Do Multisensory Stimuli Benefit the Virtual Reality Experience? A Systematic Review

Miguel Melo, Guilherme Gonçalves, Pedro Monteiro, Hugo Coelho, José Vasconcelos-Raposo, and Maximino Bessa

Abstract—The majority of virtual reality (VR) applications rely on audiovisual stimuli and do not exploit the addition of other sensory cues that could increase the potential of VR. This systematic review surveys the existing literature on multisensory VR and the impact of haptic, olfactory, and taste cues over audiovisual VR. The goal is to identify the extent to which multisensory stimuli affect the VR experience, which stimuli are used in multisensory VR, the type of VR setups used, and the application fields covered. An analysis of the 105 studies that met the eligibility criteria revealed that 84.8 percent of the studies show a positive impact of multisensory VR experiences. Haptics is the most commonly used stimulus in multisensory VR systems (86.6 percent). Non-immersive and immersive VR setups are preferred over semi-immersive setups. Regarding the application fields, a considerable part was adopted by health professionals and science and engineering professionals. We further conclude that smell and taste are still underexplored, and they can bring significant value to VR applications. More research is recommended on how to synthesize and deliver these stimuli, which still require complex and costly apparatus be integrated into the VR experience in a controlled and straightforward manner.

Index Terms—Systematic review, virtual reality, multisensory

1 Introduction

The primary purpose of a virtual reality (VR) system can be described as transporting its users to a virtual environment (VE) by offering coherent perceptual feedback corresponding to the actions that are taking place within that VE [1], leading the users to develop a psychological feeling of being there [2]. This sense is usually referred to as presence [2], [3]. Slater divides presence into two types of illusions: place illusion (PI) and plausibility illusion (Psi) [3]. PI refers to the specific feeling of "being there", and this illusion can occur in static scenes allowing the user to look around an explore the VE. PI is determined by the immersive system: the extent to which the equipment allows the user to explore the scene through natural sensorimotor contingencies (walk, look around, look under, look over, crouch, try to touch objects and feel them, etc.). Psi, on the other hand, is more difficult to achieve. It refers to the feeling that events occurring in the virtual world are truly happening despite the sure knowledge that they are not real. These events should match our expectations of how objects and people would react in the depicted situation. Additionally, they should refer to and be correlated with our actions in the VE. While the evolution and affordability of VR technologies has led to more widespread usage, the majority of VR systems heavily depend on the stimulation of only vision and audition. This dependence on only two senses can be a constraint, as our everyday experiences have a multisensory nature. In fact, the literature shows that multisensory stimulation is of notable importance, as the more deeply human senses are engaged in a VE, the more immersive the experience is and, consequently, the better the subjects' performance [4], [5], [6], [7]. However, the literature is not unanimous: there is also evidence that simply adding more stimuli to a simulation may only affect the way a participant responds to a given stimulus but not his/her experience. For instance, in a medical simulation scenario, the perception of having haptic feedback has promoted the economy of movement of the non-dominant hand, but it has not influenced the accuracy [8], [9]. Additionally, there is evidence that simply adding additional stimuli can pose a negative impact on users, as it can impose an extra cognitive load on users and overwhelm and/or distract them in regards to the purpose of the VE, especially if the multisensory information is incongruent [10], [11].

Previous literature reviews and systematic surveys have discussed the role of multisensory cues in VR. For instance, Mahrer and Gold [12] reviewed the literature regarding the use of VR systems for pain control and found that the use of multisensory cues in VR systems offers a promising method for pain distraction since they can decrease pain perception. In the medical field, Wang *et al.* [13] surveyed multisensory VR dental training systems, where they identified the leading dental simulators and highlighted the value that multisensory stimuli can provide by allowing the simulation of not only common clinical scenarios but also realistic pathological conditions. The use of haptic-visual-audio feedback can enable dentists to have a more insightful experience,

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and they can benefit from the training outcomes as they can train the required force patterns to apply as well as acquire sensory-motor skills. Nevertheless, Mahrer and Gold [12] and Wang *et al.* [13] also point out the limitations of current hardware and areas where the fidelity of the simulation has room for improvement.

Surveys are not limited to the medical field: Mikropoulos and Natsis [14] reviewed the empirical research on virtual educational environments for the time period between 1999 and 2009, and they described some works that make use of multisensory cues to facilitate students' mental models and, consequently, have a significantly positive impact on conceptual learning. Focusing on the sense of smell, Murray *et al.* [15] studied the contribution of olfaction to multimedia experiences, including VR applications. These authors found that although olfactory cues usually do not usually have a significant impact on the sense of presence, they have a main effect on memory. They also point out that some simulations are incomplete without odors. For example, in VR-based surgical training systems, odors are critical to diagnosing cases and must act in conformity. In terms of interaction and virtual experience, Nilsson *et al.*'s [16] review focuses on natural walking in VR. Once again, multisensory stimuli (with a strong focus on haptics), when correctly delivered, were shown to provide an enhanced experience, as they more coherently stimulate the proprioceptive and kinesthetic senses.

The literature has previously highlighted the effect of multisensory cues on VR applications; however, there is no comprehensive overview of this topic. With this systematic review, we aim to address this gap in the literature and to provide a comprehensive overview of studies that evaluate multisensory VR experiences against conventional VR experiences. Please note that, for this review, we consider a conventional VR experience as a VR-based simulation with visual and audio stimuli while a multisensory experience encompasses a VR-based experience that, in addition to an (audio)visual stimulus, provides haptics, smell, or taste. Thus, based on the works identified in our overview, we further analyze the findings to (1) identify how and which multisensory stimuli such as haptic, olfactory and taste cues, affect the VR experience in comparison to the effects of conventional audiovisual VR experiences. Second, our aim is to (2) identify which type of VR setup is more commonly used in such experiences; (3) which senses are more studied and whether any sense is disregarded or lacks study; and (4) the application fields of multisensory VR experiences. Another important contribution of this work is a searchable database to enable readers to easily sort through the analyzed literature, promoting knowledge sharing in the field.

2 Methods

The systematic review method followed was based on PRISMA proposed by Moher *et al.* [17], which guides the development of systematic reviews and meta-analyses to ensure transparent and complete reporting of the surveyed topics.

2.1 Eligibility Criteria

Publications considered eligible for inclusion involved user studies that evaluated multisensory VR experiences against audiovisual VR experiences to ensure a proper comparison of (audio)visual versus multisensory VR experiences. The inclusion criteria were:

1) The paper has one of following terms in the title, abstract, or keywords: "virtual reality", "virtual environments", "VR" or "Virtual Experience" along with one of the terms "multisensory" or "multi-sensory";
2) The paper is published in a refereed journal or conference;
3) The paper is written in English.

Regarding the exclusion criteria, the following were used:

1) The paper is not available;
2) The paper is written in a language other than English;
3) The paper does not consider VR;
4) The paper is a technical report, an abstract, a conference proceeding, a conference review, an editor's note, a call for papers, a book, or a thesis;
5) The paper is only theoretical (e.g., information system proposal, literature review);
6) The paper does not evaluate VR against multisensory VR.

