

# Multimodality in VR: A survey

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## Abstract

*Virtual reality has the potential to change the way we create and consume content in our everyday life. Entertainment, training, design and manufacturing, communication, or advertising are all applications that already benefit from this new medium reaching consumer level. VR is inherently different from traditional media: it offers a more immersive experience, and has the ability to elicit a sense of presence through the place and plausibility illusions. It also gives the user unprecedented capabilities to explore their environment, in contrast with traditional media. In VR, like in the real world, users integrate the multimodal sensory information they receive to create a unified perception of the virtual world. Therefore, the sensory cues that are available in a virtual environment can be leveraged to enhance the final experience. This may include increasing realism, or the sense of presence; predicting or guiding the attention of the user through the experience; or increasing their performance if the experience involves the completion of certain tasks. In this state-of-the-art report, we survey the body of work addressing multimodality in virtual reality, its role and benefits in the final user experience. The works here reviewed thus encompass several fields of research, including computer graphics, human computer interaction, or psychology and perception. Additionally, we give an overview of different applications that leverage multimodal input in areas such as medicine, training and education, or entertainment; we include works in which the integration of multiple sensory information yields significant improvements, demonstrating how multimodality can play a fundamental role in the way VR systems are designed, and VR experiences created and consumed.*

## 1 Introduction

Virtual Reality (VR) is inherently different from traditional media, introducing additional degrees of freedom, a wider field of view, more sophisticated sound spatialization, or even giving users' control of the camera. VR immersive setups (like head-mounted displays or CAVE-like systems) thus have the potential to change the way in which content is consumed, increasing realism, immersion, and engagement. This has opened many application

areas such as education and training [187, 29], rehabilitation and neuroscience [206, 161], or virtual cinematography [170].

Although visual stimuli tend to be the predominant source of information for humans [183, 21, 201], additional sensory information helps increase our understanding of the world. Our brain integrates different sources of sensory feedback including both external stimuli (visual, auditory, or haptic information) and internal stimuli (vestibular or proprioceptive cues), thus creating a coherent, stable perception of objects, events, and oneself. The unified experience of the world as we perceive it therefore emerges from all these multimodal cues [142, 171]. These different sources of information must be correctly synchronized to be perceived as belonging together [123, 138]. Synchronization sensitivity varies depending on the context, task and individual [43]. In general, different modalities will be perceived as coming from a single event or object as long as their temporal incongruency is shorter than their corresponding window of integration [101, 131, 14].

When exploring virtual environments the presence of stimuli from multiple sources and senses may also enhance the viewing experience [112]. Many works have described techniques to integrate some of these stimuli to produce more engaging VR experiences, or to analyze the rich interplay of the different senses. For instance, leveraging the window of integration mentioned above may alleviate hardware limitations and lag time, producing the illusion of real-time performance; this is particularly useful when different modalities are reproduced at different refreshing-rates [30]. Moreover, VR is also inherently well suited to systematically study the integration process of multimodal stimuli [8], and analyze the complex interactions that occur when combining different stimuli [101] (see Figure 1).

In this paper we provide an in-depth overview of multimodality in VR. Sensory modalities include information from the five senses: visual for sight, auditory for hearing, olfactory for smell, gustatory for taste, haptic and thermal for touch. Apart from the five senses, we also consider proprioception, which can be defined as the sense of self-movement and body position, and has been defined as the *sixth sense* by many researchers [34, 175, 196]. We synthesize the existing body of knowledge with special focus on the *interaction* between sensory modalities focusing on visual, auditory, haptic and proprioceptive feedback; in addition, we offer an extensive overview of existing VR applications that directly take multimodality into account.

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**Figure 1.** VR can be used to systematically analyze the interactions of multimodal information. In this example, the influence of auditory signals in the perception of visual motion is studied [101].

## 1.1 Proprioception

Proprioception arises from static (position) and dynamic (motion) information [21]. It plays a key role in the concept of self, and has been more traditionally defined as "awareness of the spatial and mechanical status of the musculoskeletal framework" [197]. Proprioceptive information comes mainly from mechanosensory neurons next to muscles, tendons and joints, although other senses can induce proprioceptive sensations as well. A well-known example are visual cues inducing the phantom limb illusion [143].

Proprioception plays an important role in VR as well. On the one hand, it helps provide the subjective sensation of *being there* [181, 157, 165]. On the other hand, proprioception is tied to cybersickness, since simulator sickness is strongly related to the consistency between visual, vestibular, and proprioceptive information; significant conflicts between them could potentially lead to discomfort [89, 111].

## 1.2 Related surveys

Several surveys exist focusing on particular applications of VR, such as communication [155], medicine [150, 93], education [49], or guidance for cinematic VR [152]. Others have studied the influence of individual senses *in isolation*, including sight [148], sound [167], or touch [91], or concern themselves with cognitive aspects, such as attention or presence [58, 79]. Other surveys study multimodality in *traditional media*, including cognition [184], interaction [72], human-computer interfaces [42, 55], or fusion and integration techniques [7].

Closer to this survey, other works have studied how multimodality in VR has been proven to have a positive impact in most of the experiences [112].

However, and different from these works, in this state-of-the-art report, we focus on the integration of multimodal information, and compile the large body of works studying the effects and benefits of integrating multiple sensory information in VR.

## 1.3 Multimodal challenges

One of the main challenges when considering full multimodal VR are the gaps of empirical knowledge that exist in this field. As

stated before, in this survey our main focus lies in the visual, auditory, haptic and proprioceptive modalities. This is simply because there is a lack of evidence on how other modalities can be integrated in VR and what their effects are on overall user experience. Another important topic to consider is the window of integration. Having to synchronize different modalities means there is a need for real-time, high fidelity computation. Hardware processing limitations might imply a constrain in what multimodal techniques can be used. In the same line, not all VR headsets are equally prepared to support multimodality. Although most of them can give audiovisual feedback, proprioception and haptic feedback are sometimes limited. For example, most of smartphone-based VR headsets don't even have controllers, which is the most common device for haptic feedback. Other basic VR systems are not able to track translations either (only head rotations), which means incomplete proprioceptive feedback.

## 1.4 Scope and organization

In this survey we provide an in-depth review of the most significant works devoted to explore the role and effects of multimodality in the virtual reality pipeline. We gather knowledge about how multiple sensory information, and their interaction, affects the perception, the creation, and the interaction with the virtual experience.

The structure of this work can be seen in Figure 2. Since our focus is not on any specific part of the VR pipeline, but rather on the *VR experience* for the user, we have identified the three main areas of the VR experience in which multimodality plays a key role. First, Section 2 is devoted to the realism of the VR experience, which is tied to immersion and the sense of presence that the user experiences. Second, Section 3 looks into how multimodality can affect the attentive process of the user in the virtual environment, determining how they explore the environment and what drives their attention within it. Third, Section 4 delves into works that demonstrate how multimodality can help the user in completing certain tasks, essentially improving user performance in the virtual environment.

Additionally, there are a number of works devoted to analyzing multimodal perceptual illusions, and to what extent they can be experienced in VR environments. These, which we compile in Section 5, can be leveraged by future techniques for their use to improve any of the aforementioned areas of the VR experience. Finally, we devote Section 6 to reviewing application areas that have benefited from the use of multimodal virtual experiences, and conclude (Section 7) with a discussion of the potential of multimodality in VR, and interesting avenues of future research.

