to play the game), engrossment (controls become invisible, overcoming a barrier of game construction), and then “total immersion” (overcoming the barriers of empathy and atmosphere), which is the highest form of immersion where gamers report a sense of presence and feel completely cut off from reality as if the game was all that mattered (Jennett et al., 2008). Therefore, based on the broad scope of scholarly findings Jennett et al. (2008) determined the following characteristics of immersion: “lack of awareness of time, loss of awareness of the real world, and involvement and a sense of being in the task environment.” (p. 642).

Defining Presence

Since the introduction of virtual reality technologies in the 1990s, presence has been a significant research topic. However, Jennett et al. (2008) noted that the presence could be measured in diverse ways depending on the way it is defined. Slater et al. (1994) supported the rationalistic tradition and defined presence as “a psychological sense of being in a virtual environment” (p. 643). According to the three-dimensional model of experience adopted by Waterworth and Waterworth (2003), a sense of presence appears from the operation of core consciousness, as opposed to extended consciousness. As explained by Mulders et al. (2020) presence and immersion are two of the main mental processes that occur among users as a type of cognitive reactions after interaction with technological stimuli. The relationship between the two concepts is also worth mentioning. As an example, Flavián et al. (2019) note that immersion is an antecedent of presence and is dependent on the technology's capabilities.

Measuring immersion and presence

This section reviewed methods for evaluating users' experience of immersion and presence in the IVR context. In their paper Cheng and Tsai (2020) claimed that the Immersive Experiences Questionnaire (IEQ) created by Jennett et al. (2008) was among the most adopted measures by scholars seeking to assess immersion. The refined version of the questionnaire focused on six factors: basic attention, temporal dissociation, transportation, challenge, emotional involvement, and enjoyment.

Waterworth and Waterworth (2003) applied the three-dimensional model of experience based on locus, focus, and sensus in order to measure sense of presence. According to the authors, this model aims to capture and reinterpret a number of relevant interpretations of elements underlying presence, including attention level, attention changes between the real and the virtual, immersion, and fidelity. More specifically, the locus concept relates to the level of attention an observer is paying to the real or virtual world. Subsequently, focus indicates the user's attentional style, namely whether they are primarily focusing on the stimuli that are currently in front of them, whereby one would either experience a high sense of presence which involves mostly perceptual (or concrete) processing, or users would address internally accessed information that mostly requires conceptual (or abstract) processing. Also, Waterworth and Waterworth (2003) refer to the more reflective state of mind as absence, referring to a low level of presence, and argue that the position on the focus dimension determines the degree of experienced presence. The researchers confirmed their hypothesis that presence increases with more concrete (conceptual) processing, while it decreases with abstract processing, showcasing the significance of the distinguished focus dimension of experience.

Understanding the Role of Haptic Devices in IVR systems

It is essential to explore the direct affordances and constraints of haptic devices as part of IVR systems. To begin with, haptic feedback has been found to enhance 3D interaction within virtual environments because even simple haptic hints, such as communicating encounters with virtual objects, can substantially boost selection accuracy and lower task completion duration (Achibet et al., 2016). In addition, the researchers argue that haptic effects are valued by users and enhance the "feeling of presence". Similarly, Qin et al. (2013) state that haptic feedback, next to visual feedback, is vital to improve the sense of both presence and immersion in VE. In their paper, Achibet et al. (2016) discuss the concept of passive haptics, which was defined by Insko (2001) as "a technique that incorporates passive physical objects into virtual environments to physically simulate the virtual objects." (p. 2/3). According to Achibet et al. (2016), passive interfaces mimic virtual objects that provide feedback through their shapes or materials and give the example of utilizing a physical ledge on the floor to replicate the haptic feeling of standing on the edge of a hole.

Technological Embodiment

The notion of embodiment is described by Ihde (1990) in his theory of human-technology mediation as the occasions in which technological devices mediate users' experience and result in the feeling that the technology has become an extension of one's body assisting interactions with immediate surroundings (Flavián et al., 2019). In addition, Wenk et al. (2021) argued that the integration of multimodal sensory information in the brain results in embodiment. According to Flavián et al. (2019), the highest level of technological embodiment results in human-technology symbiosis where users enter a state of disappearance of the technology. The authors mention that this is achievable when users experience both ownership over the tool and location overlap with the equivalent part of the body. Hence, “technological embodiment plays a key role in creating immersive experiences due to its ability to involve the human senses” (p. 550, Biocca, 1997, as cited in Flavián et al., 2019). More specifically, fully immersive VR system tools offer a sense of embodiment since users see themselves as components of the virtual environment, experiencing VR devices such as HMD or gloves as part of their bodies (Flavián et al., 2019).

Previous Systematic Literature Reviews on IVR systems and Haptic Devices

Previous research from Pacchierotti et al. (2017) outlined a taxonomy and a literature review of wearable haptic systems with a focus on wearability challenges. Their findings are summarized in two tables providing details of the most representative wearable haptic systems for fingertip and hand. Another study by Radhakrishnan et al. (2021) performed a systematic literature review by applying the Preferred Reporting Items for Systematic Literature Reviews and Meta-Analyses (PRISMA) framework while aiming to determine the effectiveness of IVR training in an industrial setting. The authors testify to the effectiveness of such training, address existing research gaps, and claim that parameters like immersion, memory, and presence require further exploration.

Considering that the field of IVR is still evolving and technology is rapidly changing there is a need to conduct an exploratory study in the area of IVR haptics and map out the relevant concepts connected to users’ cognitive responses and interactions. Moreover, while Radhakrishnan et al. (2021) reviewed IVR training’s effectiveness and research practices in an industrial setting, they urged future researchers to investigate the role of haptics devices within IVR systems across various sectors and their impact on interactivity.

In comparison to systematic literature reviews, a scoping review seeking to explore such a novel research field was deemed more appropriate. Daudt et al. (2013) defined scoping studies as research whose “aim is to map the literature on a particular topic or research area and provide an opportunity to identify key concepts; gaps in the research; and types and sources of evidence to inform practice, policymaking, and research” (p.8)

Therefore, based on the reviewed literature and the defined aim of scoping reviews, the following research questions are formulated for this thesis assignment, in addition to the first research question.

RQ2: “*What measurements are applied to evaluate users' level of presence and immersion in IVR systems?”*

RQ3: *What are the opportunities and limitations related to the integration of IVR haptic systems?”*

Methods and Data collection

Scoping Review Methodology

In order to explore the role of haptic devices in IVR systems and conceptualize their impact on users' experiences of immersion and presence, a scoping review was selected as an appropriate method. The scoping review, also known as a "mapping review" or a "scoping study," is a method of evidence synthesis that is gaining popularity around the world (Peters et al., 2020). In their paper, Arksey and O'Malley (2005) define scoping reviews as studies which

> “aim to map rapidly the key concepts underpinning a research area and the main sources and types of evidence available, and can be undertaken as stand-alone projects in their

own right, especially where an area is complex or has not been reviewed comprehensively before" (p. 20)

Moreover, according to the authors, one of the main motives to conduct scoping reviews is to summarize and disseminate research findings that congrues with the purpose of this study. A scoping study with such focus could provide more details regarding the findings and range of scholarship in the field of haptics in IVR systems, which offers a way for summarizing and sharing research findings with policymakers, practitioners, and consumers who otherwise lack the time or resources to perform such work independently (Arksey & O'Malley, 2005). Scoping reviews are suitable for assessing and understanding the extent of knowledge in an emerging field, as well as identifying, mapping, reporting, or discussing the characteristics or concepts in that field.

Protocols and Registration

As reported by Peters et al. (2020), the JBI Scoping Review Methodology Group developed guidelines for scope reviews in 2014, which were minorly updated in 2017 and were most recently updated in 2020. Furthermore, in 2018 an international expert group in scoping reviews and evidence synthesis, including members of the JBI/JBIC working group, outlined the Preferred Reporting Items for Systematic Reviews extension for Scoping Reviews (PRISMAScR) to be compatible with the JBI's scoping review methodology and to provide reviewers with a reporting checklist for their studies (Tricco et al., 2018).

Also, Peters et al. (2020) highlighted that scoping reviews should be properly organized and guided by a protocol to assure transparency and unbiased reporting. A scoping review protocol is essential because it pre-defines the objectives, methods, and reporting of the review and allows for process transparency. The protocol should specify the criteria that the reviewers will use to include and exclude sources of evidence, as well as identify what data is relevant and how it will be extracted and presented. Furthermore, the mnemonic "PCC" (population, concept, and context) is suggested by Peters et al. (2020) as a guide for developing a clear and meaningful title and inclusion criteria for a scoping review. The adjusted JBI protocol developed for this thesis can be seen in Table A2 (see Appendix A) and the PrismaScR checklist was presented in Table C1 (see Appendix C).

To summarize, the methodology followed in this thesis was inspired by the JBI scoping review methodology and makes use of the PrismaScR checklist.

Data collection

Search criteria

Data considered as a source of evidence should not be published earlier than 2017 due to the thesis' focus on novel and up-to-date scientific literature in the rapidly evolving field of IVR. Furthermore, sources are deemed appropriate regardless of the publication status being accepted because the focus of this review is to outline the novel state-of-the-art concepts currently paid attention to by researchers. Conference sources are regarded as sources of evidence due to providing cutting-edge information in the field of IVR-related technology. Lastly, sources would be regarded as evidential only if provided in English due to the researcher's language skills.

Information sources

The databases considered for the search were Web of Science, Scopus as well as IEEE Xplore and the search was executed in the period from the 20th of April 2023 until the 28th of April 2023. The final search strings for each database can be seen in Table 1.

Table 1

Final Search Queries for each Database

Date	Database	Search String	№ of Hits	Applied Filters
24-04-23	Web of Science	ALL= (immersive "virtual reality" AND ("haptic" OR "tactile" OR "proprioceptive") AND ("immersion" OR "presence"))	120	from 2017-01-01 until 2023-04-24
24-04-23	IEEE	(("All Metadata": immersive "virtual reality") AND (("All Metadata": haptic) OR ("All Metadata": proprioceptive) OR ("All Metadata": tactile)) AND (("All Metadata": immersion) OR ("All Metadata": presence)))	65	2017-2023
28-04-23	Scopus	TITLE-ABS-KEY ((immersive "virtual reality") AND ("haptic" OR "tactile" OR "proprioceptive") AND ("immersion" OR "presence")) AND PUBYEAR > 2016 AND PUBYEAR > 2016	162	2017- until now

Search strategy

The full electronic search strategy for all of the databases can be seen in Table A1 where the applied filters were presented (see Appendix A).

Data Analysis

Procedure & Instruments - Corpus composition

Data was collected based on the final search strings by exporting the references in csv format. Afterward, the data was imported in the online software screening tool Covidence. The application aids the process of data selection by providing automatic detection of duplicates as well as title and abstract screening, followed by full text screening. Title and abstract screening was performed independently by the main researcher by following the inclusion criteria presented in Table 2. The criteria were presented in the adjusted JBI Protocol shown in Table A2 (see Appendix A). Next, a fellow researcher was asked to independently perform full text screening on approximately ten percent of the remaining data, which had not been excluded during the first screening process. The second coder was familiarized with the aim of the scoping review and was presented with the main concepts and eligibility criteria as outlined in the protocol in Table A3. After the second coder completed the task, the two researchers came together to discuss any questions, compare, adjust, and decide upon the final data selection to undergo extraction. The Intercoder Agreement as calculated in Covidence was 0.7 and the researchers reviewed the differences together and reached agreement.

Table 2

Inclusion criteria Developed for Selection of Sources of Evidence

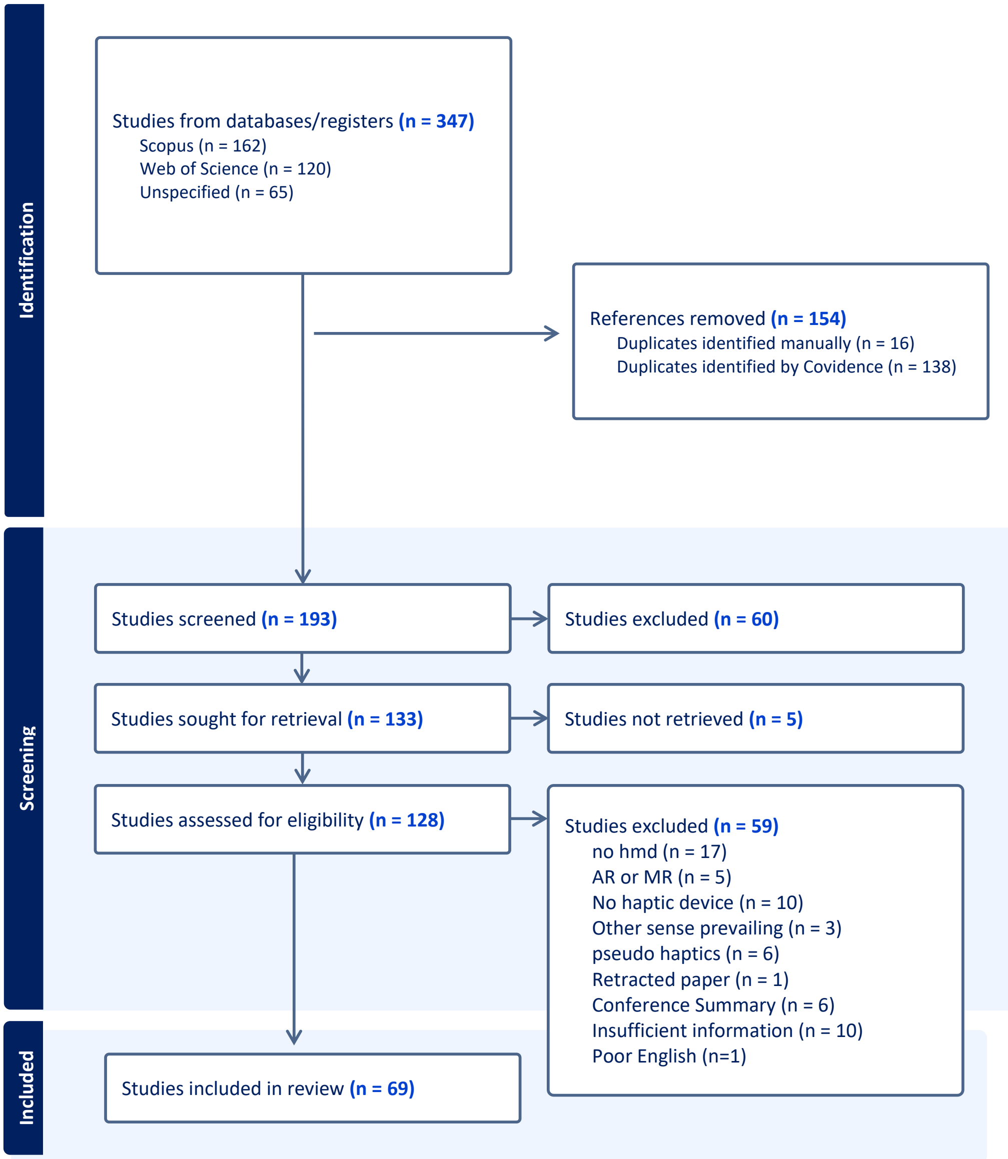
Inclusion Criteria	Exclusion criteria
- Active or passive (kinesthetic or tactile) haptic feedback is provided via a mechatronic device. - Cognitive responses such as presence or immersion are studied. - HMD is present in IVR system.	- Pseudo haptics - AR, MR, non-immersive VR - Participants with mental disabilities - Lack of mechatronic device - Predominant focus on other senses (haptic are just mentioned next to other senses) - Lack of HMD - Systematic Reviews - Insufficient information and poor English - Executive summaries of conferences