2.2 Search Strategy

The literature was identified through electronic searches by conducting an extensive searches in the databases Web of Science: Science Citation - Index Collection (Thomson Reuters), Elsevier Scopus, ACM Digital Library, IEEE Xplore and Google Scholar (first 200 results). The first search was run on 12 December 2018 and was updated on 15 April 2019. The search was performed to be equivalent to the following logical expression: Title/Keywords/Abstract contains ("virtual reality" OR "virtual environments" OR "VR" OR "Virtual Experience") AND (multisensory OR "multi-sensory").

2.3 Study Selection

Having as input those papers identified using the search method specified above, eligibility assessment and data abstraction were performed independently in a conventional unblinded standardized manner by a total of four reviewers (M. M., H. C., P. M., G. G.). Each paper was reviewed by two reviewers to determine its eligibility. When there was a consensus between both reviewers (accept or reject), the decision was based on their evaluations. When there was no consensus between the two reviewers, a third reviewer was assigned to provide a decision by majority.

2.4 Data Collection Process

The selected papers for full-text assessment were reviewed, and the data collection process was conducted using piloted forms. The variables considered were the *stimuli included in the study*, the *type of VR setup used*, *the research topic*, the *independent variables* and *dependent variables*, the *sample size*, the *impact of the multisensory VR application over the conventional VR application*, the *main findings*, and the *application field*. The type of VR setup is classified into three categories: non-immersive, semi-immersive, and immersive. This classification is inspired by Schoor *et al.* [18], who distinguishes the different setups by the field-of-regard (FOR) that the VR

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system covers; in non-immersive setups, less than half of the FOR is covered (e.g., typical desktop setups). Semi-immersive setups consist of setups that cover most of the FOR, such as stereoscopic wall screens or projection systems. Immersive setups are characterized by the use of technologies that cover almost, if not the whole, FOR, such as CAVE Automatic Virtual Environments (CAVE) or head-mounted displays (HMD). The impact, can be classified as negative, neutral, or positive and it refers to the contribution of the multisensory VR application when compared to the conventional VR application measured by the dependent variables studied. The application field variable refers to the field where the VR solution is meant to be applied, and this variable was defined based on the International Standard Classification of Occupations 2008 (ISCO-08), a system for classifying and aggregating occupational information [19].

2.5 Quantitative Analysis

Based on the data obtained from the data collection process, a quantitative analysis was conducted. The quantitative analysis comprises a table and a graphical representation of the most used terms in the analyzed papers' titles (word cloud). To avoid outliers in the word cloud, some rules were applied to the generation of the word cloud to, for example, remove words that were not important (e.g., pronouns), merge words that only made sense together (e.g., "virtual" and "reality" were merged into "virtual reality") and group words that were synonyms (e.g., "smell" and "olfactory" were grouped into "olfactory"). The quantitative analysis also comprised a set of charts that summarized the selected works for analysis in groups, taking into account the research questions of this systematic review: the impact of the multisensory setup against conventional setups, the type of VR setups used, which senses were more studied, and the application field of the studies.

2.6 Quality Assessment

To assess the quality of the papers selected for full-text analysis, a scoring system was adopted inspired by the quality assessment approaches proposed by Connolly *et al.* [20] and Feng *et al.* [21]. The scoring system ranged from 1 to 3 per question (detailed below), where 1 refers to the lowest score and 3 to the highest score. Similar to the study selection, each paper was reviewed by two reviewers. When there was a consensus between the reviewers in the scores, the scoring was closed. If there was no consensus between the two reviewers, a third reviewer was assigned to moderate the scoring and provide a consensus. To be considered a high-quality paper, the paper must be scored with seven points or higher, which implies at least one top score in one of the items and at least two points in the remaining items. The following assessment questions were considered:

- Q1: Is it a conference or a journal paper? If the paper was published in a conference as a short paper it was given 1 point, if it was published in a conference as a full paper, it was given 2 points. It the paper was published in a journal, it was given 3 points.
- Q2: The sample size to the number of independent variables and the experimental design? If the number of participants was fewer than the recommended number, 1 point was given; if the sample size was acceptable, a score of 2 was given; if the sample size exceeded the acceptable sample size a score of 3 was given.
- Q3: Was the methodology suitable for the study? This was evaluated by considering the instruments, materials, and procedure used for the evaluation study and by analyzing possible biases and limitations. This evaluation included an analysis of the materials, methods, and adopted analysis methods that verified their appropriateness for the type of study. Additionally, it was verified whether/how the findings were generalized for the target population and the extent to which the findings could be trusted. If the analysis of these parameters revealed substantial limitations, a score of 1 was given; if the analysis of these parameters revealed some limitations, a score of 2 was given; if no limitations were identified, a score of 3 was given.

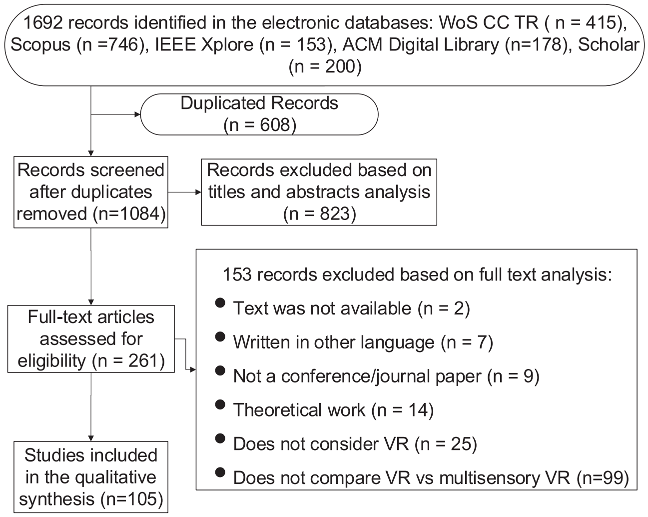

Fig. 1. Flow diagram of study selection.

3 Results

The search in the identified databases returned a total of 1,692 records, of which 608 were identified as being duplicate and were consequently removed, resulting in a total of 1,084 unique records. The title and abstracts of the unique 1,084 records were analyzed, taking into account the defined eligibility criteria. From those, 823 records were excluded for not meeting such criteria. This resulted in 261 records eligible for the full-text analysis. From those 261 records, 153 records were excluded based on the previously defined exclusion criteria resulting in a total of 105 records that were included in the qualitative synthesis. Please refer to Fig. 1 for a detailed overview of the study selection.

3.1 Qualitative Analysis

The qualitative analysis of the analyzed papers is shown in Table 1. Note that for ease of reading, only the variables related directly with the research questions were included in Table 1 and an extended version of the table is available as supplemental material, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TVCG.2020.3010088, of this manuscript.