## 2 The effects of multimodality in perceived realism

Perceived realism enhances realistic responses in immersive virtual environments [180]. However, it is important to note that perceived realism is tied to the overall perception of the experience, and therefore it is not only related to the visual realism of the depiction of the environment. There are two key orthogonal components that can lead to users' responding in a realistic manner which are not necessarily related to the visual realism of the scene: the place illusion and the plausibility illusion [179]. The former,

2/ Multimodality contribution to realism	3/ The effects of multimodality in users' attention	4/ Multimodality in task completion	5/ Multimodal illusions in virtual reality	6/ Applications
How does multimodality help improve environment fidelity and embodiment?	What draws user's attention? How can their attention be guided?	How can multimodality enhance users' performance and the outcome of virtual tasks?	How can multimodality exploit human mechanisms to enhance the experience?	Research areas that have benefited from multimodality in virtual reality

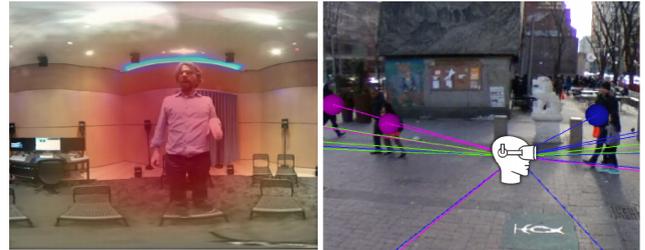
**Figure 2.** Structure of this state-of-the-art report. We divide it into the main areas of the VR experience in which multimodality can play a key role: user immersion, presence, and realism of the experience (Section 2); user attention when exploring the virtual environment (Section 3); user performance when completing tasks (Section 4); and multimodal perceptual illusions that can be leveraged in VR (Section 5). Finally, we review different applications where multimodality has been shown to improve the end goal (Section 6), and finalize with a discussion on the need for multimodality, and open avenues of research (Section 7).

also called "presence", defines the sensation of "being there", and is dependent on sensorimotor information, whilst the latter refers to the illusion that the scenario that is apparently happening is actually taking place, and is determined by the ability of the system to produce events that relate to the user, i.e., the overall credibility of the scenario being depicted in comparison with the user's expectations. Slater argued that participants respond realistically to an immersive VR environment when these two factors are present. This has been also observed in telepresence systems, which highly benefit from sensorially-rich mediated environments [186]. During this section, we will focus on how multimodality affects these two factors, and how it can be used to increase the realism in virtual experiences.

#### Perception of the environment

The perceived realism of virtual environments is a key concern when designing virtual experiences, therefore many works have been devoted to investigate how multimodality and crossmodality can indeed help achieve sensorially-rich experiences. While multimodality refers to the binding of different inputs from multiple sensory modalities, crossmodality involves interactions between different sensory modalities that influence the perception of one another [85, 185]. Chalmers et al. [25] discussed how crossmodal effects in human multisensory perception can be exploited to selectively deliver high-fidelity virtual environments, for instance, rendering with higher visual quality those items related to the current auditory information of the scene. It has been proved that integrating visual and auditory information enables a better understanding of the environment, and yields a more comfortable experience [68]. Various works have been thus devoted to this: Morgado et al. [116] presented a system that generates ambisonic audio for 360° panoramas, so that auditory information is represented in a spherical, smoother way (see Figure 3, left). Analogously, Huang et al. [66] proposed a system that automatically adds spatialized sounds to create more realistic environments (see Figure 3, right), validating by means of user studies the overall preference of this solution in terms of realism. However, special attention has to be paid in this line: Akhtar and Falk [1] surveyed current audiovisual quality assessment, which is necessary to be taken into account, since some sound information may increase the annoyance of the environment and decrease the quality of the virtual experience [156]. Stimuli should be not only realistic but also coherent to the environment.

Other modalities can also enhance environment realism by contributing to plausibility. Hoffman compared the realism of virtu-



**Figure 3.** Including correct and coherent auditory information to the environment has been proved to increase realism and immersion. Left: A system that automatically generates ambisonic information that creates a smoother acoustic information for the scene [116]. Right: A framework to include auditory information into 360° panoramas depending on the elements that conform the scene [66]. In both cases, their validation experiments yield users' preference when auditory information is included, and an overall increase in the perceived realism and immersion in the virtual experience.

ally touching an object with that of touching it physically at the same time [60], yielding a significant preference in realism when object was physically touched too; obtaining similar results with taste and olfactory cues [62]: They found a preference on smelling and physically biting a chocolate bar in contrast to only virtually biting it. Another modality that plays an important role in realism by contributing to the feeling of being there (place illusion) is proprioception: Although some works have demonstrated that some manipulations in virtual movement directions and distances can be unnoticeably performed, users tend to expect their virtual movements to match their real ones, to maintain a coherent experience. In this line, Mast and Oman [107] studied so-called visual reorientation illusions: When the environment is rotated in any axis, users' can perceive that the expected vertical axis does not match with the virtual one, and conflicts between visual and vestibular cues may arise. Although the effect of this illusion is stronger for elder users [63], an incoherent spatial estimation in VR can potentially diminish the perceived realism.

#### Perception of the self

Virtual experiences are designed for humans, and in many occasions, users are provided with a virtual representation of themselves. This is a very effective way of establishing their presence in the virtual environment, hence contributing to place illusion [179]. This representation does not need to be visually realistic, but it has

to be coherent enough with the users' actions to maintain the consistency of the experience. Multimodality can have an impact on this, since correctly integrating multiple sensory information can produce a more accurate representation of the real world, which affects the perception of the self. In this section, we review different works that have leveraged multimodality in the virtual pipeline to achieve self-consciousness and embodiment, and therefore to create realistic representations of the users.

Having the feeling of being in control of oneself is possibly one of the main characteristics that VR offers [179]. Place illusion is possible without being in control; however, being able to control a virtual body highly increases the feeling of presence [165]. The sense of embodiment gathers the feeling of owning, controlling, and being inside a body. As Kilteni et al. [77] reported, this depends on various subcomponents, namely sense of self-location (a determinate volume in space where one feels to be located), sense of agency (having the subjective experience of action, control, intention, motor selection and the conscious experience of will), and sense of body ownership (having one's self-attribution of a body, implying that the body is the source of the experienced sensations). All these concepts (such as presence or embodiment) are intrinsic characteristics that VR can achieve, and they yield the self-consciousness feeling that makes VR so different from other media.

Multimodality has been largely studied as an enhancement of those sensations. Blanke et al. [15] discussed the relevance of a series of principles to achieve a correct sensation of bodily self-consciousness, requiring body-centered perception (hand, face, and trunk), and integrating proprioceptive, vestibular, and visual bodily inputs, along with spatio-temporal multisensory information. Sakhardande et al. [158] presented a systematic study to compare the effect of tactile, visual, visuomotor, and olfactory stimuli on body association in VR, with the latter having the strongest effect on body association. The main factors to build embodiment and body-ownership in VR have been widely studied [106, 182], and so have been the negative effects that can happen when designing realistic experiences [122]. Similar insights were proposed by Pozeg et al. [140], which demonstrated the importance of first-person visuo-spatial viewpoints for the integration of visuo-tactile stimuli, in this case for the sense of leg ownership.

Place illusion (or presence) is also tied to the integration of multiple modalities, and many works have demonstrated how presence is increased when multiple sensory information is combined. [160] as opposed to unimodal (i.e., only visual) systems [74]. Different soundscapes increased the sense of presence in VR [166], and as Liao et al. [94] studied, combining visual and auditory zeitgebers, which act like synchronizers, enhances presence, and even influences time perception. Normand et al. [130], studied the effects of other modalities, showing that it is possible to induce a body distortion illusion by synchronous visual-tactile and visual-motor correlations (see Figure 4). The level of presence achieved depends on the different combinations of sensory feedback, and multi-sensory systems have been proved to be superior to traditional audio-visual virtual systems in terms of the sense of presence and user preference [74]. Similar conclusions have been obtained by Hecht et al. [58], who reported that multimodality led to a faster start of the cognitive process, which ultimately contributed to an enhanced sense of presence.