Selection of Sources of Evidence

The number of screened sources for each step of the analysis can be seen in the flow chart diagram generated in Covidence, which is shown in Figure 2. The search strategy initially identified 347 sources from the three data bases. After duplicate removal, 193 papers remained for the screening procedure on titles and abstracts. This resulted in 128 articles eligible for full-text review, which were reviewed with the developed inclusion and exclusion criteria. As can be seen in Figure 2, a total of 69 articles and conference sources remained for the final scoping review corpus. The reference list for all the sources included in this scoping review is presented in Appendix B.

Figure 2

PrismaSCR Flow Chart Generated in Covidence.



Data Extraction

Data charting was performed independently by the main researcher and an example template of the extracted data which was created in Covidence is shown in Table A3 (see Appendix A).

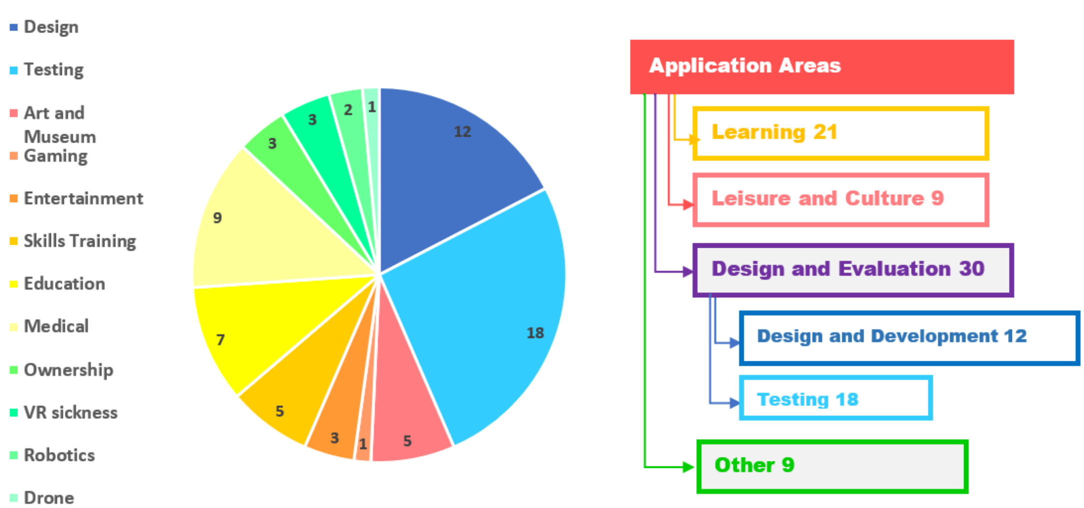
Data Categorization

The charted data was organized in Covidence by using the 'Tag' function to aid comprehension and analysis when interpreting the results. After data was extracted by using the template, tags were applied to identify the main application area the source was concerned with. As an example, tags were assigned to signal the industry type or field of application ('Medical', 'Education', 'Tourism'), device type ('controllers', 'gloves', 'fingertip', 'suit'), cognitive responses ('presence', 'immersion'). Tags were assigned to each source to serve as keywords and assist in summarizing the data, detecting patterns, and organizing the results.

The charted data was exported from Covidence in csv format and imported in Microsoft Excel for further analysis. Data cleaning was performed, and the sources were prepared for analysis. After the data was imported in excel the tags were further refined by the researcher and it was possible to outline five categories as can be seen in Figure 3.

Figure 3

Categorization of Main Tags into five categories



Category Description

First, thirty sources were grouped in the 'Learning' and 'Leisure and Culture' categories, outlining two specific application areas of IVR haptics. The largest 'Learning' group contained 21 sources investigating the integration of haptic devices in medical education (9), skills training (5), and education in general (7). Additionally, the 'Leisure and Culture' category united nine papers that explored the integration of IVR haptics in areas such as art (4) with VR painting, museum (1), gaming (1), and entertainment (3).

Second, thirty sources from the corpus focused on the design and evaluation of IVR haptic technology, which was considered the third area of haptic device application. The 'Design and Development' group organized twelve sources that introduced novel device prototypes or frameworks for haptic device integration in IVR systems. Furthermore, the 'Testing' domain was the second largest with 18 sources and dealt with validating the capabilities of new devices, comparing the performance of haptic technologies, and assessing haptic device effectiveness in various contexts.

Third, the remaining nine sources in the corpus were placed together in the 'Other' category and discussed IVR haptics concerning concepts such as VR sickness (3), ownership (3), robotics (2), and drones (1).

Results

In accordance with the JBI scoping review methodology, in this section the main findings, contributing to answering the research questions were analyzed and interpreted. First, the results from the two distinguished application areas *Learning* and *Leisure and Culture* were outlined. Subsequently, the sources from the third application field *Design and Evaluation* of haptic technology were interpreted, followed by the insights from the *Other* group.

For each of the five result categories the results were structured as follows: presenting a table with general characteristics of the sources; displaying a table with extracted data about the studied variables, applied measurements, findings, relevant concepts, and opportunities and limitations; providing narrative summaries of the sources focusing on immersion or presence.

Application Areas

Learning

General details for all twenty-one sources grouped in the learning domain can be seen in Table 3. Data about the studied variables, applied measurements, findings, relevant concepts, and opportunities and limitations was provided for each source as shown in Table 4, which informed the narrative summary.

Table 3

General Source Characteristics for the Learning Category

Author	Source	Country	Year	Study design	Sample	Haptics	IVR system
Paweł Buń	Journal Article	Poland	2017	Non-randomised experimental study	-	Robot Arm	Oculus Rift DK1 or Samsung Gear VR, the Kinect tracking system, and the Myo gesture recognition system
Pawel Buń	Conference	Poland	2018	System optimization	-	Phantom	Oculus Rift DK2, EON Studio engine, 3DS Max software
Shanthanu Chakravarthy	Journal Article	India	2018	User study	9	Longitudinal Force	VR-interface
Yonghang TAI	Journal Article	Australia	2018	user study	27	Phantom Omni	HTC Vive
Taehoon Kim	Journal Article	South Korea	2019	user study	-	Phantom Novint Falcon	Oculus Rift or HTC Vive for 3D visualization
Chongsan Kwon	Journal Article	South Korea	2019	experiment	42	HTC Vive	HTC's VIVE (AVR); Unity 5.4; Autodesk Maya 2013 and 3Ds Max 2016 were used for 3D modeling and animation,
Jinmo Kim	Journal Article	South Korea	2020	user study	20	Oculus Touch Controller	Oculus HMD
Stefan Lontschar	Conference	United States	2020	experiment	55	HTC Vive	HTC Vive HMD
Andre Zenner	Journal Article	Germany	2020	one-factorial between-subjects experiment	27	HTC Vive	HTC Vive Pro (It consists of a Lighthouse Tracking System, an HTC Vive Pro VR HMD, 2 HTC Vive Pro Controllers and additional HTC Vive

Author	Source	Country	Year	Study design	Sample	Haptics	IVR system
							Trackers for tracking physical props)
Elen Collaço	Journal Article	Brazil	2020	experimental study	163	Syringe	VIDA Odonto VR training system
Malek Racy	Journal Article	UK	2020	. Validation study	14	Entact	Oculus Rift CV1
Aylen Ricca	Conference	France	2020	within-subject design was used	41	Geomagic Touch	HTC Vive HMD; Noitom Hi5 VR Gloves, with a VIVE tracker attached to each of them to track the users' hand movements
Agapi Chrysanthakopoulou	Journal Article	Greece	2021	user study	20	Gloves	HTC Vive; Unreal Engine 4 (UE4); Vive Trackers to support hand tracking
Joy Gisler	Conference	Switzerland	2021	preliminary study	17	Gloves HTC Vive	HTC VIVE Pro Eye HMD and two SteamVR base stations 2.0 to allow real walking in a 6m × 3m room- scale tracking space
Pedro Rodrigues	Journal Article	Portugal	2022	User study	13	Phantom Omni	Oculus Quest 256G
Zoe Gozzi	Conference	France	2022	experimental study	31	Go VR Touch Controller	HTC Vive; optical hand-tracking LEAP Motion controller was physically mounted to the front of the VR headset to allow natural finger motions as input for the MATB-II VR environment
Alexis Gutierrez-Fernandez	Conference	Japan	2022	simulation task	21	Grounded Force Feedback	Oculus Quest
Mahdiyeh Moosavi	Conference	France	2022	experiment	7	HTC Vive	HTC Vive eye pro; empatica E4 wristband device
Débora Salgado	Conference	Ireland	2022	between-group design	57	wheelchair	Oculus Rift Development Kit 2
Xinyi Ye	Conference	China	2022	experiment	30	Geomagic Touch	HTC Vive
Filippo Sanfilippo	Conference	Norway	2022	human subject study	10	Valve Knuckles EV3 controllers	The HTC VIVE Pro VR

Table 4

Relevant Insights Extracted from Sources in the Learning Application Area

Descriptives	Variable	Measurement	Findings	Concepts	Limitations/ Opportunities
Paweł Buń Conference 2017 Poland	Functionality	Expert evaluations	Implementation of a haptic device allowed training of scalpel movements by the user	cricothyrotomy, training application in VR	The included forces were not realistic – there was no data in literature to build accurate models and more experiments are needed by trial and error with experienced surgeons to obtain realistic touch feelings empirically.

Descriptives	Variable	Measurement	Findings	Concepts	Limitations/ Opportunities
Pawel Buń Journal Article 2018 Poland	Efficiency	Proposed control group study	Initial results showed that the shown application, involving a haptic device with a force feedback effect, might be successfully used for teaching simple assembly operations.	-Mechanical tracking systems -Acoustic tracking systems -electromagnetic tracking systems -optical tracking systems	-Training on an operating production line in glasswork manifacturing company. -VR appears to be the perfect solution, as it prevents closing sections from the production line and prevents losses due to defective products
Shanthanu Chakravarthy Journal Article 2018 India	Immersion	Immersion/realism questionnaire	The anatomical model and the overall simulation with the haptic response is found to be satisfactory	-Finite Element (FE)-based modelling -Snap-Fit Mechanisms	The realism questionnaire was reliable and similarity ratings were consistent
Yonghang Tai Journal Article 2018 Australia	Usability	Objective operation time, Customized-built Global Rating Scale questionnaire (GRS)	the fitting rate of the whole puncture processing was 99.93%. Both subjective and objective results showed a higher performance than the existing training platform	Discusses the three levels of haptic immersion	This work may offer opportunities for highly immersive virtual surgical training on various conditions
Taehoon Kim Journal Article 2019 South Korea	Immersion And Intuition	Time for positioning pointer to target object. Heart rate measured in the most fearful parts	Presenting a VE as a stereoscopic 3D object using a VR headset, the intuitive operation performance has been improved and especially operational accuracy has been greatly enhanced.	3D immersive stereoscopic virtual reality-also useful for psychomotor skills related to the movement of one's head, such as visual scanning or observational skills	-training effect is expected to be maximized in stereoscopic environments with VR headset for intuitive and cognitive training using haptic technology. - Future studies to attempt solving the cybersickness occurring in stereoscopic visualization method with HMD;
Chongsan Kwon Journal Article 2019 South Korea	Presence, Tactile Interactivity	Simulator Sickness Susceptibility Questionnaire (SSQ), experientiality criteria developed by Gibbons and Hopkins; Witmer and Singer (1998)	the tactile interactivity and presence improved with the use of enhanced interaction technologies in VR	authentic virtual reality (AVR)—actual reality. Flow theory (Chikszentimihayi 1990)	-AVR cable restricted movement -the experiential learning potential of the VR systems providing tactile interactivity using gloves, locomotive interactivity using treadmills, and motorized interactivity could not be verified
Jinmo Kim Journal Article 2020 South Korea	Presence, Immersion, Sickness	Satisfaction, and Ease of Use (USE) questionnaire suggested by Arnold Lund	the proposed VIVR provided a satisfactory presence in the interface experience	visual impairment virtual reality (VIVR)	-try to compare users with visual impairments -simulating walking by walking in place lowers the sense of immersion compared with identifying actual braille block using a white cane
Stefan Lontschar Conference 2020	Immersion	Game immersion questionnaire	neither learning in a MR environment compared to	virtual learning environments (VLE)	-haptic feedback for simple tasks such as throwing weights, does not justify the extra costs