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TABLE 1
Data Obtained From the Systematic Review of the Analyzed Studies

Study	Stimuli	Setup	Application Area	Impact	Main Findings
Adermann *et al.* [22]	V, H	N	Health Professionals	=	When using haptic force feedback in this simulation, no significant differences were found for time, number of wall collisions, number of fatal failures, economy of hand movement, nor performance.
Ankarali *et al.* [23]	V, H	N	General Purpose	+	Applying force impulse to the hand at the moment of ball-paddle collision improves performance compared to when using visual feedback alone.
August *et al.* [24]	V, H	N	Health Professionals	+	Using real objects enhances the performance in an arm location task, promoting the recognition of body location and location of an object within peripersonal space.
Baus and Bouchard [25]	V, A, S	I	General Purpose	+	Exposure to unpleasant odors had a significant effect on the sense of presence. Nevertheless, the exposure to odor (either pleasant or unpleasant) had a positive effect on presence, sense of reality and realism.
Blom and Beckhaus [26]	V, A, H	S	General Purpose	+	For virtual travel, collision response with context-appropriate feedback should be used, regardless of the method used to provide it
Bluteau *et al.* [27]	V, H	S	General Purpose	+	Haptic cues reduced significantly the time spent in the visual warning zones, but it did not affect significantly the task performance in terms of time completion or spatial distance error.
Bouguila *et al.* [28]	V, H	S	General Purpose	+	Adding force feedback improved the time needed to perceive depths.
Bouhelal *et al.* [29]	V, H	I	Health Professionals	+	For novices, training on haptic feedback simulator resulted in a faster learning curve and required less simulator time.
Brickman *et al.* [30]	V, H	S	Science and Engineering Associate Professionals	+	Using an haptically-augmented stick increased performance, lowered crash landings and lowered the perceived workload on high turbulence conditions.
Caola *et al.* [31]	V, A, H	I	Legal, Social and Cultural Professionals	+	Synchronous visuotactile stimulations compensate for the effect of visuomotor inconsistencies. However, for slow arm movements, body ownership might be induced even without synchronous multisensory.
Carulli *et al.* [32]	V, A, S	I	Science and Engineering Professionals	+	Using smells in multisensory VR can be an effective technique to evaluate the olfactory characteristics of products in the design process.
Chen *et al.* [33]	V, A, H	I	General Purpose	+	People can perceive the environment more correctly and easily with Thermal feedback.
Choi *et al.* [34]	V, A, H	S	Legal, Social and Cultural Professionals	+	Visual-tactile stimulation shows a significantly higher effect on the illusion of body ownership when compared to visual-auditory stimulation.
Cooper *et al.* [35]	V, A, H	S	Metal, Machinery and Related Trades Workers	+	Multimodal feedback outperformed bimodal feedback that, in turn, outperformed unimodal feedback. Multimodal feedback had the most favorable effects on users' perceived sense of presence and task performance.
Cooper *et al.* [36]	V, A, H	S	Metal, Machinery and Related Trades Workers	+	The use of multisensory cues in virtual training do not hinder the perception of the VE, and it improves user's performance in the real environment.
Cooper *et al.* [37]	V, A, H	S	General Purpose	+	The three stimuli combined increased the performance and the sense of presence compared to the remaining scenarios. The use of two stimuli is more effective than using a single stimulus.
Corbett *et al.* [38]	V, H	N	General Purpose	+	Strong positive effect of haptic feedback on performance in terms of task time and root mean square error of motion.
Cui *et al.* [39]	V, A, H	I	Science and Engineering Associate Professionals	+	Results proved the usefulness of multisensory virtual guides.
de Barros *et al.* [40]	V, H	N	Science and Engineering Associate Professionals	+	The combined use of graphical and vibrotactile feedback interfaces resulted in higher quality sketch maps, lower robot collision, which indicates an increased operator situation awareness.
de Boer *et al.* [41]	V, A, H	N	Health Professionals	+	Results suggest that in a virtual learning environment force feedback is essential for satisfaction and important for performance.
Díaz *et al.* [42]	V, A, H	N	General Purpose	+	Adding audio and haptics to visual stimulus has significantly reduced the number of undesirable collisions. In bimodal scenarios, the addition of haptics was more efficient than sounds.
Dinh *et al.* [5]	V, A, H, S	I	General Purpose	+	The more sensory cues that are added, the higher the sense of presence: the overall sense of presence increased with the addition of tactile and auditory cues. There was also a trend for olfactory cues alone.
Durlach *et al.* [43]	V, A, H	I	General Purpose	+	Tactile feedback results in a higher reported sense of presence and lower disorientation than auditory feedback.
Dvorkin *et al.* [44]	V, H	N	Health Professionals	+	The use of haptic nudge cues presented significantly better results when compared to the use of break-through forces and the no-force condition. There were no statistically significant differences between break-through forces and no force conditions.
Ebrahimi *et al.* [45]	V, H	I	General Purpose	-	Overall, haptic feedback condition revealed a negative effect on task performance.
Egan *et al.* [46]	V, A, S	I	General Purpose	+	Participants scored significantly better their quality of experience when olfaction was presented - other than that there are no statistically significant effects.
Egeberg *et al.* [47]	V, A, H	I	General Purpose	+	Visuomotor feedback proved to be better for task performance than in combination with visuotactile feedback. Visuotactile feedback significantly enhanced body-ownership of the wings and agency.
Faroque *et al.* [48]	V, A, H	N	Science and Engineering Professionals	+	The use of a haptic device control resulted in higher accuracy and success rates when compared to the keyboard control method.
Feng *et al.* [7]	V, A, H	I	General Purpose	+	Wind and vibration cues significantly improved user experience. Footstep vibration significantly improved triangle-completion task performance.

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TABLE 1
(*Continued*)

