Multimodality with Eye tracking and Haptics: A New Horizon for Serious Games?

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Abstract

The goal of this review is to illustrate the emerging use of multimodal virtual reality that can benefit learning-based games. The review begins with an introduction to multimodal virtual reality in serious games and we provide a brief discussion of why cognitive processes involved in learning and training are enhanced under immersive virtual environments. We initially outline studies that have used eye tracking and haptic feedback independently in serious games, and then review some innovative applications that have already combined eye tracking and haptic devices in order to provide applicable multimodal frameworks for learning-based games. Finally, some general conclusions are identified and clarified in order to advance current understanding in multimodal serious game production as well as exploring possible areas for new applications.

Keywords: *Eye tracking, Haptic, Multimodal, Serious games, Virtual reality*

1. Introduction

The use of videogames has various benefits to learning. The design elements such as narrative context, rules, goals, rewards, multisensory cues and interactivity motivate and drive the user to devote more time repeating the task and therefore learning through playing [1]. For some time now the technology used in Virtual Reality (VR) and Human Computer Interaction (HCI) has benefited the development of videogames, which are widely used in serious gaming [2]. Multimodal virtual reality, therefore, enhances the effectiveness of learning [3] from multimodal sensory integration.

Moreno and Mayer [4] suggested that multimodal virtual reality provided an attractive form of media to present learners with instructional materials in addition to words and pictures, which utilised the brain's capacity to process different information modalities through separate channels; but also by enhanced activation and integration of prior knowledge. Guo and Guo [5] found that unisensory memory retrieval, or activation of unimodal prior knowledge, could be improved by multisensory learning conditions. Cross-modal memory transfer also occurs after preconditioning with bimodal stimuli followed by unimodal conditioning [5]. Moreover, the richness of multimodal and multimedia information eliminates ambiguity for learning satisfaction [6, 7]. These findings imply that multimodality can lead to more effective learning than unimodality. The sensory systems that have been incorporated into these immersive environments include: vision, auditory, and somatosensory. Various devices are now available for capturing or reflecting human factors. Traditional input/output devices include the mouse, keyboard, monitor, microphone, speaker and touchpad. There are also advanced devices such as eye tracker, hand tracker, haptics, motion tracker, gesture controller, EEG and EMG devices, to name but a few. Comprehensive surveys of multimodal HCI or VR were presented in [8, 9].

Graphic and haptic rendering deal with visual and somatosensory feedbacks, while tracking the eyes detects attentional shifts in the task. Integrating eye tracking and haptic techniques into serious games can introduce benefits from both sides. Tracking the movements of the eyes while users play serious games provides the opportunity to analyse the learning process. Tracking eye movements is also used as an interactive input to virtual reality [10]. Haptic feedback, has been found to improve performance on serious games and provide enhanced learning and training, such as virtual surgical training [11], rehabilitation [12-14], molecular docking [15, 16], amongst others. Multimodal virtual realities clearly require highly stable, synchronized, real-time feedback, for all sensory input and output systems. The remarkable development of hardware and computing techniques has made the new systems more feasible over the past two decades. In sum, by increasing the efficacy and credibility of the virtual environments, multimodal virtual reality improves user performance and prevents errors.

Having provided a brief synopsis of multimodal virtual reality in learning-based games and described the compelling evidences for the use of these techniques that are aimed for enhancing both user experiences and learning outcomes, we turn our attention to the main focus of this review, which is the integration of multimodal sensory that can be applied in serious games. The most prominent techniques currently used in virtual reality and serious games are eye tracking and haptic feedback. An important point to note is that eye tracking is utilised in two ways, 1) eye movements are analysed to evaluate specific learning patterns while the user performs tasks in serious games, and 2) eye movements are used in an interactive method to allow the user to impact on the virtual environment. Furthermore, haptic devices also enable two distinct modes of feedback, 1) force feedback, where motion, force, location and compliance that perceived by receptors in our muscles, tendons and joints are provided; and, 2) tactile feedback, where temperature, texture, pressure, puncture, friction, roughness, and shape that are perceived by cutaneous receptors under our skin are provided.

We provide a brief guidance and some insights for developers as to the relevant technologies (including usage of different hardware and software) and it is our main interest to introduce the emerging multimodal usability in serious games to readers; however, a comprehensive review of software and hardware is beyond the scope of this review. The paper is structured in the layout that section 2 presents the eye tracking techniques; section 3 presents the related haptics hardware and software; section 4 gives examples of frameworks that can be utilised in serious games where both eye tracking and haptics play important roles; section 5 discusses the future work and challenges and section 6 concludes the paper.

2. Eye tracking in serious games

Although there is a long history of observing eye movements within psychology and related fields (see [17, 18], for reviews), it is only recent that researchers have begun to introduce eye tracking methodologies to study the usability and learning efficiency of serious games. As such, over the past 10 years there have been considerable interests in studies that have taken cognitive science approaches to game-based learning. Latest eye tracking techniques can satisfy both offline eye movement data analysis, and real-time online interaction.

