Chapter 5

MULTIMODAL DISPLAY SYSTEMS: HAPTIC, OLFACTORY, GUSTATORY, AND VESTIBULAR

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The Sensorama is the prototypical embodiment of a virtual environment (VE), conceived and implemented years before "VR" (or "virtual reality") became a common term. Whereas VR has been often characterized as "goggles and gloves," Heilig (1962) developed a truly multimodal display system that provided for stereoscopic vision, binaural audition, haptics (wind in the face; vibration or "jolts"), and olfaction. Figure 5.1 shows the patent drawing for the containers that served as the Sensorama's olfactory sources. Those containers, coupled with the system's fan, comprise what is likely the first example of an olfactory display that was integrated with other display modalities. In many respects his invention still stands alone in terms of the degree of integration of multimodal displays in a practical device that provided a compelling virtual experience for the user. In this chapter we examine nonvisual and nonauditory displays that have been used or have the potential to be used in virtual environments for training.

INTRODUCTION

Motivation and Scope

In most virtual environments the visual display is dominant, usually followed in importance by the auditory display. These display modalities are described elsewhere (see Welch and Davis, Volume 2, Section 1, Chapter 1; Henderson and Feiner, Volume 2, Section 1, Chapter 6; and Whitton and Brooks, Volume 2, Section 1, Chapter 12). There are circumstances, however, where other display "dimensions" are critical to the effective training of a user. In fact, there is evidence that, in some cases, vision may not be the dominant sense (Shams, Kamitani, & Shimojo, 2000). In this chapter we provide access to the dimensions of haptics, olfaction, gestation, and acceleration/orientation. The inclusion of these display modalities is motivated by the need to create a virtual environment that

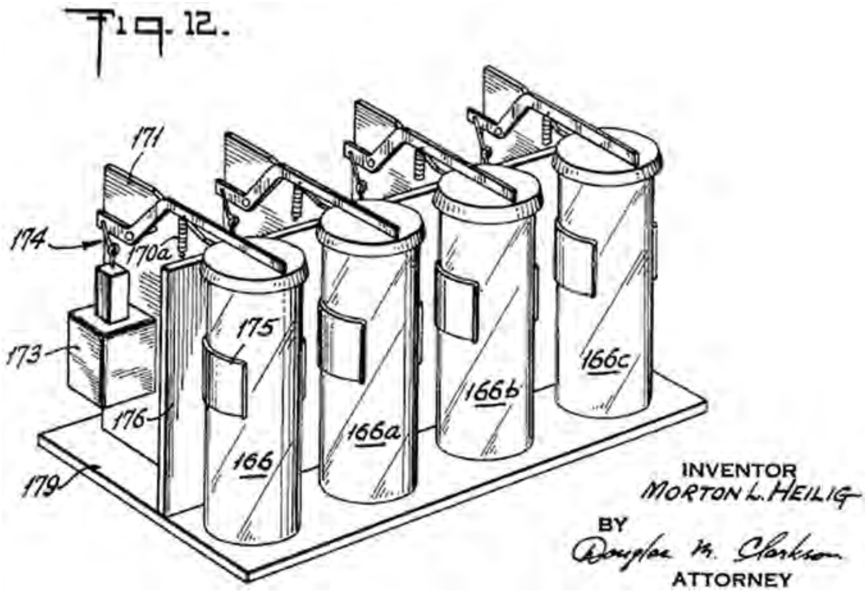

Figure 5.1. The patent drawing for the containers that served as the Sensorama's olfactory sources is shown.

maps more fully onto the real world and to exploit some uniquely human reliance on senses other than vision and audition.

Loftin (2003) has considered the potential of multimodal displays to expand the human "bandwidth" for perceiving complex, multivariate data. In the training domain this may be even more important since we may wish to replicate the real world to the greatest extent possible. After all, humans routinely employ all of their senses simultaneously as they go about their normal tasks. Certainly, we can compensate when one or more senses are impaired (for example, the common cold can compromise the sense of smell), but such compensation may not be adequate for some training purposes. Also, the use of sensory modality as a substitute for another could lead to negative training or poor transfer from the training environment to the real environment.

Consider some of the common circumstances in which the nonvisual and nonauditory senses play important roles. A surgeon may depend on olfaction (the sense of smell) to detect that the bowel has been perforated (Krueger, 1995). Smells can be very important in producing the crucial contexts for some training environments, including the smell of fire, blood, cooking food, an animal presence, or vegetation. In some cases the presence of the correct smell could "make or break" the sense of realism (fidelity) that training requires.