Study	Stimuli	Setup	Application Area	Impact	Main Findings
Feng *et al.* [49]	V, A, H	I	General Purpose	+	The use of tactile cues (wind) had a significant positive impact on users' experience while the addition of footstep vibration improved user performance.
Fröhlich and Wachsmuth *et al.* [6]	V, A, H	I	General Purpose	+	All three stimuli combined increased the perceived presence significantly. When participants were presented with one additional stimulus (audio or haptic), the perceived presence decreased.
Gardé *et al.* [50]	V, A, H	I	General Purpose	+	Vibro-kinetic feedback leads to more activation of the sympathetic nervous system and participants had better autoregulation of psychological state, suggesting less cybersickness.
Ghosh *et al.* [51]	V, A, H	I	General Purpose	+	Participants preferred audio cues over visual and haptic cues to directing attention to the visuals of notifications. Haptic cues were successful at directing the attention to on-controller notifications.
Gibo *et al.* [52]	V, A, H	N	General Purpose	+	Haptics revealed to be important to modulate the coupling grip and load force acting on the hand, affecting performance positively.
Hagelsteen *et al.* [53]	V, A, H	N and S	Health Professionals	+	The use of haptics lead to faster completion of the training course and had a significant positive impact in the number of attempts to reach proficiency of the skills in three out of four individual tasks (instrument navigation, grasping and suturing).
Han and Black [54]	V, A, H	N	Teaching Professionals	+	The use of force feedback significantly improved instruction comprehension, recall, and knowledge transfer. The use of force feedback also had a positive impact on inference.
Hecht *et al.* [55]	V, A, H	N	General Purpose	+	Mental processing times improved with multimodal events (trimodal < bimodal < unimodal).
Hiemstra *et al.* [56]	V, H	S	Health Professionals	+	The use of box training models that include haptic feedback revealed to be superior to VR systems that lack haptic feedback in terms of time and economy of movement. However, using kinematic interaction between instruments and objects can improve typical VR systems for training purposes.
Hoffman *et al.* [57]	V, H	I	Legal, Social and Cultural Professionals	+	Participants exposed to VR and tactile augmentation were able to decrease the distance between the spider and also approach with much less anxiety.
Howell *et al.* [58]	V, A, S	I	Business and Administration Professionals	+	Evidence was found that olfaction can affect the sense of presence of some users and that the effects of olfaction on advertising can be dependent of the odorant used.
Hu *et al.* [59]	V, A, H	I	General Purpose	+	Auditory and/or tactile feedback had similar effects in improving the sense of presence and subjects' performance.
Hülsmann *et al.* [60]	V, A, H	I	General Purpose	+	Wind and warmth in VR can increase the users' presence.
Ichinose *et al.* [61]	V, H	I	Health Professionals	+	The use of haptics has significantly reduced the phantom limb pain.
Jiang *et al.* [62]	V, A, S	I	Science and Engineering Professionals	=	Smell revealed an interaction with traffic level on noise annoyance - in a low condition, it decreased noise annoyance while in high noise condition it sharpened noise annoyance. Results also suggest that smell can be used to increase people attention towards the visual landscape.
Kang and Kim [63]	V, H	N	General Purpose	+	Both studies revealed that haptics had a positive influence in the human perceptibility on the curvature and texture changes of 3D virtual surfaces. across vision and touch.
Karafotias *et al.* [64]	V, A, H	I	Health Professionals	+	Tactile stimulation played a significant role in increasing pain tolerance time. For high pain tolerance participants, tactile stimulation was more effective for pain distraction compared to low pain tolerance participants.
Kim *et al.* [65]	V, H	N	Health Professionals	+	Force feedback significantly improves training transfer.
Kim *et al.* [66]	V, A, H	I	Food Processing, Woodworking, Garment and Other Craft and Related Trades Workers	+	The proposed multimodal system significantly improved presence. The usability remained the same between the immersive VR proposed multimodal system and non-multimodal.
Klašnja-Milićević *et al.* [67]	V, A, S, T	I	Teaching Professionals	+	Learning abilities improve when using different smells and tastes.
Koritnik *et al.* [68]	V, A, H	N	Health Professionals	+	Tracking task performance was better in the haptic modality than in the visual modality, and even better when combining both modalities.
Kruijff *et al.* [69]	V, A, H	I	General Purpose	+	Using walking-related vibrotactile cues and audio improves significantly the sense of presence/involvement and self-motion.
Lathan *et al.* [70]	V, H	N	Health Professionals	+	The biopsy performance improved when both visual and haptic feedback were used, significantly reducing out-of-place error values.
Lecuyer *et al.* [71]	V, A, H	N	General Purpose	+	Haptic feedback decreases the number of collisions inside the virtual environment and reduces the mental-workload of participants.
Lederman *et al.* [72]	V, A, H	N	General Purpose	+	Touch with audition and unimodal touch were significantly better than a unimodal audition, being the bimodal touch with audition the condition with better performance results in remote absolute texture identification task.
Lee and Kim [73]	V, A, H	S	Science and Engineering Associate Professionals	+	Haptic feedback was the stimulus that contributed the most to improve performance and presence, while image quality only significantly improved presence.
Lee [74]	V, A, H	N	Science and Engineering Professionals	+	Adding additional multisensory information increased immersion and enjoyment, being haptic the stimulus that contributed the more. Participants with high immersive tendencies reported higher scores for all scales.
Li and Bailenson [75]	V, H, S	I	Legal, Social and Cultural Professionals	+	The use of smell and touch increased the perceived fullness of participants significantly, with them eating fewer donuts than those who were not exposed to these cues.

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TABLE 1
(*Continued*)

Study	Stimuli	Setup	Application Area	Impact	Main Findings
Louison *et al*. [76]	V, H	I	General Purpose	+	Vibrotactile cues cannot replace kinesthetic feedback, but spatial awareness and visual-proprioceptive consistency increased, especially when these cues where localized.
Louison *et al*. [77]	V, H	I	General Purpose	+	Use of avatars and localized vibrotactile feedback allowed subjects to perceive body-environment relationships better and to be faster without overloading visual sense and preserve a visual-proprioceptive coherence.
Lyu *et al*. [78]	V, H	N	Health Professionals	+	The use of force feedback for guidance can efficiently shorten the learning curve of novice trainees.
Martin *et al*. [79]	V, A, H	N	General Purpose	+	Haptic cues outperformed visual and auditory in terms of user performance.
Meyer *et al*. [80]	V, A, H	I	Science and Engineering Associate Professionals	+	Multisensory cues were integrated and, when presented combined, contributed to the fidelity of the simulation bu. However, the impact of sensory cues must be considered having into account the nature of the tasks being simulated.
Meyer *et al*. [81]	V, A, H	S	General Purpose	+	Tactile and auditory static reference signals in VEs have effectively reduced visually evoked postural responses to laterally moving stimuli but not the response to visual motion stimuli.
Millet *et al*. [82]	V, H	N	Science and Engineering Professionals	+	Haptic feedback and graphic analogies, when used, increased focus about forces and improved the interpretation of the effect of cantilever stiffness in students that were first exposed to these notions.
Munyan *et al*. [83]	V, A, S	I	Legal, Social and Cultural Professionals	+	There is a significant relationship between olfactory stimuli and presence. Smell has a positive impact on presence.
Munyan *et al*. [84]	V, A, S	I	General Purpose	+	The use of smell significantly improved presence levels even though electrodermal activity stayed the same. Also, the removal of scents resulted in a disproportionate decrease in presence levels.
Nagao *et al*. [85]	V, H	I	General Purpose	+	The use of passive haptic feedback (in the form of small bumps on the ground) was effective in increasing the sense of presence and the user's sense of walking through stairs.
Nam *et al*. [86]	V, A, H	N	General Purpose	+	Sensory modality factor supported by collaborative VEs can affect users' behavior, with haptic and auditory feedbacks positively influencing users' perception of the collaborative VEs.
Nishino *et al*. [87]	V, H	N	Teaching Professionals	+	The use of force feedback to guide the user's hand contributed to improving its writing performance and realism of the calligraphy experience.
Ogi and Hirose [88]	V, A, H	N and I	Science and Engineering Professionals	+	The use of multisensory data sensualization methods proved to be effective in providing the user accurate perceptions of data that was being visualized.
Ogi and Hirose [89]	V, A, H	I	General Purpose	+	Multisensory data sensualization methods have improved the correct perceptions of data to users.
Ogi and Hirose [90]	V, A, H	N	Science and Engineering Professionals	=	The study suggests that multisensory cues in VE should be classified into two categories: magnitude and variety. When cues from the same category are presented, they can interfere with each other if not congruent.
Panait *et al*. [91]	V, H	N	Health Professionals	+	Haptic feedback lead to benefits in performance, especially in a complex cutting exercise. However, this was not verified in the peg transfer drill exercise.
Petrolo *et al*. [92]	V, H	N	Health Professionals	-	Accuracy decreased with the use of two-handed haptic 3D interaction with VR technologies relatively to standard interfaces for clinical training procedures.
Poling *et al*. [93]	V, H	N	General Purpose	+	The visual-haptics condition significantly improved the perception of surface roughness. However, the higher the surface amplitudes, the more the preponderance of the visual stimulus.
Ramic-Brkic and Chalmers *et al*. [94]	V, A, S	N	General Purpose	+	When first exposed to smell, participants determined the quality of animations like in the ”no smell” condition. Without adaptation, participants were not able to distinguish the quality of the animations.
Ranasinghe *et al*. [95]	V, A, H, S	I	General Purpose	+	Providing a combination of all the modalities produced the highest sense of presence. The addition of any singular modality improves the sense of presence when compared to audio-visual experiences.
Richard *et al*. [96]	V, A, H	N	General Purpose	+	Haptic force feedback led to better performance in terms of object deformation. Direct haptic feedback was superior to pseudo-feedback. The best results were obtained when both haptic and redundant auditory feedback were present.
Sakr *et al*. [97]	V, H	S	General Purpose	+	The use of visual and haptic feedback resulted in a lower watermark detection threshold in 3D meshes.
Salkini *et al*. [9]	V, H	N	Health Professionals	=	Haptic feedback did not affect the performance of the trainees, having less effect than expected. People with gaming habits tend to have faster and more economic motion in their dominant hands.
Salzman *et al*. [98]	V, A, H	I	Teaching Professionals	+	Multisensory representation aided students understanding the electrostatics concepts as they promote better mental models for abstract science concepts, and, consequently, contributed to learning gains.
Santos-Carreras *et al*. [99]	V, H	N	Health Professionals	+	Task performance improved when haptic feedback was provided. Also, it is deduced that force feedback improves subjects' dexterity, while torque feedback might not further benefit such a task.
Santos-Carreras *et al*. [100]	V, A, H	N	Health Professionals	+	The visual and tactile feedback condition enabled better performance across different difficulty levels, as well as a decrease in task-completion times.