**Figure 4.** *Left: Synchronizing different modalities increases the feeling of presence, and can even create a distortion of the perception of the self. Normand et al. [130] presented a study where a body distortion illusion is achieved by synchronous visual-tactile and visual-motor correlations. Right: Some works have studied different physical and behavioral factors than directly affect embodiment [122].*

The sense of moving (which depends of agency and body ownership as previously mentioned) is also necessary for the self-consciousness. Kruijff et al. [82] presented a work showing that adding walking related auditory, visual, and vibrotactile cues could all enhance participants' sensation of self-motion and presence. Various works have been presented in this line, investigating the integration of tendon vibrations to give standing users the impression of walking physically [81], or proposing and evaluating a virtual walking system for sitting observers using only passive sensations such as optic flow and foot vibrations [108]. As in the case of the latter, sometimes movement is not possible, and it has to be externally generated, creating the well-known self-motion illusion, to which body sometimes generates postural responses. Meyer et al. [113] explored what factors modulate these responses in virtual environments, with visual, auditory, and haptic reference points.

Many other modalities can play an important role in users' self-consciousness. Gallace et al. [50] focused on the problems associated with the stimulation of the senses of touch, smell, and taste, as well as the cognitive limitations in the human sensory perception bandwidth when users have to divide their attention between multiple sensory modalities simultaneously. Other multimodality limitations have also been studied: A recent work has shown that, although multimodality increases presence, users feel more confident in traditional virtual systems [74], and different environments or situations can also lead to diminishing presence and comfort [205]. Similar insights have been derived in terms of immersion and affective content, which have been proven to have an impact on presence [11]. Ultimately, achieving user's self-consciousness depends on finding the right balance between different multimodal cues, and the users' comfort and confidence.

### 3 The effects of multimodality in users' attention

When users are exploring or interacting with a virtual environment, different elements or events can draw their attention. Visual attention influences the processing of visual information, since it induces gaze to be directed to the regions which are considered more interesting or relevant (salient regions). The saliency of different regions results from a combination of top-down atten-



**Figure 5.** Saliency maps show the likelihood of users directing their attention to each part of the scene. Most of the current literature has been devoted to estimate saliency in unimodal, visual stimuli. This image shows the recent visual saliency estimation method proposed by Martin et al. [104] (Left: Input panorama. Right: Estimated saliency). It has been shown that each sensory modality has the potential of influencing users’ attentional behavior, therefore, there is a need for further exploration of multimodal saliency in VR.

tional modulation mechanisms and the multisensory information these regions provide (bottom-up features), creating an integrated saliency map of the environment [194]. As discussed in the previous section, VR setups may produce more realistic responses and interactions, which can be different from traditional media due to the differences in perceived realism and interaction methods. Therefore, some works have been devoted to understanding saliency and users’ attention in VR, offering some key insights about head-gaze coordination and users’ exploratory behavior in VR. For example, Sitzmann et al. [178] detected the *equator bias* when users are freely exploring omnistereo panoramas: They observed a bias towards gazing at the central latitude of the scene, which often corresponds to the horizon plane.

For the case of saliency, research has been largely evolving, both inside and outside the VR field [207]. Users are more likely to turn their attention and interact with those regions of the scene that have more sensory information. Therefore, knowing a priori which parts of the scene will be more salient may help anticipating how are users going to behave. So far, most of the works on saliency in VR have been developed from an unimodal perspective [13, 27, 92, 212, 208, 115, 104]: They all leverage visual information (i.e., users’ head position and gaze orientation) to create probabilistic maps indicating the chances of a user looking at each part of the virtual scene (see Figure 5). Following this line, various works have presented systems able to predict users’ gaze, depending on the environment and also on user’s previous behavior [209, 208, 65].

On the other hand, multimodality in saliency estimation has been only tackled in traditional approaches: The integration of visual and auditory information in videos has been widely explored [38, 75, 39, 120, 41, 114], although in all of those cases, audiovisual correlation was assumed: Elements that were moving were the source of the sonic cues. Evangelopoulos et al. [44] even proposed the addition of text information in form of subtitles, which can transform saliency to a top-down process, since the interpretation of the subtitles, as a more complex cognitive task, can distract viewer’s attention from other parts of the scene.

Multimodality in saliency prediction for VR still remains in early phases, and only very few works have been devoted to it. Chao et al. [26] proposed the first work that studies user behavior (including visual attention corresponding to sound source locations, viewing navigation congruence between observers, and



**Figure 6.** Examples of visual guidance methods in VR, adapted from Rothe et al.’s review on users’ guidance for cinematic content [152]. Three visual guidance techniques are presented in this image: Arrows pointing regions of interest, picture-in-picture techniques that show information of rear regions, and vertical and horizontal position of a point of interest marked with red bars. Most of those techniques are intrusive, hence they may break the immersion and realism. With the addition of multimodal cues, the visual and cognitive loads can be alleviated, while the experience would stay realistic.

fixations distribution) in virtual environments containing both visual and auditory cues (including both monaural and ambisonic sounds). However, there are still many open avenues for future research: Visual saliency and gaze prediction in VR is still in an early phase, and the effects of auditory cues in saliency in virtual scenarios remain to be further explored. Auditory cues in VR may produce more complex effects and interactions than in traditional scenarios, since sound sources are not always in the user’s field of view, and there might be several competing audiovisual cues. Additionally, investigating how other senses interact and predominate in saliency and attention can be useful for many applications, specially for content creation.

Although there is still much to learn about how multimodal cues compete and alter users’ behavior, it is well known that multimodality itself has consequences on how users behave [15, 195, 26]. One of the main difficulties when designing and creating content for VR lies on the fact that users’ typically have control over the camera, and therefore each user may end up paying attention to different content and creating a different experience [170, 103]. Therefore, it is usually not easy to make assumptions about users’ behavior and attention. To facilitate the creation of experiences, and maximize the likeliness of a user behaving as creators would expect, multimodality can be exploited, so that cues from different modalities can induce specific behaviors and even guide users’ attention.

For the case of attention, understanding and guiding users attention in VR has been a hot topic during the last years. Various works have explored the use of visual guiding mechanisms, such as the study of the effectiveness of central arrows and peripheral flickers to guide attention in panoramic videos [164], or the comparison of different visual guiding mechanisms to guide attention in 360° environments [204]. Lin et al. [96] proposed a picture-in-picture method that includes insets of regions of interest that are not in the current FoV, so users are aware of everything around them. Many works exist in this scope, exploiting how users can voluntarily direct their attention to this kind of cues. Inducing

the users to direct their attention to a specific part of the scene has also been explored, for example, using focus assistance techniques [95], such as indicating the direction of the relevant part, or automatically directing the world so that users' did not miss that part of the experience. Following this line, Gugenheimer et al. [54] presented a motorized swivel chair to rotate users until they were focusing on the relevant part of the scene, while Nielsen et al. [124] forced virtual body orientation to guide users attention to the most relevant region. Other techniques directly let the viewer press a button to immediately reorient the scene to the part containing the relevant information [133]. It is worth mentioning that this kind of techniques have to be taken into consideration with caution, since they can cause dizziness or discomfort due to visual-vestibular conflicts. We refer the reader to Rothe et al.'s work [152] for a complete survey about guidance in VR (see Figure 6).