In the technical descriptions, an effort has been made to build on what was provided in the *Handbook for Virtual Environments* (Stanney, 2002). Thus, we have typically included only updates on developments since 2001 for those technologies that were fully described in the *Handbook.* This approach applies primarily to the sections on haptic and vestibular displays. The *Handbook* contains a very short section on olfactory displays and nothing on gustatory displays. A recent and relatively comprehensive treatment of multimodal interfaces has been produced by Kortum (2008).

HAPTICS

Haptics Technology

Haptics is a highly interdisciplinary research area that aims to understand how humans and machines touch, explore, and manipulate objects in real, virtual, or teleoperated worlds. One of the most distinguishing features of touch from other sensory modalities is that it is a bilateral process. We can look and observe the objects using our eyes, but cannot change their state. However, when we explore an unknown object in our hand, we instinctually rotate it to change its state (Lederman & Klatzky, 1987). Haptic exploration not only gives an idea about the shape and surface properties of an object, but also provides information on its material properties, such as softness. Perception and manipulation through touch are both accomplished via tactile and kinesthetic channels. Various types of receptors located under one's skin are responsible for the tactile perception. These receptors can sense even very small variations in pressure, texture, temperature, surface details, and so on. Kinesthetic perception in the brain occurs through information supplied by the muscles, tendons, and receptors located in the joints. For example, while perception of textures or surface roughness is more of a tactile activity, feeling reaction forces when pushing an object involves kinesthetic system. Unfortunately, we know very little about how tactile and kinesthetic information is transmitted and processed by the brain.

Developing haptic devices that enable tactile and kinesthetic interactions with real and virtual objects has been challenging. Our haptic interactions with physical objects around us mainly involve the use of hands. The human hand has a complex anatomy and function, and developing interfaces that fully imitate its sensing and actuation capabilities is beyond our reach today. This challenge can be better appreciated if we consider that the human hand has 27 degrees of freedom, each finger can be actuated by more than one muscle group, and there are approximately 100 receptors in one centimeter square area of a finger pad. Several different haptic devices have been developed to enable touch interactions with objects in real, virtual, or teleoperated worlds (see the review of devices in Burdea, 1996). In general, the performance of a haptic device is highly coupled to its design. A high quality haptic device has a low apparent inertia, high stiffness, low friction, and minimal backlash. Actuator selection affects the range of dynamic forces that can be displayed using the interface. Moreover, high sensor resolution and force update rates are desired to achieve stable touch interactions. For example, the haptic loop must be updated at a rate close to one kilohertz to render rigid surfaces.

One way to categorize haptic devices is whether they are passive or active. For example, a keyboard, a mouse, and a trackball can be considered as passive devices since they supply input only (unidirectional). On the other hand, a force-reflecting robotic arm can be programmed to display forces to the user based on his or her inputs (bidirectional).

A second way that haptic devices can be categorized is based on whether they are grounded or ungrounded. For example, a joystick has a fixed base and is considered as a grounded haptic device. On the other hand, exoskeleton-type haptic devices are attached to the user's arm (and move around with it) and are considered ungrounded. Today, most of the devices in this category are bulky, heavy, and not very user friendly.

A third way to categorize haptic devices is based on whether they are net-force or tactile displays. The idea behind the net-force displays, such as the PHANTOM device (Massie & Salisbury, 1994), is to reduce to a single point the complex haptic interactions of a human hand with its environment. On the other hand, a net-force/torque display provides limited information about the complex distribution of forces that are perceived when, for example, a textured surface is stroked with one's finger tip. The tactile devices are developed to display distributed forces to a user. For example, an array of individually actuated pins (tactile pin array) has been used to perturb the skin at the user's fingertip.

Finally, one could also distinguish between impedance control, where the user's input motion (acceleration, velocity, and position) is measured and a output force is returned (as in a PHANTOM haptic device) versus admittance control, where the input forces exerted by user are measured and motion is fed back to the user, as in Haptic Master sold by Fokker Control Systems (http://www.fcs-cs.com/robotics). Impedance devices are simpler to design and are most common, while admittance devices are generally used for applications requiring high forces in a large workspace (Salisbury, Conti, & Barbagli, 2004).