Our eyes typically make 3-4 saccadic movements per second, which last only a few hundredth of a second each. Saccades enable us to align our fovea, or the high acuity part of the retina, on the most informative aspect of the scene; with this type of scanning behaviour we render ourselves virtually blind for considerable periods of time, as during a saccade we experience what is known as saccadic suppression, where no new information is taken in [19]. In between these scanning movements there are times where our eyes are relatively still, and during these periods visual information is encoded and processed. In fact during many tasks the eyes remain fixated until the stimulus is fully processed. These periods are called fixations, as such the time course of a fixation is an important indicator of visual processing during a task. Other than typical fixations and saccades, pupil size also provides an indication of learning performance. The diameter of pupil is considered to reflect cognitive load, i.e. when the pupil dilates, it indicates increased cognitive processes occurring in the brain [20]. Pupil diameter data has been utilised in serious games, such as driving simulators [21]. However, pupil dilation is not always considered a reliable indicator of learning [22].

Eye tracking devices have great variability in terms of their spatial and temporal frequency; eye tracking for game-use devices, require less accuracy and therefore, present a more affordable price. However, this means that such devices used in games are limited to track fixation behaviours as the ballistic saccadic movements that typically only span tens of milliseconds are beyond their capacity. For more information regarding the commercial eye trackers used in videogames see the study by Smith and Graham [23].

2.1. Analysis of eye movements

Offline or online analysis of eye movement behaviour is often utilised in order to understand the user's performance in game-based learning (e.g. [24-26]). For example, eye movements demonstrate the user's responses to visual changes in the virtual environments as well as behaviours the user undertake during visual search tasks, with this data we are able to extrapolate how users engage in the learning process and game playing. Issues like the fixation duration, saccade length, size of the perceptual span (the functional field of view), as well as, where and when viewers move their eyes during these tasks are dynamic means by which we can assess the development and effectiveness of serious games. Furthermore, for serious games where the intention is to provide the user with a learning opportunity it is important to understand that visual information that is looked at more frequently is better remembered [27]. Patterns of eye movement behaviour provide a measure of task difficulty and user engagement. Differences in both the density of virtual objects [28] and the organisation of the objects within the environment, also modulate patterns of eye movements [29]; i.e. as the density of the objects increases so the number and duration of the fixations increase and random object presentations require more direct fixations on the objects [27]. Importantly, for game-based learning, increased numbers and duration of fixations that directly land on visual information receives a depth of processing necessary for improved recall compared to those that do not [27].

Clearly recording eye movement behaviour provides in-depth information regarding important visual and perceptual parameters vital for the development of novel design paradigms for serious games, as well as useful information of utilising gaze interactive setups that can be applied either in a mono (visual feedback) - or multimodality (haptic and visual feedback). Binocular coordination of the two eyes can also be analysed and optimise the rendering of the 3D environments, which have been used extensively in simulators (e.g. flight simulators), 3D films and videogames [30-32]. We expect serious game designers to explore new techniques previously unavailable with the eye tracking devices.

2.2. Interaction guided by eye movements

Conventionally, users have primarily been able to interact with the virtual environment using hand motion, during eye-hand coordination tasks. However, eye movement behaviour can now act directly as a controller in the virtual environment. Eye tracking inputs can now be used for basic interactive elements of serious games in addition to traditional keyboard and mouse inputs, such as pointing, navigating, and implementing level of detail (LOD) rendering by way of Gaze Contingent paradigms (see reviews [33, 34]). In serious games, the interactivity is enforced by eye gaze - the overt attentional position of the user. Although attention is not always represented by gaze because of covert orienting [35], it is assumed that in an intensively engaging scenario such as a videogame, gaze reflects the region of interest [36].

Saccadic suppression has also been applied in the saccade contingent updating to prevent the users noticing sudden display difference. Saccade contingent update can separate "what you see" and "what you see next" by changing peripheral scene that is outside of foveal vision [37]. It is also used to hide graphic updates if the update happens within a saccade. Compared to smooth scene change, this method enables immediate large scene change with no disturbance to the users because the change is not detectable during saccades [38]. In videogames, real-time performance is important, so the latency of detecting a saccade needs to be as small as possible for seamless experience. New saccade detection methods have been proposed for reducing latency, therefore, leading to the possibility of achieving real-time performance and enhanced visual experience [39-41]. Furthermore, using saccadic behaviour to predict fixation location can provide the capacity for seamless implementation of LOD graphic rendering [42], as previously applied in high performance flight simulators.

2.3. Unimodal paradigms with eye tracking in serious games

Typically, state-of-art interactive application of gaze behaviour can be divided into two categories, one involves voluntary gaze control and the other uses reflexive gaze movements. Voluntary gaze control represents purposeful direction of gaze in order to scan more precisely a specific region of interest and is used primarily in pointing and gaze gestures for example. Duchowski has summarized the uses of online real-time recording of voluntary gaze control as text scrolling, activating game character behaviour, accessing a virtual keyboard, and accelerating cursor movements [10]. Whereas the reflexive gaze movements signal more automatic attention allocation to a particular region of interest and are used primarily for egocentric camera navigation and updating LOD rendering.