However, guidance techniques are not necessarily constrained to visual manipulations. Multimodality can be also exploited to guide, focus and redirect attention in VR, in many cases achieving more subtle, less intrusive methods. This is important to maintain the users experience, as intrusive methods can alter the sense of presence, immersion, or suspension of disbelief (the temporary acceptance as believable of events or places that would ordinarily be seen as incredible). As shown in previous sections, sound can help enhance the virtual experience. Besides, it can also be used to manipulate or guide users attention. Rothe et al. [154] demonstrated that the attention of the viewer could be effectively directed by sound and movements, and later [153] investigated and compared three methods for implicitly guiding attention: Lights, movements, and sounds, showing that sounds elicit users' exploratory behavior, while moving lights can also easily draw attention. Other works have explored various unobtrusive techniques combining auditory and visual information, showing that auditory cues indeed reinforce users' attention being drawn towards specific parts of the environment [20]. Bala et al. [9] presented a software for adding sound to panoramic videos, and studied how sound helped people direct their attention. Later, they examined the use of sound spatialization for orientation purposes [10]. In a similar fashion, some works have studied how to design sound to affect attention in VR [159], and how decision making processes are affected by auditory and visual cues of diegetic (i.e., sounds emanating for the virtual environment itself) and non-diegetic (i.e., sounds that do not originate from the virtual environment itself) origins [22]. However, non-diegetic cues need to be analyzed and presented carefully: The work by Peck et al. [135] showed that a distractor audio can be successful at fostering users' head rotations (and thus redirection); however, users considered this method as unnatural. It has been also suggested that too many sound sources in a VR cinematic video can produce clutter, and therefore hinder the identification of relevant sound sources in the movie [152]. All these multimodal effects, as well as their interactions, are challenging lines of future research that remain to be further investigated.

#### 4 Multimodality improves task completion

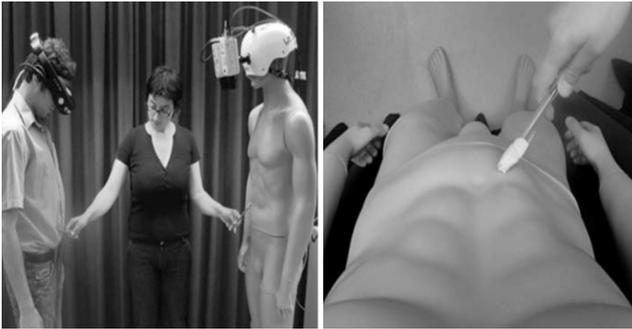
Understanding how users perform different tasks in VR is key for developing better interfaces and experiences. Additionally, VR technologies are becoming a very powerful tool for training, spe-

cially in scenarios that can be expensive or dangerous in the real life. Although in many cases task performance highly depends on the users' skills and experience, there are many scenarios where multimodality can play an important role in this aspect: By integrating multiple sensory information we can mimic better the real world, and this can enhance the way users' interact with the virtual environment. In addition, multimodality can help completing some tasks in a shorter period, or with a higher accuracy.

The effects of multimodality in task performance have been largely studied in traditional media. Lovelace et al. [97] demonstrated how the presence of a task-irrelevant light enhances the detectability of a brief, low-intensity sound. This behavior also holds in the inverse direction: Concurrent auditory stimuli could enhance the ability to detect brief visual events [127]. Thus, integrating audiovisual cues may diminish the risk of users losing some relevant information. In a similar line, Van der Burg et al. [198] reported that a simple auditory *pip* drastically decreased detection time for a synchronized visual stimuli. These effects are not only present in audiovisual stimuli: Tactile-visual interactions also affect search times for visual stimuli [199]. Furthermore, Maggioni et al. [100] studied the potential of smell for conveying and recalling information. They compared the effectiveness of visual, olfactory, and their combination in this task, and demonstrated that olfactory cues indeed improved users' confidence and performance. Therefore, the integration of multiple cues has been widely proved to be effective in terms of detectability and efficiency. In the case of VR, many of those insights hold, and multimodality also has an important role. As Hecht et al. [58] studied, when there are multiple senses involved, users start their cognitive process faster, thus they can pay attention to more cues and details, resulting in a richer, more complete and coherent experience.

Performance in spatial tasks is greatly benefited from multimodality. Auditory cues are extremely useful in spatial tasks in virtual environments, and therefore have been widely explored. The effect of sound beacons in navigation performance when no visual cues are available has been explored [203], with some works proving that navigation when no visual information is available is possible using only auditory cues [53]. Other works have exploited this, proposing a visualized echolocation method which improved the space perception in VR thanks to the integration of auditory and visual information [151], or combining the spatial information contained in echoes to benefit visual tasks requiring spatial reasoning [51]. Other senses have also been explored aiming for an enhancement of spatial tasks: Ammi and Katz [5] proposed a method coupling auditory and haptic information to improve performance in search tasks. They leveraged tempo in both signals to integrate information and to enhance spatial reasoning.

Direct interaction tasks can be also enhanced by multimodality: Auditory stimuli has been proved to facilitate touching a virtual object outside user's field of view, hence creating a more natural interaction [78]. Egocentric interaction is also likely to happen, and proprioception plays an important role on those cases. Poupyrev et al. [137] presented a formal study comparing virtual hand and virtual pointer as interaction metaphors, in object selection and positioning experiments, yielding that indeed both techniques were suitable for different interaction scenarios. In contrast, Tanriverdi and Jacob [193] did find that eye movement-based interaction was faster than pointing, although recall of spatial in-



**Figure 7.** Multimodality illusions can change the way users perceive both themselves and the environment. For instance, Petkova et al. [136] studied how proprioceptive and haptic cues could lead to body ownership illusions.

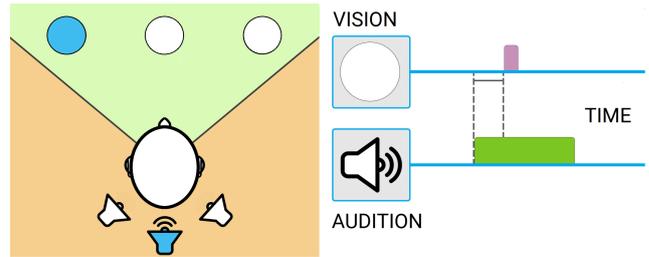
formation was weaker, hence some trade-off may have to be done when trying to improve performance by means of multimodality.

## 5 Multimodal illusions in VR

Multimodality can enhance the way users perceive themselves and the world, as well as their interactions. The integration of multiple senses can not only improve the experience, but may also allow to manipulate it. Manipulating the experience implies that some cues may be added, removed, or modified, so that users behavior is deviated from what would be expected in a non-edited scenario.

Multimodality can be leveraged to trick the self perception of the users, or to alter how they perceive the world around them, by means of facilitatory or inhibitory (suppressive) effects, which can have direct implications on how users behave in the virtual environment. Being able to manipulate the experience can be very useful in certain contexts and applications: It is sometimes necessary to guide the user towards a particular aspect of the virtual environment without disrupting the experience (e.g., in cinematography and videogames). A forced guidance could lead to reduced immersion feelings, or even rupture of the suspension of disbelief. In other cases, physical space is constrained, and manipulating user's movement may allow to reduce the necessary physical space to complete a task [169]. Manipulating the experience can even be useful to reduce simulator sickness [64]. Although this can be done using a single modality, the use of multimodal cues can improve the effectiveness of those techniques.