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TABLE 1
(*Continued*)

Study	Stimuli	Setup	Application Area	Impact	Main Findings
Sella *et al.* [101]	V, A, H	S	General Purpose	+	Behavioral results confirmed that tri-modal cues were detected faster and more accurately than bi-modal cues, which, likewise, showed advantages over unimodal responses.
Sengül *et al.* [102]	V, H	I	General Purpose	+	Congruent force feedback facilitates the integration of vision and touch, as reflected in a stronger performance difference between incongruent and congruent visuotactile stimulations.
Shing *et al.* [103]	V, A, H	N	Health Professionals	+	Haptics is a significant stimulus for improving a subject's manipulation performance with high difficulty levels in VR-based rehabilitation systems.
Sigrist *et al.* [104]	V, A, H	S	Legal, Social, Cultural and Related Associate Professionals	+	Adding sound or/and haptics to the VE has facilitated complex motor learning in rowing and, concurrent feedback fosters complex task learning.
Stepp *et al.* [105]	V, H	N and S	Science and Engineering Associate Professionals	+/-	Depending on the functional relevance of the tasks, haptics can play a different role: in a less functionally relevant motor task haptics had a positive impact whereas in a more functionally relevant motor task it had a negative impact.
Terziman *et al.* [106]	V, A, H	N	General Purpose	+	Results suggest a preference for multisensory combinations over unimodal simulations. The King-kong effect increased the real sensation of walking inside the VE.
Thompson *et al.* [107]	V, H	N	Health Professionals	=	Haptics did not improve the efficiency or effectiveness of LapMentor II VR laparoscopic surgery training. Due to its limited benefit and the significant cost, it should not be included routinely in VR laparoscopic surgery training.
Toet *et al.* [108]	V, A, S	N	General Purpose	=	Ambient odor did not affect safety-related concerns and affective connotations associated with signs of disorder in the desktop VE.
Tomono *et al.* [109]	V, A, S	I	General Purpose	+	Memorization increased when the olfactory stimulus (flower odor) was added to visual stimuli (flower image) and auditory stimuli (flower name).
Turchet *et al.* [110]	V, A, H	N	Science and Engineering Professionals	+	Results revealed a clear preference toward the simulations with haptic feedback, suggesting that the use of the haptic channel can lead to more realistic experiences.
Turner *et al.* [111]	V, H	N	Health Professionals	-	Haptic feedback had a negative impact in accurcay as it significantly increased the pin placement error. Authors attribute this to how haptic and tactile information was implemented/delivered.
Våpenstad *et al.* [112]	V, H	N	Health Professionals	-	Haptic feedback is important on VR simulators according to surgeons opinions. However, they say that handles with haptic feedback adds additional friction and, consequently, making them unrealistic.
Viciana-Abad *et al.* [113]	V, A, H	I	General Purpose	+/-	Passive haptic feedback improves presence and task performance on different interaction metaphors.
Viciana-Abad *et al.* [114]	V, A, H	S	General Purpose	+/-	Haptics has a positive impact in presence, and audio cues revealed to crucial to increase the interaction speed and should be provided in task-oriented applications. Evidence was found that multimodality may overload perception processes and affect the performance negatively.
Wang *et al.* [115]	V, A, H	N	General Purpose	-	Haptic communication can be used to complete a collaborative virtual task but is less efficient than verbal communication. A training period may help to improve its efficiency.
Wareing *et al.* [116]	V, H	I	General Purpose	+	The presence of heat stimulus provided a more realistic experience. Also, multiple heat sources proved to be more realistic than a single source.
Weisenberger and Poling [117]	V, A, H	N	General Purpose	+	There was a better performance for certain stimulus combinations under certain conditions but not for others. Authors conclude that multisensory interaction is complex and dependent on the stimulus condition.
Wiebe *et al.* [118]	V, H	N	Teaching Professionals	-	The visual and haptic group had more total fixation time but similar patterns of visual attention were seen. Haptic feedback seemed to offer little support for learning.
Wu *et al.* [119]	V, A, H	I	General Purpose	+	Virtual keyboard with haptic feedback performed better than the one without such feedback.
Yannier *et al.* [120]	V, H	N	Science and Engineering Professionals	+	Haptic feedback significantly improves the understanding of climate data and the cause-and-effect relations between climate variables.
Zahabi *et al.* [121]	V, A, H	S	General Purpose	-	Males of equivalent high fitness levels rely more on visual cues than the auditory or haptic cues for pattern recognition. The haptic modality for cognitive task decreased accuracy.
Zhou *et al.* [122]	V, A, H	N	Health Professionals	+	Haptic feedback enhances the performance of laparoscopic surgery.

In the stimuli column, V stands for visual, A for audio, H for haptic, S for smell, and T for taste. The column Setup refers to the VR setup, where N refers to non-immersive, S to semi-immersive, and I to immersive. The column Application Area follows the ISCO-08. The column Impact refers to the impact of the multisensory condition compared to that of the conventional condition, where + represents a positive impact, = a neutral impact, and - a negative impact.

3.2 Quality Assessment

The scoring of the 105 selected papers in the full-text analysis revealed an average score of 6.87. A total of 66 papers that had scores of 7 or higher were considered high-quality papers that provide a more robust methodology and, consequently, stronger confidence regarding their main findings. The quality assessment score histogram is shown in Fig. 2. Note that in the quality assessment process, the fact that top conferences can hold higher-quality works than some journal papers can be a limitation. However, this limitation is mitigated by the two other quality assessment criteria, since if the work meets such, it is scored at a 7 and thus considered a high-quality publication.