Using reflexive gaze movements, egocentric camera control provides spontaneous view changes, but also guides user's visual attention by element composition. Hillaire et al. [43] implemented a method of first-person camera navigation using eye tracking. Burelli and Yannakakis [44] developed an artificial neural network (ANN) camera behaviour prediction model by analysing eye tracking data collected from a game. It achieved over 70% accuracy for different types of game action. Similar application has been extended to teleoperation. Zhu et al. [45] implemented a gaze-driven remote camera control with the straightforward principle that it moved the region of interest into the centre of the screen.

LOD rendering was introduced for computational optimization purposes. It is suitable for games with complex simulation but require real time response, such as surgical training, which always incorporates a large amount of fine meshed deformable tissue that is computational expensive. There are two types of gaze contingent display used to implement LOD rendering. One is screen-based display, which manipulates pixels and matches the graphical display with vision mechanisms. With this approach it assigns higher resolution to the fixation vicinity and a lower resolution to peripheral areas. The other is model-based display, which statically or dynamically computes fine-to-coarse meshes of an object. Fine structure is rendered when gazed upon and coarse structure when gaze recedes [10]. Hybrid methods featuring local connectivity and rendering efficiency have been proposed. Murphy et al. [46] used Contrast Sensitivity Function (CSF) and ray casting in order to build a hybrid method, where CSF was utilized to describe the amount of visible detail changes conforming to gaze contingency and ray casting to avoid direct manipulation of the mesh.

3. Haptics in serious games

Haptic feedback has recently become an indispensable component in serious games. It provides an additional perception modality of touch, together with vision and audio to generate a more immersive user experience. Generally, with the learning and training purposes, the force/torque and tactile perception gained from haptics provides users with better cognition of how they performed in a task and helps them improve their performance in an intuitive and efficient way. Especially for some tasks that rely largely on haptic feedback, merely visual feedback helps little with improving performance or even causes errors. For instance, endoscopic surgical training is extremely difficult to achieve expected results without haptic feedback [47]. Haptics, as one essential perceptional route to interact with virtual environments, also benefits the game industry to enlarge their market to users who are not previously reachable [48]. With the incentive of repetitiveness in gaming approach, the users will be engaged on repetitive practice to generate long term memory of new knowledge or motor dexterity.

3.1. Unimodal applications with haptics in serious games

Haptics can benefit learning in two ways, one as a cognitive aux and the other as the main component. For the first type, haptic feedback delivers an improved cognitive process on top of other sensory, with fully accessible perception of the abstract scene or phenomena. This is because our brain integrates all channels of input perception to form our own understanding of a new concept, yielding a set of motor manipulation to interact with the environment. Haptics have been applied as auxiliary tools in science education and surgical training for a long time. Successful applications in science education have demonstrated improvement of user learning result using haptics compared with those without [15, 16, 49, 50]. Haptic game design examples in surgical training have been presented. Chui et al. proposed a computer-game-like surgical training simulator using force feedback joystick, Delta haptic device, wearable motion capture device CyberGlove and haptic feedback actuator CyberGrasp [51]. A first prototype of haptic-enabled suturing game for laparoscopic training has been presented [52]. A blood management game for orthopedic surgery has been developed in [53]. This simulation integrated task-oriented time-attack game features, as well as collaboration, bonus, difficulty levels and performance evaluation. A 6-DOF haptic device was applied to act as surgical tools. These applications set good examples of the full process of designing a surgical training game with integration of haptic devices. They have illustrations of the detailed game framework, game design specifications and how the haptic device and haptic rendering to be incorporated.

Impairments of sensory decrease game accessibility. For the second type, haptics is applied to augment impaired motor capability or to compensate other impaired perception, such as vision, where haptics acts as the core component of game design. When people have less ability due to their health condition and the haptic perception is impaired, the users are in need of external stimuli to help them instigate movement or aid recovery. For instance, haptics have been widely applied in post stroke rehabilitation [13, 54-56]. The augmented force helps indicate correctness or incorrectness efficiently in the process of motor training. It also provides guidance force for skills regain [57, 58]. As for visually impaired users who can hardly enjoy video games, haptic enabled games provide them with a new experience of gaming (e.g. [59, 60]). Yuan et al. [61] provided a more detailed survey of various accessible games for different types of impairments.

3.2. Haptic devices for gaming

A typical haptic device contains bidirectional haptic input and output interfaces/sensors between the device and user. Compared with visual feedback, haptic devices require much higher refresh rate (≥1000Hz) to achieve continuous and real-time perception [62].