Descriptives	Variable	Measurement	Findings	Concepts	Limitations/ Opportunities
US			learning in pure VR was strictly better than the other	Haptic feedback encompasses the modalities of force feedback, tactile feedback, and the proprioceptive feedback.	and complications of set up. -the unwieldy nature of the heavier weights, combined with the unfamiliarity of throwing such an object, caused too much conflict in MR to properly measure learning, which was not an issue in pure VR
Andre Zenner Journal Article 2020 Germany	Immersion	User experience questionnaire (UEQ) Task load NASA TLX Immersion- SUS – Slater-Usoh-Steed presence questionnaire	passive haptic feedback can increase SoP. New VR interface for non-expert users to communicate process-knowledge in an effective, motivating, and interesting way; suggest passive when experience-focused VR instead of controllers to maximize immersion.	Immersive data exploration; dynamic passive haptic feedback (DPHF)	- potential of multi-sensory VR in less time-critical professional application domains, such as employee training, communication, education, and related scenarios focusing on user interest
Elen Collaço Journal Article 2020 Brazil	Presence, Immersion	Simulator sickness questionnaire (SSQ), Task execution time. Questionnaire	Groups in immersive preceptorship and/or immersive training conditions showed more accuracy and confidence in administering anesthesia. -combining haptic feedback with HMD enhances the immersive VR experience	The VIDA Odonto is a VR training system for the administration of anesthesia to the inferior alveolar nerve. This procedure is one of the most stressful in dental training.	The machine learning technique proposed can be used as an automatic evaluation system which can contribute to the field of VR dental Training. The haptics HMD combination should test skill acquisition among novice students
Malek Racy Journal Article 2020 UK	Realism	-time, № of Xrays, tool distance travelled. -questionnaire to assess authenticity and content validity	increased realism aided participant immersion within the VE to the point where they reverted to “realistic theatre behaviour	Image intensifier: incorporation of these developments into orthopedic simulation has been slow compared to other specialities	-findings show potential in other applications such as nontechnical skill development and assessment. -low number of participants. the simulator itself had limitations, most significantly being the limited peak force of the haptic device used
Aylen Ricca Conference 2020 France	Usability	System usability questionnaire, time, errors, accuracy	These results contradict previous research and suggest that the visualization of the user’s animated hand is not needed to perform a simple	Rubber hand illusion (RHI), Sense of Embodiment (SoE). multimodal feedback is vital in VR simulators that aim to train and transfer tool-	-Important finding for the design of IVR motor skills simulators, since obtaining a high-fidelity hand animation may be technically challenging and expensive.

Descriptives	Variable	Measurement	Findings	Concepts	Limitations/ Opportunities
			tool-based motor task in VR.	based motor skills	
Agapi Chrysanthakopoulou Journal Article 2021 Greece	Presence, Realism, UX	Questionnaire of Presence (qop) (Witmer and Singer, 1998)	engaging multiple senses and visual manipulation in an immersive 3D environment can enhance the perception of visual realism and elicit stronger sense of presence, improving the educational and informative experience in a museum	virtual learning environment (VLE); The position of the fingers is automatically provided by the sensors on the gloves, data must be sent dynamically through a User Datagram Protocol (UDP)	- such applications could definitely benefit cultural institutions. - The tension and duration of the vibrations should be carefully designed so that no further fatigue is added. -reinforce more interactive use of the equipment and assist in the overall sense of presence. -Further study can evaluate this approach
Joy Gisler Conference 2021 Switzerland	Presence, User Satisfaction, Task Load	SUS presence scale, The NASA Task Load Index (TLX), standardized learner satisfaction questionnaire	enhancing a VTE with a real tracked tool and hand tracking is generally appreciated by trainees	Virtual Training Environments (VTEs) Procedural Knowledge	the potential of providing instructions in a language-independent way to improve accessibility for trainees with language deficiencies should be investigated
Pedro Rodrigues Journal Article 2022 Portugal	Immersion	Cyber sickness questionnaire; sus (system usability scale questionnaire; nasa-tlx	DENTIFY shows potential in enhancing learning in operative dentistry as it promotes self-evaluation and multimodal immersion on the dental drilling experience.	DENTIFY is a tech probe aimed at assessing perceived usability and educational potential of an immersive VE with visual, auditory, and haptic stimuli.	The introduction of haptic technology and Virtual Reality (VR) have added new dimensions to education and the approach to daily professional challenge
Zoe Gozzi Conference 2022 France	Mental and Physical Task Load	Electrocardiogram measurements	The MATB-II VR environment was more mentally and physically demanding when performed with haptic feedback. Some users were bothered by the vibration from the haptic feedback	MATB-II (Multi-Attribute Task Battery II) is a computer-based task (Comstock & Arnegard, 1992) that can be used to evaluate operator performance and workload	VR version could offer a more ecological and immersive environment for experiments in aerospace research while engaging the same type of cognitive abilities. -The haptic feedback was not always synchronized with the button press.
Alexis Gutierrez-Fernandez Conference 2022 Japan	Usability, Presence, Quality of Interaction	System usability scale (SUS). Spatial presence experience scale (spes) five statements for the quality of interaction technique	the first implementation of a new technique tackling the limited workspace of such haptics that allow flexible VR experience while maintaining a good level of accuracy.	Haptic feedback is crucial when training chest decompression, a life-saving invasive procedure for trauma-associated cardiopulmonary resuscitation that every emergency physician needs to master.	more data on the force needed for insertion of the Russell Pneomofix-8 is needed. -take into account the limitation that it is sometimes not possible to keep the haptic stylus vertical when performing the insertion

Descriptives	Variable	Measurement	Findings	Concepts	Limitations/ Opportunities
Mahdiyeh Sadat Moosavi Conference 2022 France	Presence	Questionnaire of Presence (qop) (Witmer and Singer, 1998)	Haptic retargeting approach increases the participants' sense of presence in the virtual environment.	Endotracheal intubation is a procedure vital part of treating patients who are infected with the covid-19 virus. -Visual proprioception conflict model - Haptic Retargeting	This solution is a great alternative to highly expensive solutions such as VR robotic hand gloves. This method can be used in other fields and applications of virtual reality
Débora Pereira Salgado Conference 2022 Ireland	Immersion, UX, Physiological Responses	-Empatica E4 wristband. -Igroup Presence Questionnaire (IPQ) -System Usability Scale (SUS); absolute category rating (ACR); self-assessment manikin (SAM); NASA-TLX and SSQ	The immersive set-up provided a better physiological response. The dynamic immersive simulator without adequate motion configuration may lead to an unpleasant experience with a high cognitive task load	-assistive technology (AT) -VR for training applications (VRTA) - Quality of Experience (QoE) studies to understand the user experience and quality of human-system interaction	imbalance in the groups in terms of numbers and gender and the lack of participants with impairment
Xinyi Ye Conference 2022 China	Presence, Engagement, Usability	Unified questionnaire on user experience (UX) in Immersive Virtual Environments (IVE)	The designed VLE enabled users to obtain a good sense of presence and engagement	VR based immersive learning environment. having tactile feedback enhanced presence and body tactile sensation in immersive environments	-lack of objective and professional indicators in the assessment process, such as students' EEG data and experts' scores on the system -the promotion and dissemination of VR environments to other science museums is still limited
Filippo Sanfilippo Conference 2022 Norway	Spatial Presence, Realism, Engagement, Involvement	Igroup presence questionnaire (IPQ)	The haptic-enabled framework improved student engagement and the perception of spatial presence, realism, and involvement	in the last years research groups have proposed wearable haptic interfaces, which enable a multi contact interaction with virtual or remote objects	the proposed framework could be used to develop teaching modules and to test the concept with engineering students in an experimental setting.

Immersion

As Table 4 shows, immersion was the studied variable in four articles and two conferences in the domain of skills learning and education in general. The earliest journal article by Chakravarthy et al. (2018) developed an integrated haptic system for medical skills training by simulating upper gastrointestinal endoscopy and applied an improvised immersion questionnaire as a subjective measurement. Another article by Kim et al. (2019) analyzed immersion by tracking heart rate data during the most fearful parts of the Outlast 2 horror game and confirmed that immersion, training effects, and intuitiveness were higher for stereoscopic 3D visualizations shown with HMD with the Phantom Omni, Phantom Desktop, or Novint Falcon haptic devices compared to displays on a flat screen. Zenner et al. (2020) introduced a novel multi-sensory VR system with haptic feedback for immersive process model exploration for learning abstract data such as event-driven process chains (EPCs). Immersion was measured with the SUS – Slater-Usoh-Steed Presence Questionnaire and the authors determined that passive haptics maximize immersion for experience-focused VR. Lontschar et al. (2020) utilized the Game Experience Questionnaire and Game Immersion Questionnaire and established that neither learning in a MR environment compared to learning in pure VR was strictly better than the other in terms of immersion for learning a simple mechanical throw-and-hit task. Collaço et al. (2021) conducted an experimental study on 163 clinical dental students and determined that combining haptic feedback with HMD enhances the immersive VR experience, accuracy of task, and confidence in skills training in administering anaesthesia. The immersion and haptic feedback impacts were analyzed by comparison of the immersed and non-immersed groups through technical skill features and subjective variables. The latest source focusing on immersion was a conference paper from Salgado et al. (2022) who outlined a Quality of Experience Evaluation (QoE) for an immersive multisensory wheelchair training simulator serving as a form of assistive technology (AT). Reportedly the immersive set-up resulted in better physiological response according to implicit data from the Empatica E4 wristband and explicit data from post-experience questionnaires such as the Igroup Presence Questionnaire (IPQ) and System Usability Scale (SUS). Also, the authors noted that the dynamic immersive simulator without adequate motion configuration may lead to an unpleasant experience with a high cognitive task load.

Presence

Presence was studied in three articles and four conference sources in the context of education and skills training as informed by Table 4. The article from Kwon (2019) used the presence questionnaire from Witmer and Singer (1998) in experiments among 42 fourth-grade students and confirmed that tactile interactivity and presence improved with the use of enhanced interaction technologies in experiential education with HMD-based immersive VR technologies. Also, Kim (2020) proposed the visual impairment virtual reality (VIVR), a skills training walking system for the visually impaired integrating a haptic white cane prototype in VR to assist in preparing for the real world. The presence questionnaire from Witmer and Singer (1998) was applied among 20 visually acute users and established that the proposed VIVR provided a satisfactory presence in the interface experience.

In their article, Chrysanthakopoulou et al. (2021) tested the "Personalised interaction with Culture Realities Virtually Enhanced (CuRVE)" framework used for the education of historical event interpretation by adopting the Questionnaire of Presence (QoP) (Witmer and Singer, 1998). The results outlined that engaging multiple senses and visual manipulation in an immersive 3D environment with haptic gloves can effectively enhance the perception of visual realism and sense of presence, thus improving the educational and informative experience in a museum. The authors claim that such applications could benefit cultural institutions. Similarly, the conference from Ye et al. (2022) adjusted a UX questionnaire for IVE, developed by Tcha-Tokey et al. (2016) specifically for edutainment IVE, to measure the effectiveness of force feedback-enabled VLE for education in the China Science and Technology Museum. They confirmed that the Geomagic Touch Pen facilitated object interaction in the VLE and increased the sense of presence and engagement among 30 high school students. According to the conference source, Gisler et al. (2021) applied the SUS presence questionnaire in a preliminary evaluation of a Virtual Training Environment (VTE) for an industrial pipe pressing task with VR gloves. Results showed that the system satisfied trainees, by providing a reasonable sense of presence and small levels of task load. The conference source from Moosavi et al. (2022) adopted the QoP from Witmer and Singer and outlined that a haptic retargeting approach increased participants' sense of presence in the virtual environment for teaching skills in "Endotracheal intubation" to novice medical students. The source informed that this model allowed the virtual hands to be closer together while in reality, there was a small distance between them. This solution was deemed as a great alternative to costly solutions such as

VR robotic hand gloves and this method could potentially be integrated in other fields and applications of virtual reality. Sanfilippo et al. (2022) used the Igroup Presence Questionnaire (IPQ) to evaluate a novel haptic-enabled framework for hands-on e-Learning, which allowed a fully immersive tactile, auditory, and visual experience to safely access digital laboratories. The authors confirmed that the framework enhanced student engagement and the perception of spatial presence, realism, and involvement and thus hinted at its potential application for the development of teaching modules and future validation among an experimental sample of engineering students.

To summarize, the results showed that haptic-enabled IVR simulations improved immersion for skills training in upper gastrointestinal endoscopy, anaesthesia administration, and in learning to use a wheelchair. In educational settings passive haptics maximized immersive sensations for experience-focused learning as measured with the Slater-Usoh-Steed (SUS) questionnaire. The PQ, adjusted UX questionnaire for IVE, and IPQ measurements established that haptic technologies enhanced presence in IVR educational settings like experiential learning environments, museums, and digital laboratories, respectively. According to the PQ, haptics improved presence for skills training in walking for the visually impaired and in endotracheal intubation for novice medical students, while based on the SUS presence questionnaire VR gloves enhanced presence for skills training in an industrial pipe pressing task.

Leisure and Culture

The general details regarding the nine sources categorized in this domain were organized in Table 5. Insights regarding the studied variables, applied measurements, findings, relevant concepts, and opportunities and limitations were outlined for each source in Table 6.