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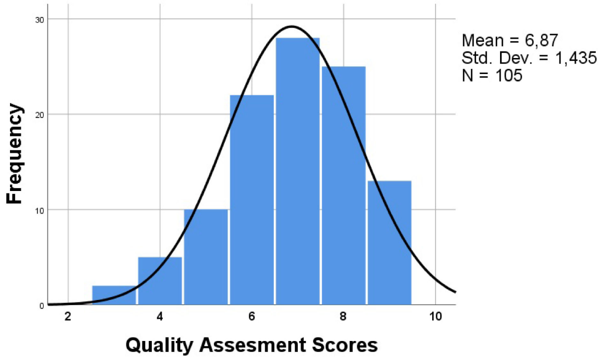

Fig. 2. Quality assessment scores histogram.

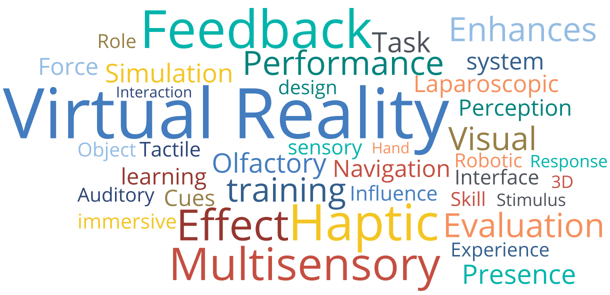

Fig. 3. Word cloud based on analyzed paper titles (generated from https://www.displayr.com/).

TABLE 2
Frequency for Each of the Word Cloud Terms
With More Than 10 Occurrences

Term	Frequency
Virtual Reality	66
Feedback	37
Haptic	34
Multisensory	27
Effect	25
Enhances	15
Performance	15
Training	15
Evaluation	15
Visual	14
Task	11
Presence	10
Olfactory	10

3.3 Quantitative Synthesis

The qualitative synthesis of studies included in the qualitative analysis was performed using a graphic representation (Fig. 3) and a table (Table 2) of the most frequently used terms in the titles of the analyzed papers, and the data directly related to the main research questions of this systematic review. Thus, the impact of the multisensory VR application compared to that of the conventional VR application is shown in Fig. 4. The groupings of the stimuli used in the papers that were analyzed are shown in Fig. 5, the type of VR setups used and their usage over the years are depicted in Figs. 6 and 7, and the field of application of the analyzed full-texts are shown in Fig. 8.

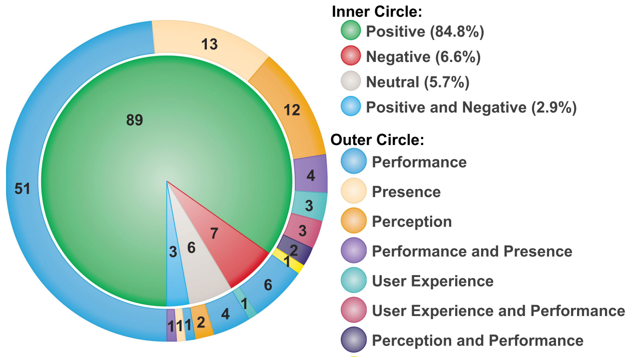

Fig. 4. Outer circle: Type of variable evaluated. Inner circle: Type of impact of multisensory VR in comparison to conventional VR.

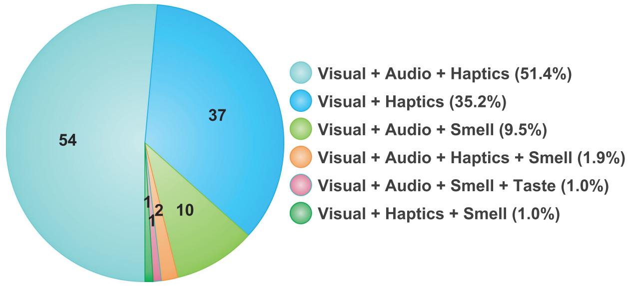

Fig. 5. Groupings of the stimuli used in the analyzed papers.

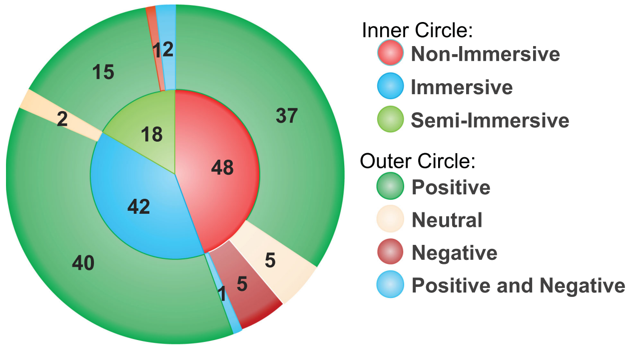

Fig. 6. Outer circle: impact of the corresponding VR setups over conventional environments (green: positive; gray: neutral; red: negative; orange: positive and negative). Inner circle: count of different VR setups.

4 Discussion

This systematic review aims to qualitatively and quantitatively survey and synthesize the literature that focuses on the study of the impact of multisensory VR applications in comparison to that of conventional VR. The goal is to provide a critical appraisal of not only the impact of multisensory VR applications but also the stimuli that are more frequently used, the type of VR setups adopted, and the field of the applications.

The graphical word cloud (Fig. 3) reveals that the keywords of the analyzed multisensory VR studies are *Feedback*, *Haptic*, *Multisensory*, *Effect*, *Enhances*, *Performance*, *Training*, *Evaluation*, *Visual*, *Task*, *Presence*, and *Olfactory*. Thus, the word cloud reflects the number of works that are devoted to the simulation of medical scenarios using haptic devices. Although laparoscopy appears as a keyword, we would also

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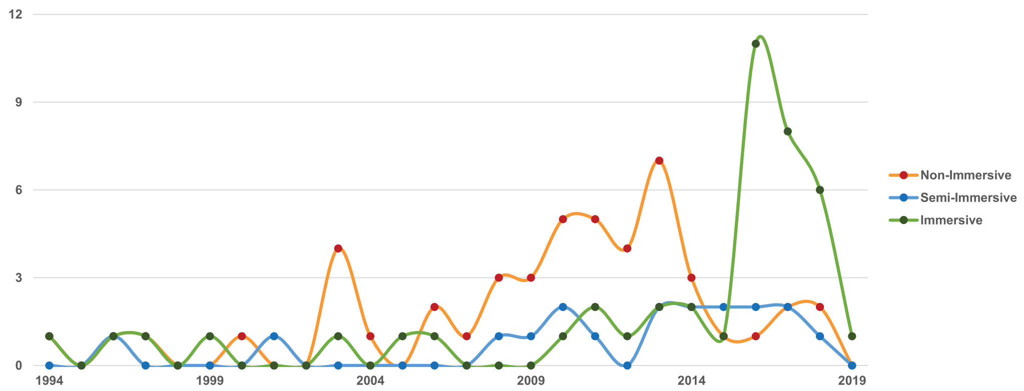

Fig. 7. Evolution of the VR setup types used over the years.