Illusion refers to an incorrect perception or interpretation of a real, external stimulus. It can lead to interpreting reality in several ways. Any healthy person can experiment illusions without experiencing any pathological condition. However, not every person is affected in the same way by an illusion. Illusions can have physiological (i.e., an after-image caused by a strong light [71]) or cognitive (i.e., the Rubin vase [134]) components. They have been widely studied, as understanding illusions gives information about what the limitations of human senses are, and helps understanding the underlying neural mechanisms that help create the perception of the outside world. What is more, we can change users responses to certain tasks, even increasing performance, us-



**Figure 8.** Spatiotemporal layout of an auditory-triggered effect that degrades visual perception. Sound cues located outside the field of view are concurrent with the appearance of a visual target (inside the field of view), causing the visual target to be missed out by participants even when they are directly fixating on it. Figure adapted from Malpica et al. [102].

ing illusions [28]. In this subsection we will focus on multimodal illusions or effects, or how illusions in other senses can affect visual perception. For visual only illusions, we refer the reader to The Oxford Compendium of Visual Illusions [173].

Multimodal illusions can be useful when user accuracy needs to be increased. For example, multisensory cues can improve depth perception when using handheld devices [19, 189]. Using a small number of worn haptic devices, Glyn et al. [90] improved spatial awareness in virtual environments without the need of creating physical prototypes. Instead of applying contact (haptic feedback) at the exact physical point of the users body that was touching a virtual object, they used a small, fixed set of haptic devices to convey the same information. Their work was based on the funnelling illusion [12], in which the perceived point of contact can be manipulated by adjusting relative intensities of adjacent tactile devices. Visuo-haptic illusions allow not only to better perceive the virtual space, but also to feel certain virtual object properties, like weight, that are not easy to simulate [24]. The rubber hand illusion is an illusion where users are induced to feel like a rubber hand is part of their body. In VR, proprioceptive and haptic cues can lead to a similar feeling induced either for an arm [211] or for the whole body [136] (see Figure 7). Regarding audiovisual illusions, the well known McGurk effect has been replicated in VR. The McGurk effect happens when the audio of a syllable is paired with visual stimuli of a second syllable, raising the perception of a third, different syllable. This illusion has been used to study how audio spatialization affects speech perception, suggesting that sounds can be located at different positions and still create a correct speech experience [177, 176]. It was also found that the spatial mismatch does not affect immersion levels, suggesting that computational resources devoted to audio localization could be decreased without affecting the overall user experience. Another interesting audiovisual illusion that appears both in conventional media and VR is the ventriloquist effect, where auditory stimuli coming from a distant source seem to emerge from an actors' lips. The best located or dominant modality (usually vision) captures information from the weak modality, giving raise to the apparent translation of sound [2]. In this sense, auditory stimuli are affected by visual cues [162], with visual stimuli influencing the processing of binaural directional cues of sound localization. In a complementary way, auditory perception can also

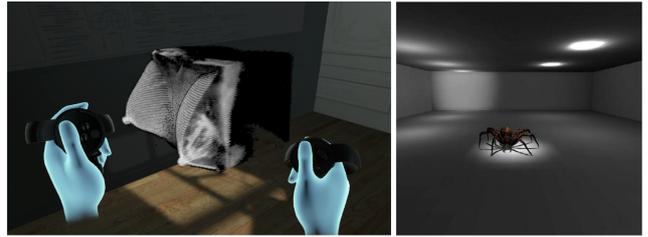
act as a support for visual perception, orienting users to regions of interest outside the field of view [84]. Not every audiovisual illusion has to do with speech. In the sound-induced flash illusion [172], a single flash paired with two brief sounds was perceived as two separate flashes. The reverse illusion also happened when two flashes were concurrent with a single beep, raising the perception of a single flash. In addition to illusions, in which new stimuli are sometimes created, there is also the phenomenon of perceptual suppression, in which one stimulus is no longer (completely or partially) perceived due to an external circumstance. For example, visual suppression is often present in the human visual system. The human brain has evolved to discard visual information when needed to maintain a coherent and stable image of the surrounding environment. Two good examples of visual suppression are blinks and saccades [17, 188], which avoid the processing of blurry information without causing perceptual breaks. Perceptual suppression has been demonstrated and used both in conventional media and in VR [188], usually allowing for environmental changes without the users awareness, which is useful in many applications, such as navigation in VR. It has also been studied how stimuli of a given modality can alter or suppress information of a different modality, usually visual. In particular, for traditional media, both auditory [59] or haptic [70] stimuli can suppress visual stimuli. Functional imaging studies [88] suggest that crossmodal suppression occurs at neural levels, involving sensory cortices of different modalities. Crossmodal suppression has not been widely studied in VR. However, a recent study [102] shows that auditory stimuli can degrade visual performance in VR using a specific spatiotemporal layout (see Figure 8). We believe that a deeper study of crossmodal interactions, both facilitatory and inhibitory, could greatly benefit VR applications, as well as increase our knowledge on sensory perceptual processing in humans.

## 6 Applications

In this work we have reviewed different aspects of multimodality in VR, as well as crossmodal interactions between the different sensory modalities: It is not enough to simply concatenate different senses' stimuli, it is also key to investigate and understand the interactions between them. Many research areas have leveraged this knowledge to enhance different VR applications, showing that multimodality is indeed capable of delivering more realistic and immersive VR experiences. In this section, we review different works in fields that are improving thanks to the multimodal use of VR, namely medicine, training and education, navigation, and entertainment.

### 6.1 Medicine

The potential uses of VR for medical applications have been studied from decades, and research on this field has evolved as the virtual technologies have done so. Satava et al. [190] presented a review about how VR technologies play an important role in telemedicine, from remote diagnosis to complex teleinterventions. Other works focused on the use of VR in the areas of surgical planning, interoperative navigation, and surgical simulations [150, 163]. This has been possible, to a large extent, due to the increasingly photorealistic representation of the anatomy (both



**Figure 9.** *Two representative examples of different applications of multimodality in medicine. Left: Data visualization and manipulation frameworks [141] are important in medical and surgical education and training, and multimodality may enhance the realism and immersion, thus achieving better learning transfer. Right: Multimodal VR is a key tool for phobia treatments, since it is able to create realistic environments that face users against their fears, without actually exposing them [174].*

in physical tissue properties and physiologic parameters) that virtual environments are achieving.

As we have discussed in previous sections, multimodal feedback (e.g., auditory or haptic) also enhances realism and immersion, becoming a more effective way for training and education. Lu et al. [98] presented a multimodal, audio-visual, platform for medical education purposes. One step further, multimodal setups have been proposed for training surgery and medicine, where the realism of the feedback (e.g., haptic) significantly improved the learning effect, for both virtual [67] and augmented [56] reality interfaces. Prange et al. [141] also exploited virtual environments and presented a multimodal medical 3D image system where users could walk freely inside a room and interact with the system by means of speech, and manipulate patients information with gestures (see Figure 9).

These research developments have not been constrained to medical training and simulation areas: Psychological research has also experienced an unprecedented growth, as Wilson and Soranzo [206] reviewed, emphasizing both the advantages and challenges of VR in this area. Similarly, Bohil et al. [16] studied the latest advances in VR technology and its applications in neuroscience research. In particular, many applications have emerged in areas like rehabilitative medicine and psychiatry, where significant progress has been made thanks to the multimodal aspect of VR.