Training Applications

In this chapter, we focus only on applications of active haptic devices in training of human operators since covering all applications of haptic devices would be a very exhaustive task. The early application of active haptic devices dates back to the 1950s. Force-reflecting devices were used to convey contact forces to a human operator during remote manipulation of radioactive substances at Argonne National Laboratory. The number of applications increased drastically in the 1990s since the appearance of commercial devices that enable touch interactions with virtual objects. Also, the concept of *haptic rendering* has emerged (Salisbury, Brock, Massie, Swarup, & Zilles, 1995; Srinivasan & Başdoğan, 1997). Displaying forces to a user through a haptic device such that he or she can touch, feel, and manipulate objects in virtual environments is known as haptic rendering (see the recent review in Başdoğan, Laycock, Day, Patoglu, & Gillespie, 2008). Analogous to graphical rendering, haptic rendering is concerned with the techniques and processes associated with generating and displaying haptic stimuli to the human user. A haptic rendering algorithm is typically made of two parts: (a) collision detection and (b) collision response. As the user holds and manipulates the end effector of the haptic device, the new position and orientation of the haptic probe are acquired, and collisions between the virtual model of the probe and virtual objects in the scene are detected. If a collision is detected, the interaction forces are computed using preprogrammed rules for collision response. The forces are then conveyed to the user through the haptic device to provide him or her with the haptic representation of the 3D object and its surface details.

With the development of desktop commercial rendering libraries, the field has shown a significant expansion during the last decade. New applications have emerged in fields, including medicine (surgical simulation, telemedicine, haptic user interfaces for blind persons, and rehabilitation for patients with neurological disorders), dental medicine, art and entertainment (3D painting, character animation, digital sculpting, and virtual museums), computer-aided product design (free-form modeling, assembly and disassembly, including insertion and removal of parts), scientific visualization (geophysical data analysis, molecular simulation, and flow visualization), and robotics (path planning and telemanipulation).

In the following discussion of applications, we focus on the use of haptics in training of human operator. There is a wide range of applications in which it is desirable to dexterously manipulate real or virtual objects while maintaining the flexibility of human control or planning. For example, there is a need to improve the ability of humans to direct remote manipulation tasks; the improved performance can be achieved through simulation-based training in virtual environments.

One of the applications of this concept is in space exploration. For example, today, the interaction between a human operator located on earth and a rover located on the remote planet is provided through a set of edited text commands only. However, this approach restricts the complexity of transmitted commands and likewise reduces the quantity and quality of data return. In addition, these commands do not always make the best set since they are not extensively tested before being transmitted to the rover. For example, if the task involves handling and manipulation of objects (for example, collecting rock samples) a rover faces several uncertainties when executing it (for example, whether the sample is at a reachable distance, how to hold the sample, and so forth). Planning, scheduling, and synchronization of rover tasks that involve autonomous manipulation of objects will be even more challenging in the future when multiple rovers are used concurrently for planetary exploration and they have to work cooperatively.

The National Aeronautics and Space Administration's (NASA's) Jet Propulsion Laboratory (JPL) has developed a multimodal virtual reality system for interacting with a fleet of rovers—so that they can plan and schedule planetary robotic missions effectively (Başdoğan & Bergman, 2001). This system utilizes dual haptic arms and a semi-immersive visualization system and is designed to train and prepare a rover operator for executing complex haptic manipulation tasks (see Figure 5.2). The training simulations involve a scenario where the operator commands a planetary rover while it collects rock samples. The observations and experiences gained from these simulations are used to help identify situations and issues the rover is likely to encounter when it performs the same tasks autonomously on the surface of Mars. In this regard, mapping the activities of a human operator to the activities of a robotic system—transforming inputs from the haptic arms into control signals for the robotic system—is a challenging research problem (Griffin, 2003).

Similar to the efforts at JPL, the Lyndon B. Johnson Space Center (JSC) at Houston trains spacecraft crew members for extravehicular activities (EVAs). EVA tasks, such as setting up an instrument, assembly, maintenance, or carrying out repairs, are inherently risky. One approach to minimizing risks is to train crew members in a multimodal virtual environment on earth, before they do it in space (Loftin & Kenney, 1995). A virtual model of the Hubble Space Telescope (HST) was constructed to train members of the NASA HST flight team on maintenance and repair procedures. Another approach is to use humanoid robots commanded through a telepresence interface to perform these tasks.