Table 5

General Source Characteristics for the Leisure and Culture Category

Author	Source	Country	Year	Study design	Sample	Haptics	IVR system
Felix Born	Conference	Germany	2020	experiment	82	HTC Vive	HTC Vive wireless

Author	Source	Country	Year	Study design	Sample	Haptics	IVR system
Angelina Aleksandrovich	Journal Article	Germany	2020	experiment	140	Vibrating Motors Wearable	Oculus Quest VR HMD
Kathy A. Mills	Journal Article	Australia	2021	experiment	44	Google Tilt Brush	HTC Vive system
Gina Clepper*	Conference	United States	2022	user study	31	Vibrotactile Motors	Oculus Quest 2
Shuo Feng	Journal Article	China	2022	user study	12	HTC Vive	PSK is a hybrid VR design system; Wacom digital tablet and stylus' pressure
Emma, EF, Fallows	Conference	UK	2022	user study	59	Sense Glove	HTC Vive, Meshroom by AliceVision, Unity
Mounia Ziat	Journal Article	United States	2022	2 x 2 experimental design	15	Vibrotactile Ultraleap	Oculus Quest 2
Zhuoshu Li	Conference	China	2023	Participatory design	12	Fans	Oculus Quest 2
Justine Saint-Aubert	Conference	France	2023	user study	20	Vibrotactile Actronika	Unity 3D, HTC Vive Pro

Table 6

Relevant Insights Extracted from Sources in the 'Leisure and Culture' application area.

Descriptives	Variable	Measurement	Findings	Concepts	Limitations/ Opportunities
Felix Born Conference 2020 Germany	Presence, Exertion, Motivation	- Borg Scale - perceived exertion. - Intrinsic Motivation Inventory (IMI) - IGroup Presence Questionnaire (IPQ) - International Physical Activity Questionnaire (IPAQ)	using a heavy controller can significantly increase the exertion without reducing the motivation in contrast to using an HTC Vive controller.	- Virtual Reality (VR) exergaming	Need to assess longer gameplays assessment of exertion.
Angelina Aleksandrovich Journal Article 2020 Germany	Sexual arousal	-self-report forms filled in by participants -direct participant interactions on a one-to-one basis and in a group -self-assessment of arousal levels before, during, and after the trial	-haptic and olfactory cues increase arousal levels.	cross-modalism of senses;	same approach can be extended for testing human interaction with biologically inspired intelligent robots [46] and/or humanoid robots
Kathy A. Mills Journal Article 2021 Australia	enabling and constraining features of the virtual painting	-story writing, interviews, video observations, screencasts using OBS Studio, videos of the virtual painting filmed with Google Tilt Brush	sensory illusion was found to be both constraining and enabling, with the lapses or gaps more often noted	Transmediation is a vital learning and knowledge generation process	VR technologies can support many pedagogies, with clear advantages for experiential and situated learning, and applied knowledge. VR painting lacks the haptically-perceived information to create a sensory illusion of painting against a physical surface.
Gina Clepper Conference USA 2022	Immersion	Questionnaire on their experience	carefully handcrafted vibrotactile signals can enhance the sense of	Affective communication is a perspective applied in studies to investigate the role haptics are	Investigate how the efficiency of actuation components (palmScape) being used to create the feedback play a role in

Descriptives	Variable	Measurement	Findings	Concepts	Limitations/ Opportunities
			immersion in virtual reality	playing in enhancing UX	delivering the multiplexed signals to the skin contact. -limitation is the inability to disentangle participants' perceptions of realism and immersion.
Shuo Feng Journal Article 2022 China	Usability	Creativity Support Index (CSI) questionnaire (Cherry and Celine 2014)	The use of pressure property of the stylus could improve the efficiency while drawing	Quill (Quill) and Tilt Brush -Flying Shapes allows users to design more detailed CAD. VR Ink designed the tool in the shape of a pen, more in line with user habits.	- investigate collaborative design allowing multiple contributors to participate in a VR design project - explore the differences between a broader range of materials and their effect on UX - Designing for a long time could easily lead to physical fatigue -drawing in the air still unrealistic compared to traditional painting due to the lack of tactile feedback
Emma, EF, Fallows Conference UK 2022	usability, realism	User Interface Satisfaction Questionnaire (QUIS)	haptic gloves offer potential to enhance a VR experience for museum visitors by added the sense of touch thus creating new dimension to what the visitor can do compared to physical displays	-Multi-sensory learning experience -Photogrammetry is a technique used to take a physical object or environment and deconstruct it into a 3D digital model using high-quality photographs	- Haptic technology is still in its very early stages and has a long road of potential to create more vigorous and polished haptic gloves that can offer full accessibility in virtual reality to interact freely. -The Sense Glove haptic device was unable to provide a weighted simulation and the ability to use fingertips to feel texture precisely
Mounia Ziat Journal Article 2022 US	Immersion	Simulator Sickness Questionnaire (SSQ); Immersive Tendencies Questionnaire (ITQ) (Witmer and Singer, 1998). Visual analog scale (VAS) walking sensations	passive haptic sensations on user feet while physically motionless and visually moving in the world could have increased the conflict between users' proprioceptive and visual systems. -any haptic combination enhanced the experience for those who felt more immersed	Passive haptics refers to tactile sensations felt on the skin without active user exploration. The PDK Emergence Gallery- new multimedia immersive experience combining science, art, and technology	the system can be improved by adding a self-view avatar that has been shown to enhance the sensation of walking, presence, and leg action, specifically when combined with passive haptics
Zhuoshu Li Conference 2023 China	Immersion	participants were asked to describe their feeling of immersion during painting with examples	participants thought the existing applications lacked sensory feedback, with complex interactions that lowered immersion	multisensory interaction can activate people's brain and facilitate the engagement of body	-Improvement of system by evaluating it through comprehensive user study and iterating it according to feedback. -Hopeful to inspire the design of future VR painting systems
Justine Saint-Aubert Conference 2023	co-presence, leadership, and persuasion	-Co-presence by Bailenson et al. -Leadership was measured with the	a positive impact of speech-synchronized vibrotactile feedback on co-	Vibrotactile feedback has been synchronized with speech to	-could help reduce biases during verbal communication, such as increasing persuasion and co-presence of shy

Descriptives	Variable	Measurement	Findings	Concepts	Limitations/ Opportunities
France		question proposed by Slater et al. -Persuasion with question suggested by Hanus et al.	presence, leadership, and persuasion of other agents	improve speech perception of impaired people	participants or women who are often perceived as less dominant than men

Immersion

As Table 6 shows, immersion was the focus of three sources in the *Leisure and Culture* application area. The article from Ziat et al. (2022) reported a 2 x 2 experimental design in which 15 participants completed the Immersive Tendencies Questionnaire (ITQ) from Witmer and Singer (1998) to evaluate passive haptics in a non-interactive virtual walking experience for visual art exploration. Haptic feedback provided to the feet via a vibrotactile Ultraleap device with Oculus Quest 2 was found to aid virtual walking for users with high immersive tendencies. The article suggested the addition of a self-view avatar to enhance presence when combined with haptics and also mentioned the PDK Emergence Gallery, which is a novel form of multimedia immersive experience combining science, art, and technology, developed by an artist named Pamela Davis Kivelson. Clepper et al. (2022) studied the role of vibrating haptics on immersion and UX in a simulated haunted house user study with 31 participants. By collecting adjective data through a questionnaire, the outcomes showed that carefully handcrafted vibrotactile signals can enhance the sense of immersion in virtual reality compared to a repeated multiplexed signal. The most recent conference source from Li et al. (2023) proposed a design for a smart VR painting system integrating multisensory interaction with controllers and fans, as well as artificial intelligence assistance. In a participatory study, twelve respondents described their feeling of immersion during painting using two of the most popular commercial VR painting applications - Painting VR and Tilt Brush. The results showed that the application lacked sensory feedback and complex interactions diminished immersion.

Presence

A conference source by Born et al. (2020) studied the concept of Virtual Reality (VR) exergaming in a sample of 82 participants by applying the IPQ to measure presence. The results showed that using a heavy controller could significantly increase the exertion without reducing the motivation in contrast to using an HTC Vive controller. Reportedly, the haptic feedback provided by the passive haptic controller could not increase the experience of presence significantly, but a positive trend was noted. A conference paper from Saint-Aubert et al. (2023) researched how tactile feedback from vibrations synchronized with speech could impact aspects related to VR social interactions such as persuasion, co-presence, and leadership. Co-presence was measured through questions proposed by Bailenson et al. (2005) and the results from a user study showed a positive impact of speech-synchronized vibrotactile feedback on co-presence, leadership, and persuasion of other agents.

To conclude, haptic feedback enhanced immersive experience in a VR gallery by aiding virtual walking for users with high immersion tendencies as measured with the ITQ. However, users' immersion was lowered by complex interactions and lack of sensory feedback in VR painting systems using the Oculus Quest 2 controllers. According to the IPQ, presence was not affected by a passive haptic controller in exergaming, although a positive trend was noted. The questionnaire from Bailenson et al. (2005) confirmed the positive effect of speech-synchronized vibrotactile feedback on co-presence of other agents in a VR meeting room.

Design and Evaluation

Design and Development

The characteristics presented in Table 7 show that there was a total of twelve sources (five conference sources and seven articles) organized in this category. As shown in Table 8 one journal article studied both immersion and presence, three conferences and three articles focused on immersion, and one journal source researched presence.

Table 7

General Source Characteristics for the Design and Development Category

Author	Source	Country	Year	Study design	Sample	Haptics	IVR system
Jinmo Kim	Journal Article	South Korea	2017	experiment	21	Vibrotactile Motors	Oculus Rift, Leap Motion
Saurabh Jadhav	Conference	United States	2017	informal pilot study	15	Wearable Gloves	Oculus Rift
Edouard Callens	Conference	France	2018	Pilot test to investigate usability	6	Pressure Matrix	VE prototyped in Unity3D
Seonghoon Ban	Journal Article	South Korea	2019	User studies	12	Direct Force Feedback (DFF)	VR application
L. Almeida	Conference	Portugal	2019	comparative study	22	Glove	Vive VR System having two AMOLED screens, a resolution of 1080 x 1200 pixels per eye (2160 x 1200 pixels combined); HTC Vive trackers
Mohammed Al-Sada*	Journal Article	UK	2020	user study	20	Wearable Robots	Oculus Rift CV1
Steeven Villa Salazar	Conference	France	2020	Three perceptual studies	28	Novint Falcon Grounded Wearable Fingertip Cutaneous	haptic system composed of a Novint Falcon grounded interface, a wearable cutaneous device for the fingertip, and a Unity-ready smartphone
Filippo Sanfilippo	Conference	Norway	2020	two case studies	-	Vibrotactile Motors	Leap Motion sensor, Oculus Rift, Unity
Alexander Achberger	Conference	Germany	2021	qualitative user study	6	Ungrounded Force Feedback	HTC Vive Pro
Alexander Achberger*	Journal Article	Germany	2022	user studies	5	Ungrounded Force Feedback	HTC Vive Pro
Uriel Martinez-Hernandez*	Conference	UK	2022	experiments	5	Wearable Fingertip	Oculus Rift Leap Motion
Peter Kudry*	Journal Article	Japan	2022	Pilot experiment	8	Stylus	Meta Quest 2

Table 8

Relevant Insights Extracted from Sources in the 'Design and Development' Category

Descriptives	Variable	Measurement	Findings	Concepts	Limitations/ Opportunities
Jinmo Kim Journal Article 2017 South Korea	Presence, Immersion, sickness	- Questionnaire of Presence (QoP) (Witmer and Singer, 1998) -simulator sickness questionnaire (SSQ)	the proposed hand haptic system provided greater presence, more immersive environment in the virtual reality and. does not cause VR sickness in VR application without camera movement	portable hand haptic system capturing tactile senses and hand motions and processing them within the haptic system can become complicated and expensive	The proposed haptic system: - must be coupled with commercial applications in order to obtain more objective verification. -can be applied to PC but also to a highly accessible mobile platform VR

Descriptives	Variable	Measurement	Findings	Concepts	Limitations/ Opportunities
					- additional motion-sensing device such as leap motion is needed
Saurabh Jadhav Conference 2017 US	functionality	Anecdotal feedback	All users agreed to the statement that the haptic glove. increases the immersive experience and augments the graphics environment.	synthetic haptic user interfaces greatly increase the degree of immersion in the virtual environments. Haptic characteristics: -tactile (temperature, vibrations, and texture) -kinesthetic (inertia, shape, weight, and deformation) -chemesthesis (reaction to certain chemicals on the skin)	The glove could potentially be developed to accurately simulate both tactile and kinesthetic feedback in a single haptic. -Improvements can be made in control of soft robotic board to reduce the lag in the fluidic control board -include more DOF
Edouard Callens Conference 2018 France	Usability	Interviews Visual Analysis Time	low-cost tactile surface device designed to sculpt 3D meshes; first step toward intuitive mesh manipulation within VE	-3D Mesh Manipulation and Virtual clay -Ishii et al. mentioned Illuminating Clay and SandScape - multi-cells architecture inspired hardware design - pressure sensor customized from Velostat fabric (piezoresistive material made of carbonized polymer whose resistance changes depending on applied pressure)	-the device is currently suitable for interaction with one finger. It can be extended to multiple fingers. blob detection could detect multiple finger inputs on the device. With this feature, more interaction techniques could also be supported such as twisting, bending, or stretching a 3D mesh
Seonghoon Ban Journal Article 2019 South Korea	presence, immersion	In-depth interviews	Direct Force Feedback (DFF) increased presence and immersion within the VR environment compared with an experiment without DFF.	-shape-changing devices that impart sensations of weight (Shifty); - “jamming suit”, conveys the sensation of freezing to the human body.	- DFF can be used in educational and professional environments in addition to consumer use. For example, DFF can be used to guide visually impaired people towards the target direction
L. Almeida Conference 2019 Portugal	immersion, presence, usability	-Time, -IBM Computer Usability Satisfaction Questionnaire and from Usoh and Slater Presence Questionnaire	cyber-glove contributes for a greater naturalness; sense of embodiment is significantly improved with the cyber-glove	cyber-gloves open a new range of applications in gaming, industry, surgery training, rehabilitation, and education. Gloves with haptic feedback are being proposed for hand and finger rehabilitation or surgery training.	the size of the glove is not suitable. for every user due to different hand sizes, and the movement of the virtual fingers exhibits a small latency in relation the real fingers movement, due the animation model.
Mohammed Al-Sada* Journal Article 2020 UK	immersion, usability, wearability	- adjusted Questionnaire for User Interaction Sat- isfaction (QUIS) (Chin et al. 1988). -semi-structured interview covering aspects of usability and wearability	robot weight, movements and the inertia of its movements broke the immersion	Gestural feedback constitutes tangential and shear forces applied on the skin. - Delivering taps on front torso and back	-can have intriguing applications across different domains - realizing Haptic Snakes for daily use has various challenges and requires significant development to ensure stability and safety.
Steeven Villa Salaza	functionality	questionnaire	-can alter the perception of stiffness	Wearable haptics and tangible objects	these results pave the way for innovative haptic