Table 1. Haptic Devices for Gaming

Types	**References**	**Devices / Model**	**Feedback**	**applicability**
Mice	Microsoft’s [63]	Explorer Touch Mouse, Arc Touch Mouse	light vibration that signals scrolling speed	Desktop games
	Schneider et al. [64]	Optical mouse	Friction	
	Mackenzie [65], Wanjoo et al. [66]	Mouse actuated by electromagnet	2-DOF force feedbacks	
Joysticks	e.g. Orozco et al. [67]	For game consoles such as XBOX, Wii or PlayStation	2-DOF force feedbacks	Console games, gear stick stimulation
Game pads / controllers	-	For game consoles such as XBOX, Wii or PlayStation	Rumble, vibration	Console games
Vest / jackets	TN Games [68]	3RD Space Vest	Tactile feedback simulated by pneumatic	Gunshot simulation
	Saurabh Palan et al. [69]	Gaming Vest (TGV)	Tactile feedback simulated by solenoids	
Steering wheels	Mohellebi et al. [70]	INRETS-FAROS	Real haptic feedback	Driving simulator
	Hwang and Ryu [71]	The Haptic Wheel	Vibro-tactile feedback	
Smart phones	-	Various brands	Vibration	Mobile games
Other	-	Haptic chairs and seating pads	Vibration	Driving simulator
	Coles et al. [11]	Advanced devices e.g. Novint Falcon	At least 3-DOF force feedbacks	Both academic research and gaming because of high cost-effectiveness

Based on the two types of touch perception, cutaneous and kinaesthetic sensory, haptics can correspondingly provide two types of perceptual feedback, tactile feedback and force/torque feedback. Depending on the feedback it provides, there are tactile devices, force feedback devices (see review in [11]) and hybrid devices which provides both. Trade-offs between functional requirements and budget restriction can be analysed when selecting the proper device.

Haptic feedback in gaming is devoted to providing immersive game experience but with an affordable price and portability for common acceptance compared with the research oriented haptic devices. More specifically, to reduce extra cost, it is vibration actuators that have been integrated with the variety of game controllers. Distinguished by their shapes, gaming haptic devices normally appear as mice, joysticks, game pads, vest/jackets, wheels and mobile phones etc. (see Table 1).

3.3. Haptic modelling

Various haptic modelling libraries are available as listed in Table 2. These libraries or toolkits provide programming interfaces (API) for rapid haptic prototyping. Most of them come with not only haptic but also graphic components using either OpenGL or DirectX. Normally commercial haptic hardware will come with software development kits (SDKs) that are only applicable to their own devices. For example, the OpenHaptics toolkit is only viable for SensAble devices that are the most popular haptic products, whilst Virtual Hand is specifically for the CyberGlove Systems hand tracking devices. Some libraries have been specifically developed as hardware-independent to adapt to more devices. Some provide virtual device adaptation for simulation without requiring a real device connected. Reachin API, HAPTIK and Virtual Hand have network support built in which enables haptic interaction between users. HaptX is designed for game haptics, especially Novint Falcon. The libraries provide relatively basic haptic features, but they also offer extensibility for customized physical modelling, shape rendering, force effects, collision detection, dynamics and other third-party engines. More haptic modelling libraries are available but not elaborated because they are not widely applied as the ones listed in Table 2.

Table 2. Common Available Haptic Modelling Libraries

Name	Devices	Languages	Network	Graphics	Opensource	Platform
OpenHaptics [72]	SensAble	C++	No	Yes	No	Windows, Linux
CHAI 3D [73]	Hardware Independent, Virtual Device	C++	No	Yes	Yes	Windows, Linux, Mac
H3DAPI [74]	SensAble, Novint, Force Dimension, MOOG FCS, G-Coder Systems	X3D, C++, Python	No	Yes	Yes	Windows, Linux, Mac
Reachin API [75]	Hardware Independent	C++, VRML, Python	Yes	Yes	No	Windows
HaptX[76]	Novint, SensAble	C++	No	Yes	No	Windows
HAPTIK [77]	Hardware Independent (need related plugin)	C++, Java, Matlab, Simulink	Yes	No	Yes	Windows, Linux, Mac
Virtual Hand	CyberGlove Systems, Virtual Hand	C++	Yes	Yes	No	Windows

4. Applications using both eye trackers and haptics devises

4.1. Post stroke rehabilitation

Impaired motor ability that is usually caused by stroke has been testified improving by intensive training. The training task is normally designed specifically for a single functionality recover. Such tasks are rarely attractive for repetition, serious games concept could benefit in this aspect by drawing patients' attention into the task, stimulate them to practice proactively. Eye tracker tracks gaze position that reflects overt visual attention, in specific scenarios, it also represents user's region of interest. As introduced in related work, haptics is proved helpful for motor rehabilitation. Some applications have already been developed for combining haptics and eye tracking techniques.