Robonaut, developed at JSC, is an anthropomorphic, astronaut-sized robot configured with two arms, two five-fingered hands, a head, and a torso (Ambrose et al., 2000). The earlier telepresence interface of the Robonaut system utilized the CyberGlove haptic system (Immersion Corporation) to guide the articulated movements of the Robonaut arm without force feedback to the human operator. Later, CyberGlove was replaced with dual force feedback joysticks to improve the grasping abilities of the operator (O'Malley & Ambrose, 2003).

Another popular application of haptics is in surgical training. From the start of medicine to the modern standardized surgical training programs, the training paradigm for surgeons has not changed substantially. Surgical training has been based traditionally on the "apprenticeship" model, in which the novice surgeon is trained with small groups of peers and superiors, over time, in the course of patient care. However, this training model has been placed under inspection, and its efficiency is being questioned by experts, physicians, and the public.

Figure 5.2. This is a view of JPL's multimodal virtual reality system used for training with a fleet of rovers.

According to the report "To Err Is Human" prepared by the National Academy of Science, Institute of Medicine in 1999, the human cost of medical errors is high, and more people die from medical mistakes each year than from highway accidents, breast cancer, or AIDS combined.

Minimally invasive surgery (MIS) is a revolutionary surgery technique in immediate need of improved training methods. MIS has been used in a range of procedures since the early 1960s (for example, if the surgery is done in the abdominal area, it is called laparoscopic surgery). This technology uses a small video camera and a few customized instruments to perform surgery. The camera and instruments are inserted into the surgery area through small skin incisions or natural orifices that enable the surgeon to explore the internal cavity without the need of making large openings. Major advantages of this type of surgery to the patient are short hospital stay, timely return to work, and less pain and scarring after the surgery.

Although MIS has several advantages over traditional open surgery, surgeons are handicapped by the limitations of the technology: Haptic cues are substantially reduced since the surgeon has to interact with internal organs by means of surgical instruments attached to long thin tubes. While the importance of training in MIS has been well acknowledged, there is no consensus on the best or most effective method to do this training. Box trainers, for instance, are an inanimate model equipped with real surgical instruments, endoscopic cameras, and plastic tissue models. These trainers provide an environment similar to that of real surgery settings. However, simulated surgical procedures are usually poor imitations of the actual ones. Currently, animal training is considered the most realistic training model available. This model is dynamic and approaches real operative conditions. Animal tissues, although not always of the same consistency as human tissues, do respond in a similar way to the forces applied to them. The use of animals for training purposes, however, is expensive and controversial. Moreover, the trainee's performance cannot be measured quantitatively.

Simulation-based training using virtual reality techniques (see Figure 5.3) has been suggested as an alternative to the traditional training in MIS. Surgical simulators developed for this purpose enable the trainee to touch, feel, and manipulate virtual tissues and organs through the haptic devices, while displaying high quality images of tool-tissue interactions on a computer monitor as in real surgery (see the review in Başdoğan, Sedef, Harders, & Wesarg, 2007).

In addition to displaying forces arising from tool-tissue interaction during the simulation of surgical procedures, haptic devices can be also used for playing back prerecorded haptic stimuli. For example, a physician relies heavily on haptic cues when guiding a needle into epidural space. The appreciation of forces at each layer is important for the proper guidance of the needle. Dang, Annaswamy, and Srinivasan (2001) experimented with two modes of haptic guidance. In the first, the simulator displays a virtual guiding needle on the screen that moves along the same path and with the same speed as an expert in a prerecorded trial. If the user's needle position exactly matches that of the guiding virtual needle, the user feels the same forces that the expert felt. In the event of a mismatch,

Figure 5.3. This is a view of simulation-based training using virtual reality techniques.

the virtual instructor applies a force to pull the trainee back to the prerecorded trajectory. In the second mode, or tunnel guidance, we disregard the time dependency of the recorded data such that users perform the task at their own speed. The needle's movement is limited to the prerecorded trajectory, allowing users to concentrate solely on the forces encountered at each layer along the needle's insertion path.

Another application of haptics in medicine is in the area of rehabilitation. Since the nervous system is highly adaptive and open to reprogramming, a haptic arm can be used to teach it how to control movements. For example, a force feedback robotic arm and artificial force fields have been used to train and improve the motor performance of patients with chronic impairment after stroke (Krebs & Hogan, 2006). Patients were asked to perform goal-directed, planar-reaching tasks that emphasized shoulder and elbow movements under the force guidance of the robotic arm. Clinical results with well over 300 stroke patients, both inpatients and outpatients, proved that movement therapy has a measurable and significant impact on recovery following brain injury.