Psychiatric therapies can also benefit from multimodality, since different aspects of behavioral syndromes can be extensively analyzed in virtual environments: Given the suitability of VR to manipulate rules and tasks execution, it has proven to be a fitting paradigm to treat diseases like OCD [33] or Parkinson's disease [32]. The case of phobia treatment is probably one of the most widely spread in virtual environments. The realism multimodality offers over only visual VR experiences enhances these experiences, and therefore effectiveness of the treatment tends to increase. In addition, VR allows to expose patients to their fears in a safe and highly controlled way, minimizing any potential risks of exposure therapy. Shibani et al. [174] studied the effect of multiple context exposure on renewal in spider phobia (see Figure 9). The work of Hoffman et al. [61] went a step further: They explored not only whether VR exposure therapy reduces fear of spiders, but also proved that giving patients the illusion of physi-

Application	Example work	Additional involved senses (other than vision)				Brief description
		Audition	Proprioception	Haptics	Other	
Rehabilitation	Fordell et al. [48]	✗	✓	✓	✗	Chronic neglect treatment, with a force feedback interface.
	Sano et al. [161]	✓	✓	✓	✗	Multimodal sensory feedback to reduce phantom limb.
Phobia treatment	Viaud et al. [202]	✓	✗	✗	✗	Effects of auditory feedback in agoraphobic patients.
	Mülberger et al. [119, 118]	✓	✓	✗	✗	Multimodality short- and long-term effects on fear of flight.
	Hoffman et al. [61]	✓	✗	✓	✗	Illusions of touching to reduce fear of spiders.
OCD therapy	Cipresso et al. [33]	✗	✓	✗	✗	Different instructions to analyze behavioral syndromes.
Medical data visualization	Prange et al. [141]	✓	✓	✓	✗	Visualize and manipulate patients' medical data in 3D.
Surgery training	Hutchins et al. [67]	✓	✗	✓	✗	Medical training simulator with haptic feedback.
	Harders et al. [56]	✗	✗	✓	✗	Medical training simulator with AR features.
Medical education	Lu et al. [98]	✓	✗	✗	✗	Virtual platform to educate on medicine.

**Table 1.** Example works of different medical applications where multimodality plays an important role.

cally touching the virtual spider increases treatment effectiveness. Muhlberger et al. [119] studied the effect of VR in the treatment of fear of flying, exploiting not only visual and acoustic cues, but also proprioceptive information, since motion simulation may increase realism and help induce fear. Later, they studied the long-term effect of the exposure treatment [118], proving its efficacy in the fear of flight. The effect of auditory feedback has been studied in other domains, such as the particular case of agoraphobic patients [202], where multimodality increases patients' immersion feeling, hence facilitating emotional responses. However, those techniques should be taken with caution, since large exposures to VR scenarios may hinder patients' ability to distinguish between the real and the virtual world [69], leading to the disorder known as Chronic Alternate-World Disorder (CAWD).

Rehabilitation has also leveraged all the advances in VR, yielding impressive results. Sano et al. [161] demonstrated that phantom limb pain (which is the sensation of an amputated limb still attached) was reliably reduced when a multimodal sensory feedback was included in the VR therapy of patients with brachial plexus avulsion or arm amputation. Fordell et al. [48] presented a treatment method for chronic neglect, where a forced feedback interface gave sensory motor activation to the contra-lesional arm, improving spatial attention and showing that this improvement was indeed transferred to daily life activities.

A list of some representative applications of multimodality in medicine can be found in Table 1.

## 6.2 Education and training

Over the last decades, VR has also been devoted to the enhancement of training and education systems, where many advances have been achieved thanks to the advantages of VR in contrast to traditional methods when acquiring new skills and knowledge. Jensen and Konradsen [73] presented a review where VR was key for training and education, and showed that in many cases, better learning transfer can be achieved in this medium compared to traditional media.

In the field of education, VR has been widely studied as a new paradigm for teaching: designing ad-hoc environments helps creating adequate scenarios for each learning purpose, thus maximizing the transferred learning. Stojvsic et al. [187] reviewed the most relevant literature of VR applications in education, and conducted a small study where teachers perceived benefits of introducing immersive technologies, as students were more immersed and motivated. Childhood education process has been proved to be enhanced thanks to multimodality, by means of many human-computer interaction methods [31] or somatic interaction (hand gestures and body movements) [47, 4]. These works also identify some of the problems and potential use of some multisensory devices in an integrated manner, as well as report a better learning experience for most of the children participating. Many frameworks have been studied in this line, demonstrating that using virtual manipulatives (i.e., virtual interaction paradigms) provides multimodal interactions and yields richer perceptual experiences than classical methodologies in the cases of mathematics learning [132] or chemistry education [3]: A virtual multimodal laboratory was designed, where the user could perform chemistry experiments like in the real world, through a 3D interaction interface with also audio-visual feedback, which indeed improved the learning capabilities of students. Similarly, Tang et al. [192] introduced an immersive multimodal virtual environment supporting interactions with 3D deformable models through haptic devices, where not only gestures were replicated but also touching forces were correctly simulated, hence generating realistic scenarios. It is worth mentioning that multimodality can also help alleviate sensory impairments, since environments can be designed to maximize the use of the non-affected senses. Following this idea, Yu and Brewster [210] studied the strengths of a multimodal interface (i.e., with speech interactions) against traditional tactile diagrams in conveying information to visually impaired and blind people, showing the benefits of this approach in terms of the accuracy obtained by users.

With a wider scope, Richard et al. [147, 146] surveyed existing works including haptic or olfactory feedback in the field of education, and described a simulation VR platform that provides

haptic, olfactory and auditory feedback, which they tested in various teaching scenarios. Lastly, Taljaard [191] reviewed the literature on multi-sensory technology in a science, technology, engineering, arts and mathematics (STEAM) classroom, and how they affect student engagement and learning. All those works in turn concluded that multimodality offered higher user engagement than unimodal or traditional environments, leading to a better experience and learning transfer.

In the field of training, Checa and Bustillo [29] reviewed the use of immersive VR serious games in the context of learning and training. Multimodal VR can benefit the learning process of these learning-based games [40], since multisensory feedback can enhance many of the cognitive processes involved. Covaci et al. [36] presented a multisensory educational game to investigate how olfactory stimuli could contribute to users' learning experience: It made the experience more enjoyable, but also led to an improvement in users' performance and overall learning. High cognitive loads are also required for simulating and training real-life skills. Gopher [52] highlighted how virtual multimodal training conditions give better results when compared with traditional training conditions in many domains, including sports, rehabilitation, industry, or surgery; with the latter being the core of Van der Meijden et al.'s work [200], which reviewed the use of haptic feedback for surgery training, concluding how the addition of this information yields positive assessments in the majority of the cases and even reduce surgical errors. Transferring learning from training simulators to real life situations is one of the most relevant parts of the learning process, and multimodality has been proved to enhance it [87].

In the manufacturing industry, many processes require specific skills learning, hence multimodal virtual environments can offer new ways of training. Some works have studied and reported the usability of VR for a manufacturing application such as the assembly of component into a final product, where proprioception and haptic manipulation was required [18], or proposed a virtual system dedicated to train workers in the use and programming of milling machines, offering visual, audio and haptic (force) feedback [37], also replacing the use of conventional mechanical milling machines. Since fine motor skills can be transferred to the performance of manual tasks, other studies have analyzed the effectiveness of virtual training in the specific case of industry in contrast to real-life training [139]. At the end, all those works agree that virtual training could replace real training, since learning is correctly transferred, and some of those processes in real life are more expensive and time-consuming, depending on the complexity of the task itself.

Other complex tasks can also benefit from multimodal virtual training. Macdonald et al. [99] focused on the air traffic control problem, and evaluated the relevant aspects of the auditory modality to improve the detection of sonic warnings, including the best design patterns to maximize performance, including signals positioning and optimal distances on the interaural axis depending on the sound amplitudes.