Descriptives	Variable	Measurement	Findings	Concepts	Limitations/ Opportunities
Conference 2020 France			by varying the pressure applied by the wearable device. - can simulate the presence of bumps and holes by providing timely pressure and skin stretch sensations	-Tangible objects effective at conveying haptic information about distributed shape and weight, improving the immersiveness of Virtual Reality	approaches in VR/AR, whose objective is to better exploit the many new haptic technologies providing haptic sensations in a simple and inexpensive way
Filippo Sanfilippo Conference 2020 Norway	presence, performance	subjective questionnaire adopting a 9-point Likert scale.	that the proposed haptic-enabled framework improves the performance and illusion of presence.	Multi-modal rendering strategies. The multi-modal rendering is achieved by simultaneously combining auditory, visual, and tactile rendering together.	-This architecture helps researchers to incorporate haptic capabilities to their systems conveniently. - It is therefore possible to create a variety of local and remote applications. -One of the most promising application scenarios is gaming.
Alexander Achberger Journal Article 2022 Germany	immersion	7-point Likert scale questionnaire - explain definition of immersion by Witmer et al. (2005), to participants and then ask them to rank their perceived level of immersion	PropellerHand improves users' immersion in virtual reality	ungrounded haptic devices in the following categories: air-based, drone-based, propeller-based, and other methods	-potential benefits in using PropellerHand in immersive visualization - limitation is when PropellerHand obscures important information due to its size
Alexander Achberger Conference 2021 Germany	immersion	7-point Likert scale questions (1: very strongly disagree - 7: very strongly agree). The questions asked in how far PropellerHand increased the immersion in VR	increased immersion	grounded and ungrounded devices, based on attachment. Grounded devices are fixed to the user's environment. They are mostly large and expensive but can generate strong forces with high accuracy. Ungrounded devices can be handheld, attached to the user's body, or move on their own.	-more potential in the simulation of soft resistances than impact forces, such as weight simulation, pressing against soft objects, or simulating current. -noise is an issue even when wearing earplugs or headphones - the device cannot provide thrust in the left-right direction or rotate and move the user's hand in different directions simultaneously
Uriel Martinez-Hernandez Conference 2022 UK	functionality, immersion	participants were asked to indicate, in a range of 1 to 10, the level of immersion perceived for each feedback modality while pressing the buttons.	-proposed wearable fingertip device is capable of reliably delivering individual and combined touch, sliding and vibration feedback to the human fingertip.	Wearable haptic technology Fingertip motion tracking	offers an alternative platform with the potential of enhancing the feeling and experience of immersion in VE, exploration of objects and telerobotics
Peter Kudry Journal Article 2022 Japan	immersion	User Experience Questionnaire (UEQ)	suggest the potential of a combination of haptic force feedback and ambulatory VR to improve immersion in free-range virtual environments.	-immersive CAD -substitute multimodal sensory feedback can enhance overall task performance as well as the perceived sense of presence	-Changing the parameters (gain, friction, shear, etc.) of each haptic effect - choice of materials was not optimal.

Immersion and Presence

There was one paper focusing on both feelings of immersion and presence. Ban and Do (2019) conducted in-depth interviews with twelve participants and discovered that Direct Force Feedback (DFF) increased presence and immersion within VR environments. Also, the source hinted that DFF can be used in educational and professional environments, as well as consumer use. Potential applications proposed were that DFF can be used in VR sport games, as interaction interface in social VR, or to guide visually impaired people towards the target direction.

Immersion

After conducting a comparative study with 22 participants by adjusting the Usoh and Slater Presence Questionnaire, Almeida et al. (2019) reported that in comparison to controllers, the cyber-glove prototype they designed facilitated greater naturalness, significantly enhanced the sense of embodiment, and offered similar degrees of usability and immersion. The source further reported that cyber-gloves offer a new range of application in gaming, industry, surgery training, rehabilitation, and education. Al-Sada et al. (2020) proposed a design of multi-haptic feedback wearable robots and after conducting semi-structured interviews on usability and wearability they determined that the device weight, movements, and the inertia of its movement's broke immersion. According to both an article and a conference source Achberger et al. (2022) developed the ungrounded force feedback device PropellerHand and confirmed that it improved users' immersion in virtual reality by explaining Witmer et al. (2005) definition of immersion to the participants and then asking them to rank their perceived level of immersion. The paper discussed the categorization of ungrounded haptic devices into air-based, drone-based, propeller-based, and others. The source outlined the limitation of PropellerHand to obscure important information due to its size and noted the potential benefit of the device in immersive visualization. Kudry and Cohen (2022) performed a pilot study experiment with the Meta Quest 2 to test their prototype of a wearable force-feedback mechanism for a free range IVR experience. The insights from the User Experience Questionnaire (UEQ) showed the potential of combining haptic force feedback with walking VR to improve immersion in free-range VE. In a recent conference source, Martinez-Hernandez and Al (2022) asked five participants to score their perceived level of immersion on a scale from one until ten and concluded that their wearable fingertip device prototype can enhance the feeling of immersion and interaction in virtual reality environments, but also in applications such as telepresence, telerobotics and gaming.

Presence

The only journal source that studied presence was from Kim et al. (2017) who designed a wearable hand haptic system providing vibration and heat to each fingertip (thumb and index finger). According to the results from the applied Witmer and Singer's presence questionnaire their prototype provided greater presence and a more immersive environment in virtual reality when compared to a condition with motion tracking only. The authors suggested that the system can be applied not only to a PC but also to a highly accessible mobile platform VR.

Overall, this group introduced haptic device prototypes such as DFF, which increased both immersion and presence in IVR according to in-depth interviews. The Usoh and Slater Presence Questionnaire established that cyber-glove prototype offered similar degree of immersion and usability compared to controllers. Nevertheless, immersion was broken for a prototype device of a multi-haptic feedback wearable robot due to its weight, movement, and movement inertia. Based on the UEQ, another wearable force-feedback mechanism showed potential to improve immersion in free-range VE. A wearable hand haptic system providing vibrating and thermal feedback enhanced presence and immersion in VR as measured with the PQ. Two sources relied on users to score their perceived level of immersion, and this resulted in positive evaluations of the designed prototypes of a wearable fingertip prototype and an ungrounded force feedback in terms of immersion.

Testing

The general characteristics of all eighteen sources placed in this category are shown in Table 9 and notably only three of them were journal articles. According to Table 10, there were two conference sources that researched both immersion and presence and they were summarized first. Afterward, four conferences focusing on immersion were discussed, followed by a journal article, and seven conference sources that studied presence were presented.

Table 9

General Source Characteristics for the Testing Category

Author	Source	Country	Year	Study design	Sample	Haptics	IVR system
Oliver Kaul	Conference	Germany	2017	user study	20	Vibrotactile Motors	Oculus Rift CV1, Unity
Myungho Lee	Conference	United States	2017	between-subject design three conditions	41	Platform Vibrotactile	Oculus Rift DK2 head-mounted display (HMD) tracked by the Oculus tracking camera;
Tobias Gunther	Conference	Germany	2019	within-subjects design with between-subjects' factors.	24	HTC Vive	HTC Vive
Ping-Hsuan Han	Conference	Taiwan	2019	user study	21	Multiple tactile Display	VIVE Pro HMD and WH-1000XM3 noise cancelling headphones
Shaoyu Cai	Conference	Japan	2020	3 user-perception experiments	12	Gloves	HTC Vive Pro; Leap-Motion hand-tracking
Alexander Wilberz	Conference	United States	2020	User Study	16	Robot Arm	Oculus Rift CV1.
Teng Han	Conference	United States	2020	formative user study	12	Tactile Surface	HTC VIVE Pro (study 2)
Neung Ryu	Conference	South Korea	2020	2 separate user studies	16	Handheld vibrating	The VIVE HMD
Eros Viola	Conference	Italy	2021	experiment	6	Manus Prime	Oculus Rift CV1, leap Motion
Neung Ryu	Conference	South Korea	2021	within-subjects design with two factors	12	Controllers	HTC VIVE PRO, Unity,
Elisa Galofar	Journal Article	Germany	2022	user studies	12	Teslasuit	Oculus Rift S

Author	Source	Country	Year	Study design	Sample	Haptics	IVR system
Reza Amini Gougeh	Conference	Canada	2022	pilot experiment	11	bHaptics	Oculus Quest VR headset:16 ExG sensors connected to a wireless bioamplifier; OVR ION2 scent diffuser device (OVR Technologies, USA)
Sungchul Jung	Conference	United States	2022	game experiment	78	Platform	VR headset (Vive Pro Eye)
Grzegorz Zwolinski	Conference	Poland	2022	user study	22	Platform	Unity and C# programming language; HTC Vive
Federico Morosi	Journal Article	Italy	2022	test campaign	10	Haptic Master	Oculus Rift, Leap Motion mounted on HMD
Xunshi Li	Conference	China	2022	preliminary experiment	15	Teslasuit	Oculus Quest 2
Lukas Gehrke	Journal Article	Germany	2022	experiment	20	VIVE tracker Vibrotactile	HTC Vive
Reza Amini Gougeh	Conference	Canada	2022	Pilot experiment with five conditions	11	bHaptics	Oculus Quest

Table 10

Relevant Insights Extracted from Sources in the Testing Category

Author	Variable	Measurement	Findings	Concepts	Limitations/ Opportunities
Oliver Kaul Conference 2017 Germany	immersion, presence	-the "Immersion Tendency Questionnaire" (ITQ) - the "Presence Questionnaire" (PQ).	some participants rated the vibrotactile feedback negatively in most of the statements while others rated it positively in most statements which comes down to whether they liked it overall or not	ActiveBelt is the first vibrotactile belt for directional navigation. Vibrotactile belts have been used to increase the situational awareness of gamers and for guiding visually impaired	Potential application in immersive games or VR training simulations where the level of presence or spatial awareness matters such as in complex maintenance jobs, anxiety therapy, or flight training. -low number of participants
Myungho Lee Conference 2017 US	social presence, avoidance behaviour	-social presence questionnaire by Bailenson et al. - PQ -informal comments on interaction verbally and on paper - head orientation and position and Skin Conductance Response (SCR)	Vibrotactile haptic feedback of Virtual Agent footsteps increases its' social presence	Midas touch phenomenon where casual touch, such as a tapping on one's shoulder, promotes altruistic behaviours and willingness to comply with the one who touched	-Superior headphones or masking sounds should be used -While debriefing the participants we noticed that some of them stated that they did not notice the vibrations. It seemed to happen. when they wore shoes with thick soles
Tobias Gunther Conference 2017 Germany	presence, UX	-the User Experience Questionnaire (UEQ). -Igroup Presence Questionnaire (IPQ). Objective: - task completion time -performance scores;	elastic feedback can enhance the sense of presence and improve subjective impressions of VR interactions	elastic (EL) feedback; isotonic (ISO) feedback	Next to realistic virtual worlds, abstract virtual data visualization environments are an opportunistic field.