There are also applications of haptic technology in military training. At Massachusetts Institute of Technology (MIT), under a large interdisciplinary program called Virtual Environments Technology for Training (VETT) funded by the Office of Naval Research, software and hardware technologies were developed to augment the perceptual and cognitive skills of the U.S. Navy students in training. For example, a virtual model of an electronics test console was developed to teach students basic electricity and electronics. Haptic interactions with toggle buttons, multimeter probes, and switches on the console were simulated

(Davidson, 1996). In another study, experiments were designed to investigate whether haptic feedback improves their ability to control the direction of a surface ship while they navigate the ship in a complex virtual environment where there are other ships and harbor hazards such as bridges. The main goal of this study was to teach U.S. Navy students basic concepts of vector algebra and dynamical systems. The results of this study showed that subjects have learned the influence of ship inertia and water currents on its heading better under the guidance of force feedback (see MIT RLE-Report 142).

Artificial Force Fields for Training and Task Guidance

One of the benefits of active haptic devices in training for telemanipulation tasks stems from the fact that they can be programmed to guide or restrict the movements of the user by introducing *artificial force fields.* Artificial force fields, also known as *virtual fixtures,* have been shown to improve user performance and learning in telemanipulation tasks in real world and training tasks simulated in virtual environments (Rosenberg, 1993; Payandeh & Stanisic, 2002; Bettini, Lang, Okamura, & Hager, 2002; Bukusoglu, Başdoğan, Kiraz, & Kurt, 2006). The term virtual fixture refers to a software implemented haptic guidance tool that helps the user perform a task by limiting his or her movements to restricted regions and/or influencing its movement along a desired path (Rosenberg, 1993). The virtual fixtures can be thought of as a ruler or a stencil (Abbott & Okamura, 2003). By the help of a ruler or stencil, a person can draw lines and shapes faster and more precisely than the ones drawn by free hand. Similar to the passive stencil, an active haptic device can be programmed to apply forces to the user in a virtual environment to train him or her for executing a task more efficiently and precisely. Obviously, this concept is not only useful for training, but also for actual execution of the task in the real world.

In comparison to real physical constraints, the type and the number of virtual constraints that can be programmed are unlimited. Artificial force fields offer an excellent balance between automated operation and direct human control. They can be programmed to help the operator carry out a structured task faster and more precisely, or they can act as safety elements preventing the manipulators from entering dangerous or undesired regions. For example, studies on telemanipulation systems show that user performance on a given task can increase as much as 70 percent with the introduction of virtual fixtures (Rosenberg, 1993).

Some other applications of virtual fixtures include robotic-assisted surgery and optical manipulation (Abbott & Okamura, 2003; Başdoğan, Kiraz, Bukusoglu, Varol, & Doganay, 2007). For example, Başdoğan and his colleagues have trained users in virtual environments to manipulate microspheres in a fluid bed using optical tweezers to form patterns of coupled optical microresonators. The task was to construct a coupled microsphere resonator made of four microspheres by individually steering and binding three spheres to an anchor sphere. One group was trained and used a system giving only visual feedback; the other group trained with and used a system providing both visual and haptic feedback. An artificial force field was used to help subjects position the particles precisely and to make the binding process easier. The summation of guidance forces (an artificial force field) and the estimated drag force was displayed to the subjects in the second group through a haptic interface. After the training, the performance of both groups was tested in the physical setup. Experiments showed that guidance under haptic feedback resulted in almost twofold improvements in the average path error and average speed.

Challenges

Aerospace, maritime, military, nuclear energy, and other high-risk professions have been using simulators for training difficult and demanding tasks for the last 50 years. By integrating force feedback devices into simulators, some of these industries have augmented the perceptual, cognitive, and motor control skills of the human operators and reduced errors significantly. The flight simulators equipped with force feedback joysticks provide a convincing example for the importance of simulation technology and the significant role that haptics play in training. Just as flight simulators are used to train pilots nowadays, it is, for example, anticipated that surgical simulators will be used to train physicians in the near future. The role of haptic feedback in this application is also unquestionable. Moreover, several studies in the past have shown the significance of haptics in teleoperation tasks in real and virtual worlds. For example, artificial force fields not only enable us to train the human operator in virtual environments, but also help him or her execute the teleoperated task better and faster in the real world.