Frisoli et al. [78] proposed an attention-driven multimodal architecture for upper limb stroke rehabilitation using eye tracker and robotic exoskeleton. This system consisted of four components (see Figure 1): 1) an arm exoskeleton for guiding patient's right arm with force to accomplish

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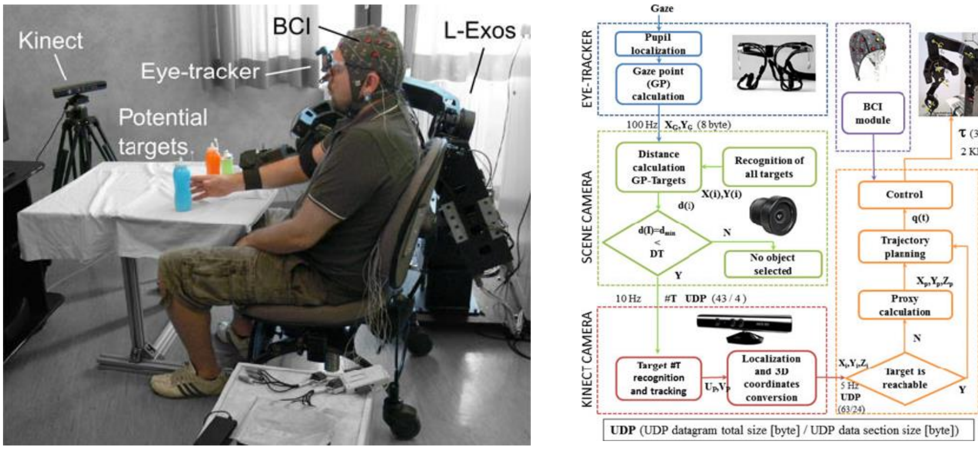
reaching tasks; 2) an eye tracker for 2D object selection with gaze; 3) a Kinect for 3D object tracking, selection and communication with the exoskeleton; and 4) a BCI (Brain-Computer Interface) module for estimating patient's motor intention with motor imagery. The BCI module mainly applied an EEG classifier for discriminating brain activity for right arm movement intention and the rest. Based on the output of the BCI classifier, the eye tracker will select the target object and send it to the Kinect, which calculates the depth and location information for the exoskeleton to make the kinaesthetic movement plan.



(a) (b)

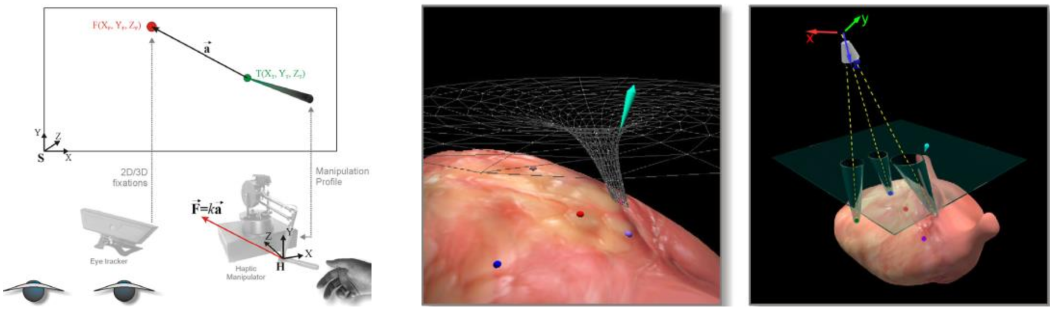
Figure 1. Rehabilitation framework designed by Frisoli et al. [78]. (a) Proposed paradigm: The user is guided by motor imagery and gaze through the exoskeleton to real objects identified by machine vision. (b) Representation of the data flows in the system.

Troncossi et al. [79] proposed another upper limb rehabilitation framework facilitated with eye tracking and exoskeleton, BRAVO. They extended the design and manufacture of the exoskeleton with a hand-and-wrist part. Similarly, they used eye tracker for object location detection, and BCI for planning hand opening/closure intention. However, eye tracker only provides 2D coordination; simply using it for location detection could not provide robust performance without assistance from other depth detecting device such as Kinect. In this case, its applicability has been limited to scenarios that based on structured environments.

4.2. Virtual surgery

Minimally invasive surgery (MIS) is a surgical procedure performed by entering through a small incision with long thin tools to achieve less tissue damage and equal treatment results. The procedure is conducted with the aid of a camera to provide view of the operation area. This process requires intensive practice for hand motor dexterity and eye hand coordination, so game-like virtual simulation is an ideal approach for its training. Some surgical simulations are facilitated with master-slave robots naming teleoperation or telesurgery. Its effectiveness is often limited by the lack of haptic sensory when operating with remote robot. In both scenarios, haptic feedback is a crucial element for operator's safe performance. Eye tracking provides a way for forbidden-region virtual fixtures (FRVFs) which helps surgeons to locate target tissue with a safety margin to prevent injury to other structures [80].

Mylonas et al. [81] proposed two FRVF methods, Gaze-Contingent Motor Channelling (GCMC) and Gaze-Contingent Haptic Constraints (GCHC). GCMC described the concept that a dynamical force exerted from the haptic tooltip towards the position of gaze in planar manual tracking as shown in Figure 2a. The tracking accuracy has been tested in a task that tracks a target on a mesh with regularly deformable patterns such as heartbeat, where the target moves with the deformation movement. GCHC extended the GCMC framework into 3D manipulations. A binocular eye tracker was integrated in this method that provided the availability for ocular vergence calculation. The haptic constraint reflected in that the exerted force was proportional to the distance between fixation point and tooltip within a small pre-set range. The force maintained constant outside of this range, it formed a tube-like force field for each target on the mesh surface, see Figure 2b. A planar hard boundary was also introduced at a small distance from the mesh surface for safety purposes. A shooting game based on the GCMC paradigm was developed for familiarisation. The task was to shoot flying objects appeared on the computer screen. There were three stages in the game, the first stage had no constraints or force, the second stage needed aiming purely with gaze, and third stage had GCMC fully engaged. The user study showed improved concentration on task learning quality of novices. James et al. [82] verified the learning advantages of GCMC compared with "free-hand".