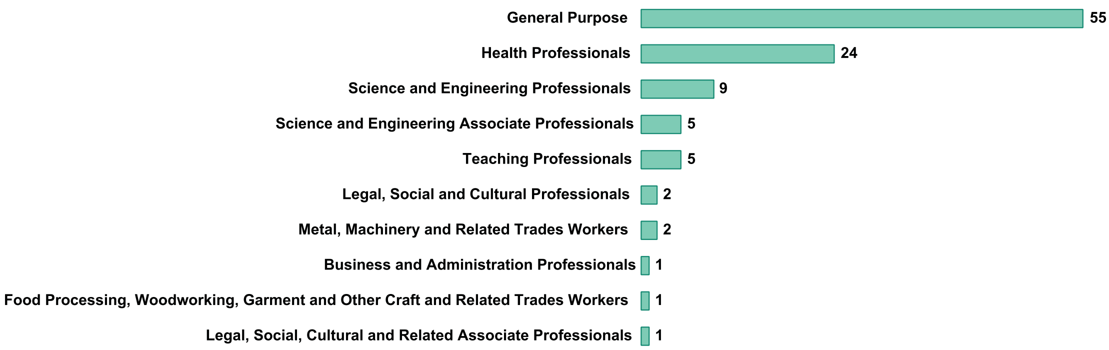

Fig. 8. Distribution of VR applications per application field.

like to highlight that haptic devices are often used for more general surgical procedures. It should also be noted that the word cloud highlights the metrics that are frequently used for evaluation: effect(s) of the multisensory system, the sense of presence, and task execution and perception related variables. The term "immersive" is also a common keyword that reveals that there is a considerable number of works that adopt an immersive VR setup.

4.1 What is the Impact of Multisensory Stimuli on VR Experiences?

Regarding the impact of multisensory VR in comparison to that of conventional VR systems (represented in the inner circle of Fig. 4), the analyzed literature points clearly in one direction: 84.8 percent of the studies reported a positive impact of multisensory VR systems. This outcome was expected, as the more stimuli used, the more realistic the user experience will be, corroborating previous works [4], [5], [6]. A closer look at the works that presented a negative impact of the multisensory applications also partially supports this claim. One cause that was raised by the authors was that the stimuli did not realistically represent reality. For instance, Våpenstad *et al.* [112] noted that the materials used to deliver the haptic stimulus caused additional friction, which negatively affected task performance. This is in line with the literature that finds that the credibility of the sensory feedback affects the users, and if the stimulus is not coherent with the real-world scenario, it negatively affects the virtual experience [11]. From the studies finding a neutral impact, we verified that, in some cases, the multisensory stimuli were used more as a complement than as a critical stimulus for accomplishing the goal for which the VR application was developed. For instance, in Toet *et al.* [108], unpleasant and pleasant smells were introduced to see if they would affect the detection of disorder signs; however, there was no relationship between the presented smells and the virtual objects that indicated the signs of a disorder. In such studies, the multisensory stimulus can be inadvertently disregarded by participants who are focused on fulfilling the tasks at hand and who, due to their focus on the task, do not become aware of the additional stimuli. Taking this into account, to obtain the full advantage of multisensory setups, it is important that the multisensory stimulus has a direct relationship with the purpose of the goal of the VR experience.

To better understand the role of the multisensory stimuli, it is important to go beyond the type of impact that they have and to understand which variables were evaluated in the analyzed studies. The variables were categorized into four main categories – (user) performance , presence, perception (of the VE), and user experience – which are represented in the outer circle of Fig. 4. In some cases, there are studies that consider more than one category, and they are also represented in the outer circle of Fig. 4. As can be verified, the majority of the studies fall into the performance category, which indicates that multisensory stimuli, beyond aesthetic purposes, are being added to VR experiences to enhance the user performance, allowing users to be more effective and take greater advantage of the virtual experience. Presence and perception also deserve the attention of researchers when evaluating multisensory setups. Despite being different variables, they have a common purpose: while presence

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aims at using multisensory stimuli to transport users to the VE, perception variables evaluate the use of multisensory stimuli to delude the user's perception and to have them perceive that the VE is as close to reality as possible. This suggests that, in addition to increasing user performance, the credibility of the VE is also a concern of the analyzed studies.

Although the majority of the analyzed papers indicate a positive impact of multisensory VR, some limitations must be pointed out: only 14.3 percent of the surveyed studies consider user perception, indicating that there is little attention given to how users will perceive multisensory stimuli. Thus, it becomes essential to ensure proper calibration of multisensory stimuli in term of intensity or duration to provide the intended impact of each sensory modality among users instead of simply being felt by them. Furthermore, it is common to have multisensory stimuli that, instead of being coherent with the context of the scene, are just generic stimuli that are synchronized with the VR scene. For instance, when there is a virtual scene depicting a garden full of lavender, the smell of lavender should be delivered for an authentic experience, but instead of delivering the smell of lavender, a generic pleasant smell is associated with the scene. It is true that a generic smell can be introduced to represent the scene; however, we argue that the stimulus must be as close as possible to the real stimulus to elicit an authentic virtual experience. It is noted that there is still little work that devotes attention to the study of cross-modal effects between the different stimuli.

4.2 Which Multisensory Stimuli are More Used?

The usage of haptics is predominant, representing 86.6 percent (51.4 percent visual, audio + haptics and 35.2 percent visual and haptics) of the reviewed studies. We can attribute this result to how technology has evolved, as currently, simple haptics, such as a simple vibration, are a relatively easy stimulus to provide since it is widely supported by interaction interfaces, especially when compared to other devices where integration in a VR experience is often a challenge. Nevertheless, simple vibration might not suffice, as haptics can assume different forms that go beyond a simple vibration (e.g., thermal, tactile, kinesthetic) and such feedback fidelity can be critical for some application fields such as the medical field (e.g., surgical procedures). Thus, beyond simply delivering haptics, the fidelity of haptic stimuli is still an open challenge, as it requires specific hardware that is scarce, complex, and costly [123]. The analyzed papers reveal that haptics are widely used for medical training, namely, for surgical training. These papers are based on haptic devices that offer 3D touch with six degrees of freedom or, for laparoscopic procedures, similar haptic devices incorporated in simulators that reproduce 3D touch. Haptics are also often used not to simulate touch, but to get users' attention when some action is required, to warn users when something is being done incorrectly, or to guide users during procedures.

While technology offers a comprehensive set of solutions for providing haptic feedback, the same does not happen for smell and taste stimuli, as smell devices are often complex and expensive, and taste devices are almost nonexistent and very intrusive. There are also additional barriers that limit the usage of smell and taste stimuli, as they are very complex senses, and it is not straightforward to synthesize and deliver them expeditiously. Unlike visual stimuli, that are based on three color components (red, green, blue), these senses have a very complex chemical nature, and there are no off-the-shelf devices available to consumers that allow them to experience smell in VR. Nevertheless, the surveyed work has revealed that the sense of smell and taste can increase the sense of presence ([83], [84]), improve memorization and learning abilities ([67], [109]), or even affect the perception of the scene due to the enriched context ([32]). Thus, it is crucial to overcome the constraints associated with smell and taste stimulation, as in addition to being remarkable senses, they can play an essential role in the virtual experience. For instance, in firefighter training, providing the correct stimuli can be critical when simulating smells such as gas. This allows the trainees to be exposed to a realistic environment and to adapt their procedures according to the presence/absence of such stimuli, as different procedures can be required based on the depicted scenario.