It should be also mentioned that multimodality in the scope of training is not only constrained to VR head-mounted displays. CAVE environments have also been a target of these techniques. As a particular case, Kopp et al. [80] designed a virtual avatar that increased the users' engagement in the task and collaboratively

helped them to complete an assembly task by means of deliberative and reactive behaviors combining synthetic speech, gaze, facial expressions, and gestures.

A list of some representative applications of multimodality in training and education can be found in Table 2.

### 6.3 Navigation

As discussed in previous sections, agency has an effect in the feeling of realism in a virtual experience: body ownership is achieved when the user feels that her avatar responses are coherent with her real actions. Many applications are now including full locomotion to increase agency, hence increasing presence and immersion too, by allowing the user to freely move in the virtual space. However, the limited size of physical spaces in which users consume VR heavily constrains the maximum displacements that can be executed. Redirected walking techniques (RDW) emerged in the pursuit of alleviating these limitations: these techniques propose different ways to subtly or overtly manipulate either the user or the environment during locomotion, in order to allow the exploration of virtual worlds larger than the available physical space. Nilsson et al. [125] presented an overview of research works in this field since redirected walking was first practically demonstrated. Nevertheless, most of these works rely on visual manipulations: some of them exploit only visual cues or mechanisms, such as saccades [188] or blinks [86] to perform inadvertent manipulations, whereas others exploit continuous manipulations that remain unnoticed by users [169, 109]. However, those works neglect the information provided by other cues. As we have presented along this work, integrating multiple senses can take these kind of techniques a step further.

Serafin et al. [168] described two psychophysical experiments showing that humans can unknowingly be virtually turned about 20% more or 12% less than their physical rotation by using auditory stimuli: With no visual information available, and with an alarm sound as the only informative cue, users' could not reliably discriminate whether their physical rotations had been smaller or larger than the virtual ones. Nogalski and Fohl [128] presented a similar experiment, aiming for detection thresholds for acoustic redirected walking, in this case by means of wave field synthesis: By designing a scenario surrounded by speakers, and with no visual information available, they demonstrated that some curvature gains can be applied when users walk towards, or turn away from some sound source. Moreover, they work yielded similar rotation detection thresholds of  $\pm 20\%$ , which is additionally in line with other works proving the ability of acoustic signals to manipulate users' movements [45] and the potential benefits of using auditory stimuli in complex navigational tasks [145]. Nilsson et al. [126] revealed similar detection thresholds for conditions involving moving or static correlated audio-visual stimuli. Additionally, Nogalski and Fohl [129] summarized how users behavior significantly varies between audio-visual and auditory only stimuli, with the latter yielding more pronounced and less constant curvatures than with audio-visual information.

Many other sensory modalities can be used both to manipulate user's virtual movement and to enhance the navigation feeling. Hayashi et al. [57] presented a technique that allows to manipulate the mapping of the user's physical jumping distance and direction.

Application	Example work	Additional involved senses (other than vision)				Brief description
		Audition	Proprioception	Haptics	Other	
Education	Christopoulos and Gaitatzes [31]	✓	✓	✗	✗	Children education on history
	Alves et al. [4]	✗	✓	✗	✗	Serious games for children education on history
	Ali et al. [3]	✓	✗	✗	✗	Children education on chemistry
	Tang et al. [192]	✗	✗	✓	✗	Education on deformable materials
	Lu et al. [98]	✓	✗	✗	✗	Education on medicine
	Richard et al. [147, 146]	✓	✗	✓	Olfactory	Education on physics
Accessibility in education	Yu and Brewster [210]	✓	✗	✓	✗	Accessibility for blind people
Serious games	Deng et al. [40]	✗	✗	✓	✗	Review on multimodality for serious games
Skill training	Gopher [52]	✓	✗	✓	✗	Review on multimodality for skill training
	Boud et al. [18]	✗	✗	✓	✗	Skill training for industrial processes
	Crison et al. [37]	✓	✗	✓	✗	Skill training for industrial processes
	MacDonald et al. [99]	✓	✗	✗	✗	Skill training for air traffic control

**Table 2.** Example works of different educational and training applications where multimodality plays an important role.

Jumping is an action strongly correlated to proprioception, but it is usually unfeasible due to the available physical space. Manipulating the virtual distance when jumping can allow users to physically jump even when space is constrained, hence proprioceptive cues and realism can be maintained in the experience. Campos et al. [23] also introduced an integration of visual and proprioceptive cues for travelled distance perception, demonstrating that body-based cues contributed to walked distance estimation, attributable to vestibular inputs. Matsumoto et al. [110] presented a combination of redirected walking techniques with visuo-haptic interaction and a path planning algorithm. Exogenous cues can also play a role in these kind of manipulations. Feng et al. [46] examined the effects, influence and interactions of multi-sensory cues during non-fatiguing walking, including movement directional wind, footstep vibrations, and footstep sounds, yielding results that evidenced the improvement on user experience and realism when these cues were available.

In some cases, motion is not possible at all, hence it is necessary to generate an external, visual motion. This self-motion illusion is commonly known asvection, and sometimes leads to some postural responses (pursuing a correct vestibular and proprioceptive integration of information). It has been demonstrated that auditory cues increasevection strength in comparison with purely visual cues [76], and that moving sounds enhance circularvection [149]. Moreover,vection may also depend on the environment itself: Meyer et al. [113] explored which factors actually modulate those postural responses, and showed that real and virtual foreground objects serve as static visual, auditory and haptic reference points.

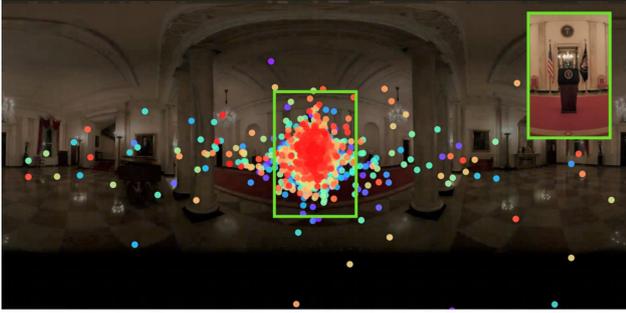
## 6.4 Entertainment

Another field that is undergoing an important revolution is entertainment: As VR devices are becoming more affordable, its

use at consumer level is rapidly increasing. Leisure by means of VR videogames, cinematography, or narrative experiences is becoming increasingly common, hence creating realistic, engaging experiences is the main goal for content creators. Designing experiences taking multimodality into account has the potential to enhance entertainment in VR.

Videogames allow users to interact with a virtual environment, controlling characters or avatars which respond depending on their actions. Traditional videogames have leveraged narrative characteristics to connect with the player, to immerse them in the virtual world, so that the experience feels more engaging. With the appearance of VR, immersive games are evolving: Higher realism, and stronger feelings of presence and agency can now be potentially achieved with this technology. However, as this work has shown in previous sections, all senses should be carefully presented in order to create an integrated experience and achieve an immersion feeling, going a step further from the traditional audiovisual games.