(a) (b)

Figure 2. Visual fixture frameworks proposed by Mylonas et al. in MIS [81]. (a) Illustration of GCMC framework. Eye tracker localizes the 2D/3D fixation *F* of the user on a screen or stereoscope. Virtual tool *T* is achieved through a haptic manipulator. Depending on the Cartesian distance between *F* and *T*, a force toward the fixation point is exerted on the hand of the user via the haptic manipulator. (b) Illustration of GCHC. The fiducial markers are locked that can only be accessible through the pathways with virtual tool. The hard planar provides a safety boundary.

Stark et al. [83] proposed a telesurgical system Telelap Alf-x. This system has haptic sensation to aid confidence in surgeon's operating remotely and a unique eye tracking system for zooming into regions of interest and panning the image with the gaze at the centre of screen. The experiment showed a shorter average operation time of 31.75 min compared to 91 min using conventional telesurgical systems. More examples can be found in [84].

4.3. Driving simulators

Driving simulation games are commonly adapted in major game consoles. As introduced in previous sections about gaming haptic devices, there are haptic joysticks, wheels and seating pads for driving simulators especially. Eye tracking techniques were widely applied for analysing driver's attention hotspots and patterns, and there are interesting findings in comparison between novice and expert. It has also been used for detecting driver fatigue assisting driver's safety [85].

Rouzier and Murakami [86] proposed a new driving assisting system which models the driver's intentions and their overall state with facial feature analysis. Strictly speaking, they did not use eye tracking on this implementation, but a camera to detect blinks, gaze direction and yawning. However, replacing this with eye tracking could largely simplify their algorithms of blinking and gaze direction detection. One interesting part of this work is the virtual force calculated according to potential fields and road shapes detected by the driving assistant, which helps the driver to continue on a safe trajectory. The other interesting part is the alarm setup for drowsiness. Sudden alarms or vibration from the wheels might surprise the driver and make the situation more dangerous. In this study, they have proposed the solution of not just waking up the driver but also taking over the driving before the driver's attention recovers, which is detected and diagnosed by the computer vision algorithm. One possible drawbacks of this approach is the control conflict within the vehicle between the driving assistant system and the driver.

4.4. Mobile games and application

Touch screen phones and tablets are popular among all types of users, regardless of age and gender. Therefore, mobiles games designed for education purposes are emerging. Haptic vibration is a common setting on mobile devices. Not long ago, eye tracking was also been integrated onto commercial smart phones for functions such as scrolling up and down, or pausing/playing videos. The combination unveils tremendous potentials in enriching mobile games accessibility. For example, Kangas et al. [87] proposed an interactive method for using gaze gestures as an input method with vibrotactile feedback as confirmation of the gaze event. They designed four gestures using gaze strokes for a contact list browsing task, which were scrolling up and down, selecting, and cancelling. Haptic feedback was given in four different conditions to assess how it would impact on user performances. Those were no haptic feedback, only haptic feedback when stroke from outside the device to inside the device, only haptic feedback when stroke from inside the device to outside the device, and full haptic feedback. The results showed improvement of the gesture performance with less errors, especially when gaze stroke moving from inside the device to outside.

Facilitation with eye tracking on mobile devices provides with additional game control on top of regular finger taps, strokes and tilting if gravity sensor installed. This can be utilised for more complicated level design that is built with multiple targets of intention, or more task-efficient design such as replacing left and right swipe in direction control in some games. The eye movement data can also be collected for analysing user's phone usage and habits. The portability of mobile devices also brings flexibility of time schedule for game consumption without requiring of computers, which enables learning at anytime and anywhere.

4.5. Wearable devices application

Similar with the success of Google Glasses, wearable technology that represents a hotspot of mobile biometric devices has emerged, including wristbands, smart watches, belts, trackers etc. However, in haptic applications, wearable device is not a new story, such as haptic gloves [88], exoskeleton as mentioned in previous applications, navigation vest [89], devices for gravity sensation [90].

Figure 3. Prototype glasses with the locations of the three vibrotactile actuators illustrated with circles proposed by Rantala et al. [91].

Applications that combine eye tracking with haptic feedback on wearable devices just came out recently. Rantala et al. [91] introduced a pair of gaze gesture eyeglasses with three haptic actuators, one on each end of the glasses frame legs, and one on the bridge (see Figure 3). They conducted two user studies to find out the accuracy of distinguishing stimulations from the three actuators, and the timing of haptic feedback the users preferred to use during gaze gestures. The results showed that the accuracy of one actuator outperformed two or more actuators and it was in line with the preference of the users. The haptic feedback was useful mostly at the first stroke of gaze gestures. These glasses could be applied in virtual reality or mixed reality applications that focus more on mobility. They can also benefit hearing impaired users with better lifestyle.