Author	Variable	Measurement	Findings	Concepts	Limitations/ Opportunities
					-Limitation is that EL only applied to the arms of the used. -small sample size
Ping-Hsuan Han Conference 2019 Taiwan	immersion, QoE	questionnaire on perceived intensity and persistence -short interview; immersion and quality 7-point Likert scale; overall interview	participants rated their experience as more immersive and higher quality when they were in the cave and snow mountain environments, which were cool and cold scene. Both hot environments scored low.	locomotion techniques multiple tactile display	System could be affected by the indoor environment, such as whether the room is big or small, room ventilation, open or closed areas
Shaoyu Cai Conference 2020 Japan	presence	haptic-related questions from the presence questionnaire	using TAGlove in immersive VR could significantly improve users' experience of presence compared to current VR settings in the commercial markets. Thermal feedback improved VR experience	Pneumatic Thermal Control System - thermoelectric cooler (TEC) can provide thermal cues to simulate the perception of materials and support material identification. -HydroRing	thermal feedback of virtual materials contact might contribute to skill training (e.g., fire escape, surgery, etc.) -could enhance VR exploration for visually impaired people. -the control mechanism can be improved using the thermal sensor with higher response speed
Alexander Wilberz Conference 2020 US	emotional response, presence, realism, memorability	interviews, 9-point Self-Assessment Manikin (SAM) scale to rate emotional response in terms of valence and arousal	The improvement in emotional response (valence and arousal) is rather striking and seems to be stronger than the effect of the multisensory cues on presence.	directionality of haptic feedback; spatialized haptic cues	-Face Haptics system for fear-inducing or other adverse situations like phobia treatment or immersive horror games or to enhance positive experiences such as awe, compassion, or love. - advantage and limitation that it can reach parts of the face not covered by HMD
Teng Han Conference 2020 US	functionality	5-point Likert scale "I felt that I just touched [the item]"	temperature change is a key factor to generate wetness illusions, and pressure and friction are secondary factors that do not directly enhance wetness illusion	people commonly use their fingers to sense wetness and adapt their interactions with objects accordingly, such as adjusting grip forces upon sensing wet surfaces	Investigate the effect of Mouille on enhancing virtual presence and embodiment using Witmer and Singer's questionnaire and Gonzalez-Franco and Peck's questionnaire. -Future work should improve measurements and control of active

Author	Variable	Measurement	Findings	Concepts	Limitations/ Opportunities
					pressure and friction applied by users when using Mouille in VR tasks.
Neung Ryu Conference 2020 South Korea	Immersion, realism, enjoyment	questionnaire 7-point Likert scale questions about immersion, realism, and enjoyment. -post-hoc interview overall experience and various feedback.	participants rated the visual + haptic condition higher than the visual-only condition in terms of immersion, realism, and enjoyment	Just-Noticeable Differences (JND) Estimation	ElaStick's form-factor can be modified to support handheld interactions beyond shaking with one hand. -the heaviness of Elastic disturbed the haptic experience: - reduce weight by using smaller motors or reducing the size of the joint structure. -take advantage of the device's weight for generating stronger force feedback.
Eros Viola Conference 2021 Italy	presence, UX	-total time to completion (TTC) -error rate, -User Experience Questionnaire (UEQ) (Schrepp et al., 2014) -Igroup Presence Questionnaire (IPQ) (Regenbrecht and Schubert, 2002)	Due to the ease of interaction, the subjects seem to prefer the Controllers, then the Manus Prime haptic gloves, and then the Leap Motion	skeletal tracking features of an RGB-D sensor to build the user's avatar,	+The role of the haptic feedback in interaction should be further analysed. -drawbacks of our solution are caused by the problems of the RGB-D camera, which interferes with the HTC Vive tracking system, thus, hampering the use with the Manus gloves
Neung Ryu Conference 2021 South Korea	realism, immersion, enjoyment	-7-points Likert scale the perceived level of realism, immersion, and enjoyment of using the specified configuration. -post-hoc interviews to gather qualitative insights about the users' experiences	GamesBond increased the realism, immersion, and enjoyment of the VR experience, particularly for rendering soft and dynamic bodies. The findings supported the hypothesis that the system improves user engagement in VR.	inesthetic reference frame Bimanual Haptic Illusion	+ add sensing and input capabilities to the controllers. -The min-max ranges of motions are limited, and in the case of bending, the torque is uneven depending on the direction of motion due to the placement of the internal tendons.
Elisa Galofar Journal Article 2022	Realism	Respiratory Exchange Ratio (RER)	NMES is a well-suited technology for providing more realistic haptic	Haptic illusion is the most common approach adopted to merge virtual and augmented realities,	-more degrees of freedom should be included -could be used for a wide range of

Author	Variable	Measurement	Findings	Concepts	Limitations/ Opportunities
Germany			feedback during interaction with objects in a virtual environment	which can be achieved through vibrotactile or ultrasonic stimulations or with robotic force fields	applications involving the entire upper body that can be from surgical training to rehabilitation. -lack of stimulation from other muscle channels - no feedback on the hand palm during NMES
Reza Amini Gougeh Conference 2022 Canada	perceived immersion, engagement, presence, realism, overall QoE	- 5-point Likert-type scale questionnaire on perceived levels of immersion, presence, realism, engagement, and overall experience -real-time EEG/ECG/EOG	majority of the participants referred to the multisensory experience as enjoyable, more realistic, and mentioned that in the AVSH condition they had greater motivation to shoot the oranges to receive the desired multisensory feedback	immersive media experiences (IMEx) electrooculograms (EOG); electrocardiograms (ECG); Electroencephalograms (EEG)	+In the future, the real-time benefits of bio signals measurement, combined with the integration of ExG sensors directly on the VR headset, can enable user-aware game adaptation to maximize QoE
Sungchul Jung Conference 2022 US	Co-presence, QoE	Jung & Lindeman's quality model of VR experience	participants showed the highest perceptual response with vibration feedback during the game experience.	deeper understanding of shared VR experiences is needed	- subjective responses might not be sufficient for answering our research questions
Grzegorz Zwolinski Conference 2022 Poland	immersion	objective - EEG sensor and subjective (questionnaire) features	the haptic sensations induced by the SIM-Motion platform increase the users' level of immersion in the VR environment	Peripheral solutions stimulating and enriching VR experience are now typical, and many haptic systems are being developed for maximizing VR immersion	This platform can be easily adjusted to be used for rehabilitation for motor disabilities or phobias, rescue environments, and educational issues
Federico Morosi Journal Article 2022 Italy	Usability, task load,	-NASA TLX survey, -VR assessment questionnaire -self-made monitoring criteria	The haptic feedback has been evaluated less important than expected and the preferred haptic feedback (contact) is not the more efficient one (shaker)	implementation of haptic feedbacks for coordinated controls is aimed at improving the system usability and the operational indexes like time, energy efficiency, safety, and accuracy	It shows how the implementation of a haptic feedback, which renders a physical event, is not trivial and different solutions can lead to the same result
Xunshi Li Conference 2022	Presence	I group presence questionnaire (IPQ)	AmbientTransfer yields stronger presence than the two	Somatosensory equipment. Teslasuit is a smart textile suit that can provide full-body	+snowing conditions, could be converted to

Author	Variable	Measurement	Findings	Concepts	Limitations/ Opportunities
China			baselines, particularly from the "experienced realism" perspective.	haptic and thermal feedback through electrostimulation	electrostimulation in an equivalent way. -only dealing with the rainy ambient
Lukas Gehrke Journal Article 2022 Germany	presence	electroencephalography (EEG)	contributed towards the overarching goal to develop a continuous method to validate the effectiveness of haptic devices that foster presence experience	Prediction error' negativity (PEN) as a feature for fast, real-time, detection of VR system errors which may, in turn, cause a loss in the sense of physical immersion	Midline cingulate EEG sources contributed to prediction error ERPs, 'PENs', and may serve as a robust source to detect violations of user's predictions about the interaction with virtual worlds. - Due to the high-level of immersion in VR, classifying event-related activity such as that occurring during object interaction, may be improved by an unfolding of overlapping activity.
Reza Amini Gougeh Conference 2022 Canada	immersion, engagement index, arousal and valence indices, frontal alpha asymmetry, heart rate, several EEG sub-band powers, and eye blink rate	electroencephalography (EEG) electrocardiograph-y (ECG), electrooculography (EOG)	a significant impact of smells on sense of immersion and of haptic feedback on engagement. A complete multisensory immersive experience combining audio-visual-olfactory-haptic stimuli achieved the highest values across all ratings, including QoE	measurement of human influential factors (HIFs) is important for IMEX QoE measurement. Measuring HIFs and their influence on IMEx QoE can follow three principles: questionnaires, behavioural, and psychophysiological data analysis	Limitation due to sixth wave of the COVID-19 and restrictions

Immersion and Presence

Both conferences from Gougeh and Falk (2022) and Gougeh et al. (2022) reported the same pilot experiment study utilizing the bHaptics haptic sleeve and real-time electroencephalography (EEG), electrocardiography (ECG), and electrooculography (EOG) to measure both immersion and presence, next to realism, engagement, and UX. The results showed a substantial impact of smells on sense of immersion and of haptics on engagement. Also, the audio-visual-olfactory-haptic stimuli were rated the highest across all variables and QoE. The source emphasized the importance of human influential factors (HIFs) evaluation for immersive media experiences (IMEX) and suggested adhering to the following three principles: questionnaires, behavioral, and psychophysiological data analysis.

Immersion

Han et al. (2019) studied immersion and quality of their multiple tactile display haptic device prototype for simulating weather in the immersive environment, which can provide thermal, wind, and humidity feedback simultaneously in a room-scale space. Questionnaires using 7-point Likert scales were applied in user studies among 21 participants and determined that the immersive experience can be enhanced via the proposed haptic technique. Also, the cool and cold environments such as cave and snowy mountain scored higher on immersion and quality compared to the hot desert environments. Both conferences from Ryu et al. (2021) and Ryu et al. (2020) reported using 7-point Likert scale questions to measure immersion, realism, and enjoyment, as well as-post-hoc interviews to capture the overall experience and various feedback. Ryu et al. (2021) introduced their prototype controller GamesBond which afford users to perceive a single connected object between the hands, such as a jumping rope, and evaluated that they increased the realism, immersion, and enjoyment of the VR experience. Ryu et al. (2020) presented ElaStick, a variable-stiffness controller that recreated the sensation from shaking or swinging flexible virtual objects and reported results from a user experience study showed that visual-haptic condition was rated higher than visual-only in terms of immersion, realism, and enjoyment. A conference source from Zwoliński et al. (2022) measured immersion both objectively with EEG data and subjectively with a questionnaire and concluded that the haptic sensations induced by a vibrating platform increased the users' level of immersion in the VR environment.

Presence

Lee et al. (2017) researched social presence and avoidance behavior by applying the social presence questionnaire by Bailenson and the presence questionnaire by Witmer and Singer in a between-subject design study with three conditions on 41 participants who experienced a vibrating platform. The source concluded that vibrotactile haptic feedback of a Virtual Agent's footsteps increased its' social presence. Kaul et al. (2017) adjusted Witmer's "Immersion Tendency Questionnaire" (ITQ) and the "Presence Questionnaire" (PQ) for their user studies with a sample of 20 participants. The authors discovered that vibrotactile haptic feedback provided on the head through HMD enhanced presence in VR. The potential application was hypothesized in immersive games or VR training simulations where the level of presence or spatial awareness matters such as in complex maintenance jobs, anxiety therapy, or flight training. Günther et al. (2019) studied presence and UX with the Igroup Presence Questionnaire (IPQ) and the User Experience Questionnaire (UEQ) and confirmed that elastic feedback can enhance the sense of presence and improve subjective impressions of VR interactions. Cai et al. (2020) investigated how their pneumatic glove for thermal perception could impact users' sense of presence in immersive VR by conducting 3 user-perception experiments and using the haptic-related items from the Witmer and Singer's presence questionnaire. The research claimed that the gloves could significantly improve users' experience of presence compared to the current VR settings in the commercial markets.

Wilberz et al. (2020) measured presence with the IPQ questionnaire for their prototype of a robot arm haptic display attached to a HMD which provides localized, multi-directional, and movable haptic cues in various forms. Their second study demonstrated that integrating the prototype into a VR walkthrough can significantly enhance UX, presence, and emotional responses. Also, Viola et al. (2021) used the UEQ (Schrepp et al., 2014) and IPQ (Regenbrecht and Schubert, 2002) to measure presence and UX in an experiment comparing three different interaction technologies: a Leap Motion, the Manus Prime haptic gloves, and the Oculus Controllers. Due to the ease of interaction, the highest rated were the Controllers, then the Manus Prime haptic gloves, and then the Leap Motion. Jung et al. (2022) evaluated the effect of a vibrating platform among 39 dyads in a game experiment on co-presence by applying Jung & Lindeman's quality model of VR experience and outlined that vibration haptic feedback evoked the highest perceptual response during the game experience. Li et al. (2022) measured presence with the IPQ questionnaire in a preliminary experiment with 15 participants using the Teslasuit and Oculus Quest 2 and reported that their framework for obtaining and converting video ambient factors such as rain intensity into dynamic electrostimulation haptic feedback can considerably enhance the users' presence. Lastly, the article from Gehrke et al. (2022) contributed towards the overarching goal to develop a continuous method to validate the effectiveness of haptic devices that foster presence experience. Their experiment on a sample of 20 participants measured the effect of vibrotactile feedback in the HTC Vive IVR system on presence with electroencephalography (EEG). The article provides a design of a new method based on neural interface technology to assess the effectiveness of haptic devices that foster the emergence of presence experience.

Overall, sources in the *Testing* group demonstrated that electrograms such as EEG, ECG, and EOG were applied in more recent studies as objective measures of users' immersion and presence in haptic-enabled IVR systems. Also, more papers in this domain researched presence instead of immersion, by applying a wider range of subjective questionnaires. Social presence of a virtual agent was evaluated positively with Bailensons' questionnaire for a vibrating tilt platform, the ITQ and PQ confirmed that a vibrotactile HMD enhanced presence, and IPQ confirmed that both elastic feedback and a robot arm haptic display enhanced presence. According to the PQ, a new pneumatic thermal glove prototype could significantly improve presence. A framework for translating video ambient into electrostimulation haptic feedback with the Teslasuit enhanced presence, while a new neural interface using EEG was designed to measure the effectiveness of haptic devices eliciting presence.

Other

General characteristics for the nine sources in this category were outlined in Table 11. Insights from extracted data were presented in Table 12, according to which only two sources studied immersion. Also, ownership illusion was the focus of three sources in this group.