4.3 What Type of VR Setups are More Often Used?

Following an evolutionary principle, one might expect that in the first phase, non-immersive setups were widely adopted, since they were the first to appear, followed by semi-immersive setups, which are a natural step forward in technology, and finally immersive setups. However, the literature analysis revealed that, in a multisensory context, non-immersive and immersive setups are used more frequently than semi-immersive setups. For a better understanding, a chart was made to show the evolution of the types of VR setups used over the years in the analyzed studies (Fig. 6). The chart revealed the adoption of non-immersive setups first, some works with semi-immersive setups, and then a significant decrease in non-immersive setups followed by a significant increase in immersive setups. It is expected that non-immersive setups were more widely used, as they were the first type of VR setup to be viable. However, semi-immersive systems were not widely adopted compared to the other types of VR setups. Authors point to two reasons for such a scenario. The first is that semi-immersive setups are more expensive than conventional or HMD setups, and the user experience is not optimized compared to other setups. The second reason, supported by the evolution of VR setup usage over time (Fig. 7), is that technology's evolutionary pace is swift, and immersive setups have become affordable and capable of delivering high-quality virtual experiences before semi-immersive systems were able to become established. A closer analysis of Fig. 7 reveals a significant increase in the use of immersive setups since 2015, which can be explained by the release of the Oculus Rift DK1 in 2013, which had the ability to deliver quality VR experiences at an affordable price. This product contributed to the widespread of immersive setups: there are reports in 2014 that say that the Oculus Rift DK1 sold more than 60 000 units and that more than 45,000 units of its successor (Oculus Rift DK2) were sold [124].

4.4 What are the Application Fields of Multisensory VR Studies?

As illustrated in Fig. 8, a large portion of the analyzed works does not have a specific application field, being classified as general purpose works. These works focus on research on the effects of a multisensory VR experience on user perception or

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performance (e.g., effect of a given stimulus on the sense of presence or task performance), and their outcomes can be applied as insights to any application field. Despite the potential of VR for application to any field, these works focus on the technology itself and evaluate, at a fundamental level, the effect of the different stimuli on multisensory VR setups compared to the effects of conventional VR setups. This indicates that the research community is devoting attention to multisensory VR technologies and studying them to generate knowledge on how they can be used more efficiently. Within the works that have a specific application field, the health professionals group stands out. There are a considerable number of works that take advantage of VR to train health professionals in general surgical procedures. This popularity occurs because VR allows a fully customized training environment where the trainees have room for error and improvement under a controlled scenario and without compromising patient safety. This allows health professionals to enhance their skills before going to real-world critical scenarios.

The second and third groups on the list of applied usage are science and engineering professionals and associate professionals. As the names suggest, they are interrelated application fields, but the main difference is in the functions they perform in their occupation: the first refers to professionals who perform research and development activities to increase the body of knowledge and transfer knowledge to different fields of science and engineering (e.g., physicist, pharmacist, biologist), while the latter refers to professionals involved in more technical activities to ensure operational methods in science and engineering (e.g., clerk of works, power plant operator, electronics mechanic). In terms of the works analyzed, they have a common goal: to provide/adopt methods and tools to be used for training procedures in the fields of science and engineering. VR is popular in this fields because the training process for such specialized technicians is often complex, costly and requires a significant time for them to acquire the desired competencies and be ready for the job. Using VR for training has advantages when compared to real-world training, such as the reduction in costs and risks [125], the greater control over the training procedures, or the promotion of experiential learning [126].

It was expected to find works on the usage of multisensory VR applied to aviation due to their past relationship. However, we attribute this lack to the fact that aviation simulators are always of a multisensory nature, and this falls into the exclusion criteria, as there are no works that compare conventional versus multisensory aviation simulators.

Regarding fields of application such as tourism or marketing, there is little work devoted to the multisensory component, which could be attributed to the fact that multisensory setups are expensive and are still not widespread on the consumer's side. Consequently, there is less uptake by the industry, as the investment would not reach its audience as widely as a conventional VR setup would reach.

4.4.1 Limitations

The search query was designed to find papers that contain in the title, keywords, or abstract the terms "virtual reality", "virtual environments", "VR" or "virtual experience" and the terms "multisensory" or "multi-sensory". The adoption of the multisensory-related terms might have excluded papers that address multisensory setups, as authors might have used the terms associated with the stimuli itself. This decision was made following exploratory search queries that used all the terms associated with each of the senses (e.g., touch, tactile, thermoception, temperature or force feedback for haptic feedback and olfaction, scent or aroma for smell), which were found to return an overwhelming number of matches comprising a significant portion of papers that were not pertinent for the scope of the survey.

5 Conclusion

This systematic review shows that multisensory VR systems have a positive impact when compared to the impact of conventional VR systems. However, it is notable that the surveyed multisensory studies focus on the user's performance rather than on the user's perception (only 14.3 percent of the surveyed studies considered the user's perception versus 59.1 percent of studies that focused on the user's performance). By disregarding the user's perception of multisensory cues, their added value can be compromised, and, consequently, the user may not take full advantage of such multisensory cues. Future work should consider the study of cross-modal effects between the different senses in VR as well as devote more attention to not only how the stimuli are delivered to the participants but also how the participants perceive them.

Haptics is, by far, the most used stimuli in multisensory setups. We may attribute this to haptic devices' technological maturity, affordability, and availability based on a large set of devices and the simplicity of their integration in simulations. Despite the importance of smell and taste, their nature, as well as the apparatus required to deliver such stimuli, are often complex, expensive and intrusive (especially when stimulating taste). Therefore, it is necessary to devote more research and development to smell and taste delivery and its impact on VR experiences. Regarding the type of VR setups used in the multisensory context, it is notable that in the first stage, non-immersive setups were widely used, followed by the adoption of immersive systems. Semi-immersive systems were never widely adopted, and we attribute this to the fact that such setups require a large apparatus as well as its interface devices can be complex and intrusive (eg. data gloves) when compared to conventional or HMD setups, which has an impact on the user experience. Also, semi-immersive setups have considerable acquisition and maintenance costs that are more significant than the costs of other types of VR setups.

Although most of the analyzed papers are focused on the technical aspects of the technology and effects on users, there are already application fields that take advantage of multisensory VR technologies such as health professionals and science and engineering professionals. This is explained by the fact that VR-based training promotes a more controlled environment that, at the same time, reduces costs and safeguards trainees from possible life-threatening risks.

Despite the evident positive impact of multisensory VR over conventional VR setups, there are key points that deserve to be addressed to allow widespread multisensory

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VR. The affordability and quality of the stimuli are drivers of the adoption of such technologies. The analyzed works show that smell and taste deserve more attention, as the technology associated with these senses is still very intrusive and costly. A significant challenge is to study and establish how technology can deal with their complex nature and deliver them with realism.

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