Wearable devices bring possibility and applicability of augmented reality games without restriction on location. For example, the haptic enabled eye tracking glasses can be used as tennis training assistance. The glasses catch oncoming ball's speed and direction then vibrate at the best timing of next hit. The vibration can also occur when the glasses detect player's eyes have lost track of the ball and highlight the ball's position on the glasses screen to bring the player's attention back on track. Another possible beneficiary can be the snooker game. It can use eye tracking to locate the next target ball and pocket then calculate the best hitting angle and use different intensity of haptic vibration to indicate the proper hitting strength.

4.6. Magic pointing

In training and learning, accuracy and measurement of performance are key elements for serious games. Eye tracking improves the pointing efficiency and haptic feedback enhances the accuracy. However, there are also problems. An essential one is the Midas Touch problem that gaze can locate at anywhere without explicit confirmation of the selection. Another issue is the accuracy of gaze pointing. It has been reported in object selection tasks that gaze can provide good performance when object is large [92], instead, for meticulous selections mouse outperforms gaze.

To solve these problems, Jacob [93] proposed possible solutions such as confirmation with blinks, button clicks and dwelling fixations. A common solution is to roughly select by gaze with further haptic refine. For instance, Kumar et al. [94] presented a technique combining gaze and keyboard triggers to compensate the accuracy limitation. However, their aim was to provide transparent control, with the user knowing as less as possible of the controlling process. Zhai et al. [95] proposed the MAGIC pointing method as an alternative by warping the mouse cursor to the vicinity of gaze position. Fares et al. [96] improved the eye tracking accuracy of MAGIC pointing by applying animated cursor moving trace and Dynamic Local Calibration (DLC). DLC was designed for correcting the gaze selection point with averaged distance-weight of gaze-cursor offset vectors. Pointing and selection using touch-assisted eye tracking techniques, or MAGIC pointing methods, have also been integrated into touchscreen devices, such as mobile phones or tablets [97-99]. The user studies demonstrated overall improvement of performance and usability.

5. Future work and challenges

Unimodal serious games only with eye tracking or only with haptics have been studied intensively, inspired from the knowledge of engineering, psychology, neuroscience and cognitive science. Although we have found successful applications in various areas combining eye tracking with haptic feedback, the development in this area is still in its infancy.

Clearly some unimodal applications can be improved by integrating with other modalities. For example, egocentricity viewpoint facilitated with eye tracking could also be used in haptic manipulation in virtual environments. De Boeck et al. [100] summarised all available camera metaphors for haptic applications, and user centric camera control was one of them. Otaduy and Lin [101] presented several user-centric viewpoint algorithms for intuitive haptic visualization considering intra and inter-object occlusions and object geometry. These algorithms for enforcing user centric views can be substituted by eye tracking to simplify the development complexity.

Another example is that, LOD rendering can also be applied in haptic display. Otaduy and Lin [102] summarised haptic collision detection methods based on LOD. O'Sullivan and Dingliana [103] implemented and evaluated one of the methods, which was incorporated with eye tracking. This method was a collision degradation approach based on gaze perceptual parameters. It assigned higher computation priority to collisions happened within perceptual span. The user study and comparison experiment reported perception improvement. Considering tooltip of some haptic devices is the region of touch interest, higher fidelity should be provided in this area in addition to the region of visual interest.

For some applications that have already combined both devices, a big challenge will be introducing game concept into the design, or gamification. Such as the rehabilitation frameworks, it can be merged into games for enhancing training performances, for example, LEGO games. The game can also be designed with narrative stories. The mobility of wearable eye tracker and exoskeleton provides more flexibility of game design for reality or augmented reality and enriches variety of background stories, without just sitting in front of a desk and reaching for boring objects. In the aforementioned virtual surgery frameworks, the method of testing performance accuracy and error rate has already been developed for user study. To further complete it to be a training game, the accuracy and error rate can be part of the score scheme, and the incentive can be to achieve as high score as possible. The explicit score can intrigue competition among novices to practice more. Eye tracking generally indicates how user performs in games, it detects if the user misses important information and the level of user's engagement etc. This type of diagnostic information can be paired with haptic facilitated games for real-time scoring, for example, but can also inform the users of why mistakes have been made and how to avoid them. It will be useful to provide users with playbacks of their eye movement in games, which can give them an intuitive feedback of their playing performance.

Gaze pattern recognition appears to be a promising trend in recent years. It furthers the conventional analysis methods from diagnostic level to a more applicable stage. It is possible to classify the type of information the reader is processing with eye tracking data [104]. Interesting results can be found in specific tasks, such as the work Doshi and Trivedi [105] presented to predict driver's intention to change lanes by analysing gaze and head movement data. Considering the driving assistance introduced in previous section, this method has the potential to be implemented on top of that framework to plan vehicle trajectory when changing lanes. As for current solution of Midas Touch problem, it requires a manual confirmation to validate the gaze control. Gaze pattern analysis provides the potential to achieve more unobtrusive gaze control by recognizing eye movement pattern to determine a valid operation without additional confirmation. Possibly, the BCI module that was used in rehabilitation applications for detecting movement intention could be replaced by gaze pattern learning.