Table 11

General Source Characteristics for the Other Category

Author	Source	Country	Year	Study design	Sample	Haptics	IVR system
Alexandre Gardé	Conference	Canada	2018	lab experiment	46	D-Box	Oculus Rift Cv1
Alexandre Gardé	Journal Article	Canada	2018	between-subject experiment	45	D-Box Vibro-kinetic	Oculus Rift Cv1
Dario Pittera	Conference	UK	2019	control experiments	20	Ultrahaptics	Oculus Rift DK2, Leap Motion tracking
Da-Chung Yi	Conference	Taiwan	2020	user study	12	Force Feedback	ELASTIC-BOX, ELASTIC-ROPE
Gabriele Fusco	Journal Article	Italy	2020	experiment	30	Vibrotactile Motors	Oculus Rift
Yan Yixian	Conference	Japan	2020	user study	12	Ungrounded Encounter Feedback	HTC Vive
Dongbin Kim	Conference	United States	2021	user studies	-	HTC Vive	HTC Vive
Difeng Yu	Conference	Australia	2022	-	-	Drones	Oculus Quest 2; RoboMaster Tello Talent micro-drone
Dixuan Cui	Conference	United States	2022	2x2 within-subject VR study	24	Oculus Quest 2 Controllers	Oculus Quest 2, Unreal Engine 4, inverse kinematics (IK) partial body tracking system using controllers and HMD locations

Table 12

Relevant Insights Extracted from Sources in the Other Category

Descriptives	Variable	Measurement	Findings	Concepts	Limitations/ Opportunities
Alexandre Gardé Journal Article 2018 Canada	immersion	head tracking via Facereader (Wageningen, Netherlands), psychophysiological state via EDA, ECG, SCR, PNS	VK contributes to the VR experience by pushing the immersion further, inducing a better psychophysiological state that is more optimal for VR experience and by fostering more natural head movements for users, leading to a higher sense of presence in the VR	vibro-kinetic (VK) technologies Cybersickness - cybersickness could be linked with feelings of presence. -an inverse relation between cybersickness and sense of presence. subjective vertical (SV) conflict theory	VK technology could help VR users to autoregulate and stay in a relaxed state leading to fewer symptoms of cybersickness. This study provides encouraging results for future research in this area. -the study was conducted with a passive VR stimulus - too short
Alexandre Gardé Conference 2018 Canada	psychophysiological states	psychophysiological states: -electrodermal activity, -heart rate - user perceptions. Sympathetic nervous system (SNS) reactions were measured using electrodermal activity (EDA). Parasympathetic nervous system (PNS) reactions were measured using high frequency (HF) of heart rate variability (HRV).	VK seems to create a psychological state that requires less conscious autoregulation, which could suggest that users experience less cybersickness in this condition	VK technology can be defined as artifacts providing whole-body motion and vibration feedback (0-100 Hz frequency response) synchronized with the media scenes	VK technology could generate 30% more emotional response in a VR context. -longer stimuli would need to be tested. -Repeat usage should also be investigated. -used a passive VR experience. Future studies should be conducted to test our hypotheses using an interactive VR task.
Dario Pittera Conference 2019 UK	ownership, illusion	a questionnaire for the subjective feeling of the illusion, and the proprioceptive drift measurement	VHI of ownership toward virtual arm is subjectively felt during congruent condition, however also for multiple incongruent conditions	proprioceptive drift Player Involvement Model (PIM) -users need to be unaware of the presence of the tactile device, while still being able to feel the stimulation generated from them -rubber hand illusion (RHI)	These findings will be useful to design more compelling and immersive scenarios in multimedia technology such as movie theaters, home cinemas, and VR interactions. -the range of perceivability of the tactile stimulus on the body is still limited, following the Pacinian mechanoreceptors distribution on the body
Da-Chung Yi Conference 2020	postural stability	simulator sickness questionnaire (SSQ)	Because Elastic-Rope and Elastic-Box provide passive force feedback to the	Locomotion. The postural instability theory states that prolonged	This work suggests that passive force feedback can effectively reduce VR sickness

Descriptives	Variable	Measurement	Findings	Concepts	Limitations/ Opportunities
Taiwan			user, they can help users increase their postural stability	postural instability is the cause of motion sickness symptoms	
Gabriele Fusco Journal Article 2020 Italy	ownership, illusion	questionnaire on Feeling of Ownership (FO) and Vicarious Agency (VA) the illusory sensation to have motor control over the external body	closer visual resemblance between the virtual and real limb results in a greater effect on proprioceptive processing	tendon vibration (TV) elicits illusory kinesthetic sensations around the vibrated body parts. -embodiment illusion (the sense of embodying a virtual surrogate)	Application in investigating clinical symptoms associated with body representation disorders such as somatoparaphrenia and alien hand syndrome. - developing assistive technologies that harness multisensory integration to improve motor performance in people with sensorimotor diseases
Yan Yixian Conference 2020 Japan	immersion, UX	Witmer and Singer's Presence Questionnaire, objective measures to assess system performance, and subjective measures to assess the user experience	ZoomWall improved participants immersive and fun experience of the VR environment	Room-scale virtual reality (VR) -haptic retargeting	Our participants suggested embodying the ZoomWalls in the simulation using semi-translucent assets/objects. -noise from the ZoomWall was distracting; participants described feeling uneasy knowing that the ZoomWalls were moving around them throughout the study.
Dongbin Kim Conference 2021 US	functionality	-	Haptic feedback allowed the operator to account for the package about to slip from its end-effector.	Avatar-Drone can physically interact with objects and socially interact with actual workers who are on the work site	Real time 3D vision feedback can provide more suitable situational awareness to the operator. Sensed reaction forces were fluctuating which could provide inaccurate haptic feedback to the operator
Difeng Yu Conference 2022 Australia	functionality	-	drone delivers origami to the user's hand when they are about to touch a virtual object.	-encountered-type haptics, where haptic devices autonomously position haptic proxies at the corresponding physical location of the virtual object.	the solution can inspire ISMAR audiences including VR researchers, designers, developers for new applications. -existing methods that leverage drones to provide VR haptics require sophisticated prototyping techniques, such as customized electronics or 3D printed models, for its haptic props

There were two sources studying immersion in this category. The article from Gardé et al. (2018) confirmed that vibro-kinetic (VK) haptic feedback supported the VR experience by pushing the immersion further, causing a better psychophysiological state that is more desirable for VR experience. Also, VK haptics fostered more natural head movements for a large number of users, resulting in higher sense of presence. They conducted a between-subject experiment using the D-Box vibrating chair and Oculus Rift Cv1 headset within a sample of 45 users and the results of the analysis of psychophysiological data and head tracking showed that VK contributes to induce a more immersive VR experience for the users. The potential of VK technology to aid VR users in autoregulating and maintaining a relaxed state is suggested to provoke fewer cybersickness symptoms. Further focus on immersion was presented by Yixian et al. (2020) who discussed Room-scale virtual reality (VR) and the technique of haptic retargeting for autonomous robots. Based on a user study applying Witmer and Singer's Presence Questionnaire among 12 participants, the developed prototype of Zoom Wall enhanced users' immersive and fun experience in the VR environment. An outlined limitation was that the noise from the ZoomWall was distracting as well as participants reported discomfort due to the device moving around them throughout the study.

Overall, this category informed that VK haptic feedback improved immersion in IVR by aiding autoregulation, which lowered cybersickness symptoms. Also, the PQ assessed that autonomous haptic robots in room-scale VR increased immersion.

Discussion

Main Findings

The goal of this scoping review was to uncover relevant insights regarding the role haptic devices play on users' cognitive responses in IVR systems by posing the following research question: What is the role of haptic devices on users' feeling of presence and immersion in IVR systems within different areas of application? Previous systematic literature reviews on haptic devices have focused specifically on wearable haptics and could be considered outdated (Pacchierotti et al., 2017). Therefore, this thesis provided novel insights by reviewing various IVR haptic technologies by adhering to the recommendations from Radhakrishnan et al. (2021) to investigate the role of haptics devices within IVR systems across various sectors. Furthermore, as the field of IVR and haptic technology has been evolving at a rapid speed, this scoping review aimed to provide insights from more up-to-date scientific sources published after 2017. The designed tables and five narrative summaries in the result section provided the needed information to answer the research questions guiding this thesis and will be discussed in greater detail.

RQ1: What is the role of haptic devices on users' feeling of presence and immersion in IVR systems within different areas of application?

Overall, based on the result interpretations from this scoping review, this thesis outlined three application areas where IVR haptics essentially had a positive impact on users' immersion or presence: Learning; Leisure and Culture; and Design and Evaluation.

The main findings outlined that from 2017 until 2022 a significant part of IVR haptic research targeting users' feelings of immersion and presence was conducted in the context of learning. Several sources confirmed that haptics enhanced immersion and presence in VR skills training in the operative medical field, while fewer studies established a positive trend in educational settings. Those outcomes align with findings from Mäkinen et al. (2020) who reported that haptic simulators were the most implemented technologies for learning in healthcare. Furthermore, a study from Matovu et al. (2022) noted that haptic feedback was lacking in 56 out of 64 reviewed papers about IVR science learning. This demonstrated that scholars efforts in the area were focused on applications benefitting human health, rather than general education.

Additionally, the findings show that in 2020 the IVR haptic scholarship published research in the leisure and culture area and confirmed that haptic feedback enhanced immersion by aiding walking in a VR gallery as measured with the ITQ. However, passive haptics did not affect presence in exergaming and complex interactions with the Oculus Quest 2 controllers lowered immersion in VR painting. Also, Haptic feedback synchronized with speech increased co-presence of others in a VR meeting room as measured by questions from Bailenson et al. (2005).

Furthermore, the design and evaluation application area provided insights about recent IVR haptic prototypes, which were being developed and validated by considering immersion and presence as user requirements. Regarding development, sources informed about several wearable device prototypes that increased immersion or presence. Immersion was broken for a prototype device of a multi-haptic feedback wearable robot due to its weight, movement, and movement inertia. In terms of testing, the results showed that physiological data from electrograms such as EEG, ECG, and EOG were applied in more recent studies as a form of objective measurement of users' immersion and presence in haptic-enabled IVR systems. This is supported by Radhakrishnan et al. (2022) who discussed how physiological measures such as ECG and EDA signals could study the impact of various stimuli on different brain regions as long as they are integrated in a way that does not harm immersion or presence.

Lastly, the main findings from the Other application area explained how haptic devices offered solutions for dealing with VR sickness, thus improving immersion. Aligned with the concept of embodiment by Ihde (1990) described in the theoretical framework, haptics were found to facilitate users' feeling of ownership or embodiment of their virtual body in IVR.

RQ2: What measurements are applied to evaluate users' level of presence and immersion in IVR systems?

This scoping review builds up on the theoretical background by introducing various subjective measures that were applied in the scientific field of IVR haptics. Immersion was measured with subjective measurements such as the Usoh-Steed Presence Questionnaire (SUS) from Slater et al. (1994), Igroup Presence Questionnaire (IPQ) from Schubert et al. (2001), User Experience Questionnaire (UEQ) from Schrepp et al. (2014), Witmer and Singer's (1998) Immersive Tendencies Questionnaire (ITQ) and System Usability Scale (SUS) from Brooke (1996).

Presence was predominantly assessed with the Presence Questionnaire (PQ) from Witmer and Singer (1998), as well as with the IPQ and SUS questionnaires. This corresponds to a statement from Coelho et al. (2023) who claimed that these three were among the most applied questionnaires to evaluate presence. Additionally, one study used the new quality model of VR experience from Jung and Lindeman (2021) and another source adopted the adjusted UX questionnaire for IVE developed by Tcha-Tokey et al. (2016). Also, objective physiological measures like EEG data were analysed to study both immersion and presence and were used to develop a continuous model for assessment of haptic device effectiveness.

RQ3: What are the opportunities and limitations related to the integration of IVR haptic systems?

Integration of haptics devices was proposed for studying human interactions with robots or for allowing multiple contributors VR designing. Self-avatars were a recommended addition to haptics to enhance presence, while physical fatigue was seen as a downside of adopting such devices. Additionally, passive haptics were suggested for experience-orientated VLEs, and haptics overall offered potential to improve learning practices in the operative industry. The risk of high cognitive load due to poor motion configuration was mentioned as a limitation. Furthermore, the potential areas for integration of DFF were said to be VR sports games, interaction interfaces in social VR or guidance systems for visually impaired people. A limitation of integrating gloves in studies was their size which did not fit all users, as well as the slight latency that virtual fingers depicted compared to real finger movement due to the animation model. The potential of haptic feedback to boost chances of learning complex tasks was noted, while vibrations were recommended for immersive gaming or VTE where the level of presence matters such as in complex maintenance jobs, anxiety therapy, or flight training. The benefits of tactile sensation to the face could be applied in phobia treatment or immersive horror gaming. The potential of vibro-kinetic haptic feedback to increase emotional responses by 30 % in VR and to assist users in autoregulation and reducing cybersickness was suggested. Illusory kinesthetic sensations stimulated through tendon vibration were proposed for the treatment of body representation disorders such as somatoparaphrenia and alien hand syndrome. A limitation of integrating encounter ungrounded haptic robots was the discomfort users experienced while knowing that something moves around them.

Strengths and Limitations

The main strength of the thesis research at hand is that it is among the few scoping reviews in the field of IVR, and the first, to summarize and disseminate research findings in the field of haptic devices in IVR. Additionally, this study contributes to the body of literature focusing on immersion and presence in IVR systems as advised by Radhakrishnan et al. (2021).

This thesis assignment achieved the purpose of scoping reviews to map out the current developments and state of this complex and continuously evolving field. The tabular data achieved this goal by outlining essential study-related data regarding characteristics of the IVR system and haptic devices, studied variables, findings, relevant concepts, measurements, as well as limitations and opportunities. This comprehensive overview could benefit practitioners and developers by informing decision-making related to the integration of haptics in IVR systems in different areas. Furthermore, scholars from various fields could potentially draw inspiration from this scoping review and consider the potential integration of haptic technology in their upcoming study experiments.

The scoping review methodology was a suitable method for investigating the field of haptic technology in IVR due to the complexity of the area, which had not been reviewed extensively before. In support, a statement from Arksey and O'Malley (2005) emphasized that this research design is an appropriate choice "…especially where an area is complex or has not been reviewed comprehensively before" (p. 20). Furthermore, the Covidence screening software proved to be an efficient tool for performing the screening of sources during data analysis.