With this in mind, Nesbitt and Hoskens [121] hypothesized that integrating information from different senses could assist players in their performance. They evaluated visual, auditory and haptic information combinations, and although no significant performance improvement was achieved, players reported improved immersion, confidence and satisfaction in the multisensory cases. Since haptic devices may enhance the experience, some works have devoted in developing different toolkits to offer these interactions in VR (e.g., vibrotactile interactions [105]), whilst other works have exploited somatic interactions, including not only haptic but whole proprioceptive cues. Alves et al. [4] studied user experience in games which included hand gestures and body movements, identifying problems and potential uses of these devices in an integrated manner. Many narrative experiences may require the user to have the feeling of walking, and it may be one of the hardest scenarios to get a realistic response, since multiple sensory infor-



**Figure 10.** Representative image of the work of Marañes et al. [103], where they analyze users' gaze behavior during visualization of VR cinematic content. One of the key open problems in VR is the generation of engaging virtual experiences that meet users' expectations. To that end, it is necessary to understand users' behavior in such virtual experiences.

mation is combined. In this scope, some works investigated the addition of multisensory walking-related cues in locomotion [82], showing that adding auditory cues (i.e., footstep sounds), visual cues (i.e., head-motions from walking), and vibrotactile cues (under participants' feet) could all enhance participants' sensation of self-motion (vection) and presence. Sometimes, full locomotion is not permitted, however realism can still be achieved: Colley et al. [35] went a step further in exploiting body proprioception, presenting a work that proposed using a HMD in skiing and snowboarding training while the user was on a real slope, so that proprioceptive cues were completely realistic, therefore merging virtuality with reality.

As some of those aforementioned works have shown, multisensory cues can trigger different users' emotional responses in immersive games. Kruijff et al. [83] reported another work where they investigated those effects and proposed guidelines that can be applied to reproduce similar emotional responses. Whether because of emotional responses or because of the complexity of the games, cognitive loads can be quite high. This is indeed related to works that previously illustrated how multisensory feedback can enhance many of the cognitive processes involved [40].

Although many of the current VR videogames exploit audiovisual and somatic cues (which are in turn the easiest to get, given the current state of the technology itself), many other works have tried to work with additional cues. As in previously mentioned learning processes, some works have explored the use of olfactory cues [36] to investigate how enabling olfaction can contribute to users' learning performance, engagement and quality of experience. In a similar manner, gustatory cues have been studied in several works. Arnold et al. [6] presented a game involving eating real food to survive, which combined with the capture and reproduction of chewing sounds increased the realism of the experience. Following this line, Mueller et al. [117] highlighted the potential technologies and designs to support eating as a form of play, to achieve an increased engagement.

In particular, cinematographic and narrative experiences in VR have been emerging during the last years. Guiding users' attention, as seen in previous sections, is specially challenging in virtual environments, where users cannot see the whole scenario at once.

Given this, Serrano et al. [170] studied whether traditional continuity editing rules hold for VR, suggesting that cognitive event segmentation theories are also useful guides for VR editing, and that different types of edits are equally well understood in terms of continuity. Further, Marañes et al. [103] explored the impact of different cuts on 360° movies (see Figure 10), suggesting that different types of regions of interest (static and dynamic) can elicit different exploratory behaviors.

To explore how different cues might define how users drive their attention in cinematic VR, many works have explored how to use diegetic and non-diegetic cues to guide users. However, most of them have usually been visually-induced. A few works have investigated implicitly guiding the attention of the viewer by means of lights, movements, and sounds, integrating auditory and visual modality [153], while others have proposed multisensory virtual narrations, adding olfactory and haptic (thermal and wind) stimuli to achieve enhanced sensory engagement [144]. They show not only that including any singular modality improved the sense of presence, but also that the combination of multiple modalities produced even a higher significant enhancement.

A list of some representative applications of multimodality in entertainment can be found in Table 3.

## 7 Conclusions

Virtual reality can dramatically change the way we create and consume content in many aspects of our everyday life, including entertainment, training, design and manufacturing, communication, or advertising. In the last years, it has been rapidly growing and evolving as a field, with the thrust of impressive technical innovations in both acquisition and visualization hardware and software. However, if the new medium is going to succeed, it will be based on its ability to create *compelling user experiences*. The interaction between different sensory modalities has always been of interest to content creators, but in a VR setting, in which the user is immersed in an alternative reality, the importance of multimodal sensory input plays a more relevant role: It becomes both a possible liability, if not handled properly, and a potential strength, that if adequately leveraged can boost realism, help direct user attention, or improve user performance. Throughout this survey, we have summarized not only the main lines of research in these areas, but also outlined relevant insights for future directions in each of them.

While making use of multimodal setups can provide benefits to the experience, it also increases costs and complexity. From the point of view of the hardware, however, audiovisual integration is almost always present in current systems, and this is also the case for proprioception (except for smartphone-based and related headsets). Most controllers also include some kind of haptic feedback, although in this case it is quite simple and rudimentary, with ample room for improvement and sophistication in consumer-level systems. Taste and smell are almost untapped in terms of hardware. From the point of view of the software, inclusion of multimodal input increases the bandwidth and computational resources needed, both current stumbling blocks of VR experiences, particularly collaborative ones. Thus, compression techniques and computational optimizations (both hardware and software-based) are two of the most active areas of research in VR that would also help an in-

Application	Example work	Additional involved senses (other than vision)				Brief description
		Audition	Proprioception	Haptics	Other	
Videogames	Nesbitt et al. [121]	✓	✗	✓	✗	Multimodality to assist players' performance
	Martinez et al. [105]	✗	✗	✓	✗	Vibrotactile toolkit for immersive videogames
	Alves et al. [4]	✗	✓	✗	✗	Serious games for children education on history
Physical activity simulation	Kruijff et al. [82]	✓	✓	✓	✗	Walking simulation for leisure applications
	Colley et al. [35]	✗	✓	✗	✗	Proprioceptive cues to simulate skiing
Cognitive and emotional effects	Kruijff et al. [83]	✓	✗	✓	Olfactory	Study of emotional responses in virtual experiences
	Deng et al. [40]	✓	✗	✓	✗	Cognitive load and processes in serious games
Narrative experiences	Rothe et al.. [154, 153]	✓	✗	✗	✗	Attention guidance in narrative experiences
	Ranasinghe et al. [144]	✓	✗	✓	Olfactory	Enhancing engagement in narrative experiences

**Table 3.** Example works of different applications in entertainment where multimodality plays an important role.

creased use of multimodal input. At the same time, works have shown that multimodal input can help maintain realism and immersion with lower quality visual input, so it can also be an advantage in these areas. Additionally, even if it implies an increase in cost and complexity, and depending on the final application scenario, these increased costs may still be more than advantageous if the alternative is setting up a similar, real scenario, in, e.g., emergency or medical training.

The inherent increased complexity also imposes a challenge for researchers in this area: While we have reviewed a number of studies analyzing the interaction of two sensory modalities, those exploring three or more modalities are more rare. The integration of input from multiple senses has been an open area of research for over a century in vision science, partly because of the curse of dimensionality into which one runs when tackling this problem: The size of the parameter space grows exponentially and soon becomes intractable. Even when the data was available, deriving models to explain it has been a challenge, and analytical models often failed short to explain phenomena outside the particular scenario and parameter space explored, partly because of their lack of generality, partly because the type of data gathered can be very sensitive to the particular experimental setup. Current data-driven approaches certainly provide a new tool to address the problem, and some works have already started to rely on them, as is the case with audiovisual attention modeling. For this to be a solid path forward, however, we need public, carefully-crafted datasets that can be used by the community and in benchmarks, and we need reproducible experimental setups. Incidentally, VR is in itself a great experimental scenario for reproducibility, as opposed to physical, real-world setups.

Being aware of how the different sensory inputs interact thus helps researchers and practitioners in the field in two ways: In a first level, it aids them to create believable, successful experiences with the limited hardware and software resources available to them. At the next level, they can leverage the way the different sensory inputs will interact to overcome some of the limitations imposed by the hardware and software available, and even to improve the *design* of such hardware and software. As multimodal interactions become known and well understood, they can then be

leveraged for algorithm design, content generation, or even hardware development, essentially contributing to create better virtual experiences for users, and helping unleash the true potential of this medium.

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