Significant efforts have been put into cross-modal modelling which simulates and brings new understanding of the working mechanism of human brain. Not only additional automated control can be provided by the system, it also gives serious game designers an innovative approach for prototyping and evaluation of the learning performance. Because the brain reconstructs the mental representation of the environment based on multisensory inputs and prior experiences, Bayesian inference has been widely proved to be acting very close to the perception mechanism [106]. A Bayesian framework with force sensor and visual input for haptic feedback is possible to be developed. Ferreira et al. [107] implemented a rather complete Bayesian framework of multimodal perception using parallel computing with GPUs. It provided a systematic solution of simulating dorsal perceptual pathway of human brain and achieved real-time performance for large data structure processing. Although this implementation only integrated stereovision, binaural and inertia data without haptic feedback, it inspired the extendibility for future effort.

There are some areas which have been less touched in terms of serious games. As for tactile feedback, except for vibration, it still lacks enough attention in integration for real life application partly due to the limitation of available hardware. In addition to fixations and saccades, eye trackers can also detect pupil size. However, such information of pupil has not been given enough attention in serious games design.

Apart from the potentials in integration, general challenges for mono-modality also exist. First of all, computational expensive haptic rendering compromises stability. Although pre-computed topology data can greatly accelerate haptic rendering, for complex scenes and dynamically changing topology, such as fracturing and cutting, or fluid modelling, it introduces more computational complexity [108]. The trade-off between stability and fidelity still attracts a lot of research interests nowadays.

The second challenge is the latency generated by the eye tracking device or the transmission from eye tracker to both visual and haptic displays. In real-time applications, the asynchronization can be very perceptual sensitive. Recent study proposed the approach to find the accurate latency [109] and the methods that predicted the saccade trajectory for solving this problem [110].

Moreover, multiplayer games highlight the compatibility problems between players, and between players and the devices. For instance, in training games and therapy sessions that have collaboration between experts-novices or physicians-patients, it requires local or network based haptic interactivity support for a shared virtual environment. Multiuser system introduces multiple collision and mutual force impact, which means even more loaded computational task and synchronization issues. Haptic data compression and transmission latency are additional burden introduced by network communications. Some efforts have been made to solve this problem. For instance, Liu and Lu [111] proposed a method to improve performance by limiting the dimension of the object's movement that each user could control, but still giving feedbacks of other users' movements. Eye trackers in collaborative tasks can help with defining or configuring mutual attention area to reduce disparity between users and provide comparison between experts and novices as performance measurement criteria.

6. Conclusion

A number of multimodal applications using eye tracking and haptic devices have been reviewed. They have been demonstrated to have great potential to be utilised in serious games. Empirical research testified that higher degree of modalities provided additional channels for information presentation and delivery, which facilitated sense-making process in learning and game playing [112]. The integration of multimodality into games can enhance user engagement and create immersive user experiences. We would envisage their great potentials in increasing learning-based applicability and categories of user base in serious games.

The process of game production includes design, implementation and evaluation. Considering that eye tracking and haptic feedback both impact on user's learning efficiency and cognitive process, there are several issues need to be noted in each phase of game production, especially in game design and implementation according to the scope of this survey.

In game design and implementation phase, it is necessary to notice that the two modalities integrated either in a complementary or exclusive way. For perceiving different features of a scene or an object, each modality contributes independently and fully to the final sensation, where both modalities act as supplements to the other sensory. For example, eye tracking provides spatial information and haptic provides texture details. Alternatively, it sometimes can be a drawback that when perceiving same features using both eye tracker and haptics, conflicts might exist. In this case, one sensory input will completely dominate the other. If eye tracker and haptic device both provide spatial information, vision capture will occur, i.e. visual perception dominates [113]. Designers need to confirm whether the integration will improve or undermine user experience and game performance before implementation.

Economic consideration and accessibility to special hardware is also essential in practical game design and implementation. The selection of hardware and suitable development libraries can be largely different by functionality of the game and the budget. To promote wide usability of a particular game, cost-effectiveness is necessary to be considered carefully in the design and implementation phase.

In game evaluation phase, both modalities enable subjective user experience to be recorded. Moreover, eye tracking can provide pre-recorded off-line eye movement analysis for learning effectiveness and game engagement evaluation. However, this review provided limited discussion of user study and game evaluation in the focused applications. It could be further explored because of its critical influence in game study.

We would suggest a design that exploits the adaptability of both modalities to achieve most efficient implementation. Eye tracking can be designed as input methods, i.e. using gaze to reflect region of interest or directly using it as interaction tool within the virtual reality; or output records, i.e. using gaze pattern for motor prediction or other post-session analysis of learning. Haptics is regularly integrated with other sensations for its particular use as output for haptic feedbacks, which improves the overall immersive user experience. We envisage the technological advances in both hardware and software that drive designers and engineers to push the boundary of existing applications and contribute to the constantly updating new realm.

7. References

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