Although this thesis provided valuable and detailed insights regarding IVR haptics, it also has limitations and points for improvement, which could translate into recommendations for future research. To begin with, it was challenging to summarize such an extensive amount of extracted data in tables. Moreover, this thesis did not address all of the information presented in the tables such as country of origin and sample size in the discussion of main findings. Additionally, selecting the year 2017 as the threshold during the data collection process could have been reconsidered and aligned with the release of the Oculus Quest 2 in 2020. This would have slightly lowered the number of sources in the corpus and therefore the work effort, while increasing the novelty and state-of-the-art aspect of the scoping review in general.

Future Research Recommendations

The present research provides guidance for future research based on the distinguished limitations and information obtained from reading literature in the field of IVR haptics. In alignment with the recommendations from Shazhaev et al. (2023), future research could focus on the development of haptic technology for use in areas such as surgery and telemedicine. Furthermore, forthcoming studies could consider analysing the meaning of extracted data such as sources' country of origin and provide insights into the development per countries. Additionally, as hardware becomes more available, future research should continue exploring the potential of IVR haptic systems in greater depth for vital areas such as skills training in healthcare and education. Nevertheless, future studies should further investigate how IVR haptic technology could be utilized for creative and leisure purposes.

Practical Implications

The findings from this scoping review could assist IVR system developers and game designers by providing them with a clear overview of recent developments in the field. This thesis could help inform practice or policymaking, who would otherwise lack the time and resources to perform this extensive research independently.

Conclusion

The purpose of this study was to investigate the role of haptic devices in fully immersive virtual reality (IVR) on users' cognitive responses to immersion and presence by conducting a systematic scoping review. The relevance of exploring more recent scientific sources was motivated by the novelty and complexity of the field, as well as by the continuous development of IVR and haptic technology. Based on the distinguished findings, in the domain of learning the role of haptic devices was to maximize immersion by integrating passive haptics for experience-focused simulations, to provide realism to facilitate immersion and increase educational and informative experience. Haptic devices had to facilitate accurate and smooth object interaction in VLE, and haptic devices such as controllers had to undergo haptic retargeting to enable hands to appear closer in the medical field, to boost engagement in a medical training context.

Furthermore, the role of haptics in the leisure and culture domain was to facilitate immersion and presence by aiding virtual walking, providing exertion without lowering motivation, offering carefully designed stimuli synchronized with the speech of virtual human to increase presence, and improving artefact interaction in museum VR exhibitions.

Moreover, findings from the design and evaluation application area noted that weight and movement inertia were important design considerations to prevent breaking of immersion when designing wearable robot haptic devices. Also, haptics had to facilitate more naturalness and some devices were combined with walking VR to improve immersion. Haptic devices had to be continuously validated for their effectiveness in IVR systems because object interaction could break realism. Therefore, more recent studies began utilizing physiological data from electrograms such as EEG, ECG, and EOG to objectively assess immersion and presence in haptic-enabled IVR systems.

According to the sources from the other application areas, the role of haptic devices was to foster natural head movement in order to improve users' psychophysiological state, to reduce VR sickness. In terms of ownership, haptic devices had to provide accurate resemblance between virtual and real limbs to increase proprioceptive processing and aid users to understand their virtual bodies better. The haptic retargeting approach had to be applied to encountered-type robotic props to increase immersion and UX within room-scale VR systems.

Overall, the scoping review highlighted the positive effect of haptic devices on users' feelings of immersion and presence in IVR systems by distinguishing three current areas of application: learning, leisure and culture, and design and development. Furthermore, the thesis provided an overview of the applied measurements of immersion and presence in the field of IVR haptics. This scoping review thesis outlined comprehensive tables that map out relevant concepts, limitations, and opportunities in the field. Nevertheless, future research should also investigate the integration of IVR haptics in fields other than healthcare skills training in greater detail. All in all, the outcomes of this study highlighted the significant position of haptic devices in IVR systems, especially when designed for medical skills training where achieving the required learning goals is arguably most vital.

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Appendix A - Data collection

Table A1

Electronic Search Strategy Log

Date	Database	Search String	Hits	Filters and remarks
24.04.23	Scopus	TITLE-ABS-KEY ("immersive virtual reality" AND ("haptic" OR "tactile") AND ("immersion" OR "presence"))	*41*	
24.04.23	Scopus	TITLE-ABS-KEY (immersive "virtual reality" AND ("haptic" OR "tactile") AND ("immersion" OR "presence"))	*226*	
24.04.23	Scopus	TITLE-ABS-KEY (immersive "virtual reality" AND ("haptic" OR "tactile" OR "sensory") AND ("immersion" OR "presence"))	*430*	
27.04.23	Scopus	TITLE-ABS-KEY (fully AND immersive "virtual reality" AND ("haptic" OR "tactile") AND ("immersion" OR "presence"))	*14*	*By adding the word fully**
27.04.23	Scopus	TITLE-ABS-KEY (immersive "virtual reality" AND ("haptic" OR "tactile" OR "multisensory") AND ("immersion" OR "presence"))	*274*	*mutisensory*
27.04.23	Scopus	TITLE-ABS-KEY (immersive "virtual reality" AND ("haptic interface" OR "tactile" OR "multisensory") AND ("immersion" OR "presence"))	*170*	*Haptic interface*
27.04.23	Scopus	TITLE-ABS-KEY ("immersive virtual reality" AND ("haptic interface" OR "tactile" OR "multisensory") AND ("immersion" OR "presence"))	*35*	*"immersive virtual reality"*
27.04.23	Scopus	TITLE-ABS-KEY ((immersive "virtual reality" OR "IVR") AND ("haptic interface" OR "tactile" OR "multisensory") AND ("immersion" OR "presence"))	*170*	tangible user interface (TUI) 10.3389/frvir.2022.824886
27.04.23	Scopus	TITLE-ABS-KEY ((immersive "virtual reality" OR "IVR") AND "haptic interface" AND ("immersion" OR "presence")) AND PUBYEAR > 2016 AND PUBYEAR > 2016	*16*	Only duplicates
27.04.23	Scopus	TITLE-ABS-KEY ((immersive "virtual reality" OR "IVR") AND ("haptic interface" OR "proprioceptive") AND ("immersion" OR "presence")) AND PUBYEAR > 2016 AND PUBYEAR > 2016	*23*	2017-2023 exported
28.04.23	Scopus	TITLE-ABS-KEY ((immersive "virtual reality" OR "IVR") AND ("haptic interface" OR "tactile") AND ("immersion" OR "presence")) AND PUBYEAR > 2016 AND PUBYEAR > 2016	*68*	2017-2023
28-04-23	Scopus	TITLE-ABS-KEY ((immersive "virtual reality") AND ("haptic" OR "tactile" OR "proprioceptive") AND ("immersion" OR "presence")) AND PUBYEAR > 2016 AND PUBYEAR > 2016	162	2017- until now
24.04.23	Web of Science	(TS=(("immersive virtual reality" AND ("haptic" OR "tactile") AND ("immersion" OR "presence")))) AND TS=("immersive virtual reality" AND (haptic OR tactile) AND (immersion OR presence))	27	Imported -> removed 13 articles added. 14 duplicates removed

24.04.23	Web of Science	https://www.webofscience.com/wos/woscc/summary/6779f29b-55c0-4b2b-a70e-647189b99499-889aa01c/relevance/1	23	Same as above from 2017-01-01 until 2023-04-24
24.04.23	Web of Science	(TS=(("immersive virtual reality" AND ("haptic" OR "tactile") AND ("immersion" OR "presence")))) AND TS=("immersive virtual reality" AND (haptic OR tactile) AND (immersion OR presence))	16	Last 5 years 5 studies added/ 11 duplicates removed
27.04.23	Web of Science	ALL=(immersive "virtual reality" AND ("haptic" OR "tactile" OR "proprioceptive") AND ("immersion" OR "presence"))	95	Last 5 years 1 duplicate 37 documents added 58 duplicates removed
27.04.23	Web of Science	ALL=(immersive "virtual reality" AND ("haptic" OR "tactile" OR "proprioceptive") AND ("immersion" OR "presence") AND ("communication" OR "interactivity"))	8	Last 5 years/ all duplicates
28-04-23	Web of Science	ALL=(immersive "virtual reality" AND ("haptic" OR "tactile" OR "proprioceptive") AND ("immersion" OR "presence"))	120	Filter: from 2017-01-01 until 2023-04-24 Query: https://www.webofscience.com/wos/woscc/summary/46da7169-a4c3-45ec-b325-53f7ceca7003-889b207b/relevance/1
24.04.23	IEEE Xplore	("All Metadata":immersive "virtual reality") AND ("All Metadata":haptic) AND ("All Metadata":immersion OR "All Metadata":presence)	84	
24.04.23	IEEE Xplore	("All Metadata":immersive "virtual reality") AND ("All Metadata":haptic) AND ("All Metadata":cognitive) AND ("All Metadata":immersive) AND ("All Metadata":presence)	1	Filter since 2018
24.04.23	IEEE Xplore	"All Metadata":immersive "virtual reality") AND ("All Metadata":haptic OR "All Metadata":tactile) AND ("All Metadata":immersion OR "All Metadata":presence)	63	Filter since 2017
24.04.23	IEEE Xplore	("All Metadata":"immersive virtual reality") AND ("All Metadata":haptic interface) OR ("All Metadata":proprioceptive) AND ("All Metadata":immersion) AND ("All Metadata":presence)	66	2017-2023
24.04.23	IEEE Xplore	"All Metadata: "immersive virtual reality") AND ("All Metadata":haptic) AND ("All Metadata":immersion OR "All Metadata":presence)	8	2015 - 2023
24.04.23	IEEE Xplore	("All Metadata":immersive "virtual reality") AND ("All Metadata":haptic) AND ("All Metadata":immersion) AND ("All Metadata":presence)	7	2017-2023
25.04.23	IEEE Xplore	("All Metadata":immersive "virtual reality") AND ("All Metadata":haptic) OR ("All Metadata":tactile) AND ("All Metadata":immersion) OR ("All Metadata":presence)	42,944	2017-2023
25.04.23	IEEE Xplore	("All Metadata":fully immersive "virtual reality") AND ("All Metadata":haptic) AND ("All Metadata":immersion) AND ("All Metadata":presence)	1	2017-2023 10.1109/MetroXRAINE54828.2022.9967498
25.04.23	IEEE Xplore	("All Metadata": immersive "virtual reality") AND ("All Metadata":multisensory) AND ("All Metadata":haptic) OR ("All Metadata":tactile) AND ("All Metadata":presence) AND ("All Metadata":immersion	26	https://doi-org.ezproxy2.utwente.nl/10.1109/VR.2019.8797906
28-04-23	IEEE	(("All Metadata":immersive "virtual reality") AND (("All Metadata":haptic) OR ("All Metadata":proprioceptive) OR	65	2017-2023 exported

	("All Metadata":tactile)) AND (("All Metadata":immersion) OR ("All Metadata":presence)))	

Table A2

JBI Protocol presenting the Eligibility Criteria developed in accordance with the PCC mnemonic.

Population	Concepts	Context
- Studies focusing on participants with mental disabilities would be excluded. - Studies with physically impaired participants are included.	Haptics Definition - Haptic technology refers to any system that recreates the feeling of touch when interacting in a virtual environment. (Actual device to provide either kinaesthetic or tactile information) Immersive Virtual Reality (IVR) - Fully immersive virtual reality where the user is completely surrounded in a virtual world, uses a head mounted device (HMD). The goal of IVR is to fully immerse the user inside the computer-generated world, providing the impression to the user that he/she has “stepped inside” the synthetic environment (Furht, 2008).	- research in other contexts of VR such as desktop VR, AR, CAVE, 360-degree videos, web-based VR are not going to added to the corpus unless the study compares them to IVR technology. - Other systematic reviews are not included in the research.

Inclusion Criteria	Exclusion criteria
- Active or passive (kinesthetic or tactile) haptic feedback is provided via a mechatronic device in a IVR system. - cognitive responses such as presence or immersion are studied. - HMD is present in IVR system.	- Pseudo haptics - AR, MR, non-immersive VR - Participants with mental disabilities - Lack of mechatronic device - Predominant focus on other senses (haptic are just mentioned next to other senses) - Lack of HMD - Systematic Reviews - Insufficient information - Poor English - Executive summaries of conferences

Table A3

Data Extraction Template used in Covidence

Data Group	Extracted Data	
General information	- Study ID - Title - Source Type - Research Field - Lead author - Industry	- Year of Publication - Country - Notes
Participants	- Population description	- Total number of participants
Method	- Aim of study - Measurement - IVR system - Haptic Device - Prototype OR Finished Product	- Device Characteristics - Study design
Other	- Relavant Concepts	- Interactivity/Communication - Findings
Recommendations	- Opportunities - Limitations	

Appendix B - Corpus References

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Appendix C - PRISMA-ScR Checklist

Table C1

Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
TITLE			
Title	1	Identify the report as a scoping review.	1
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	3
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	Click here to enter text.
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	Click here to enter text.
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	Click here to enter text.
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	Click here to enter text.
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	Click here to enter text.
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	Click here to enter text.
Selection of sources of evidence†	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	Click here to enter text.
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	Click here to enter text.
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	Click here to enter text.
Critical appraisal of individual sources of evidence§	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	Click here to enter text.

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	Click here to enter text.
RESULTS			
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	Click here to enter text.
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	Click here to enter text.
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	Click here to enter text.
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	Click here to enter text.
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	Click here to enter text.
DISCUSSION			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	Click here to enter text.
Limitations	20	Discuss the limitations of the scoping review process.	Click here to enter text.
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	Click here to enter text.
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	Click here to enter text.