Significant progress has been made in academia and industry in haptics, but there are still many research questions waiting to be answered. While it is difficult, and outside the scope of this chapter, to answer all these questions, we highlight some of the outstanding research challenges that require further attention: One of the constant challenges in integrating haptics into virtual environments is the need for a variety of haptic devices with the requisite degrees of freedom, range, resolution, and frequency bandwidth, both in terms of forces and displacements. Also, the price of next generation haptic devices must be significantly lower in order to be purchased by all computer users. In this regard, it is worth mentioning the Falcon haptic device, which was recently introduced by Novint Technologies and costs less than $200. It is hard to imagine that a single universal device can be used for all applications since the requirements of each application are different. For example, the motions and forces involved in laparoscopic surgical operations are small. Ideally, the haptic device used for laparoscopic training must have a fine resolution and 6 to 7 degrees of freedom. On the other hand, a haptic device designed for rehabilitation applications may have a lower resolution, but require a larger workspace.

Another area of hardware design that requires further investigation is multifingered haptic devices and tactile displays. It has been demonstrated that when we gather information about the shape and size of an object through touch, our fingers and hand move in an optimal manner. Moreover, robotics studies show that at least three fingers are necessary for stable grasp. On the other hand, there are only a few multifingered haptic devices that are commercially available today. For example, CyberGrasp from Immersion Corporation is an exoskeleton having individual wires pulling each finger to prevent its penetration into a virtual object during the simulation of grasping. Designing and building multifingered haptic devices becomes increasingly more difficult as the degrees of freedom of the device increases. Hardware for displaying distributed forces on the skin also remains to be a challenging problem. Very crude tactile displays for VEs are now available in the market; many of them are vibrotactile displays. The tactile devices developed in research laboratories are mostly in the form of an array of pins actuated individually. Packaging an array of actuators that does not break or hinder an active user is highly challenging, and new technologies must be explored to make significant progress in this area (see the review in Biggs & Srinivasan, 2002).

There are also several challenges that remain to be solved in the area of haptic rendering. Computational cost of rendering virtual objects grows drastically with the geometric complexity of the scene, type of haptic interactions, and the material properties of the objects (for example, soft versus rigid). The simulation of haptic interactions between a point probe and a rigid virtual object has been achieved (that is, 3 degrees of freedom haptic rendering), and many of the point-based rendering algorithms have been already incorporated into commercial software products, but the simulation of object-object interactions is still an active area of research (see the review of 6 degrees of freedom haptic rendering techniques in Otaduy & Lin, 2008). While point-based interaction approaches are sufficient for the exploration of object surfaces, more advanced rendering techniques are necessary for simulating *tool-object* interactions. For example, in medical simulation, side collisions occur frequently between simulated surgical instruments and deformable organs, and 3 degrees of freedom haptic rendering techniques cannot accurately handle this situation (see the details in Başdoğan, De, Kim, Muniyandi, & Srinivasan, 2004). In fact, simulating the nonlinear dynamics of physical contact between an organ and a surgical instrument, as well as surrounding tissues, is very challenging, and there will be a continued demand for efficient algorithms, especially when the haptic display needs to be synchronized with the display of visual, auditory, and other modalities. In this regard, one of the missing components is the lack of detailed human-factors studies. Even if we assume that the hardware and software components of visual, haptic, and auditory displays will improve one day to provide richer stimulation for our sensory channels, the perception of the information is still going to be performed by the user. Hence, a better understanding and measurement of human perceptual and cognitive abilities is important for more effective training and better training transfer.

OLFACTORY DISPLAYS

Today few virtual environments employ olfactory displays. Nonetheless, olfaction is an important sense and has been shown to stimulate both emotional

(Corbin, 1982) and recall (Chu & Downes, 2000; Degel, Piper, & Koester, 2001) responses. Most of us have had the experience of detecting a specific smell that "took us back" to a place or an event. In addition, olfaction can have both directional and nondirectional capabilities. From a training perspective there are certainly virtual environment application areas (medical, combat, electronic fault detection, and so forth) that have a demonstrable need for an olfactory "dimension."

Technology

Work on olfactory displays is fairly recent. A good body of literature on olfaction is extant (see, for example, Ohloff, 1994). Barfield and Danas (1996) established the "baseline" for this display technology in their paper. Another excellent compilation is Joseph Kaye's (2001) MIT master's thesis "Symbolic Olfactory Display." These two resources gather what was known prior to 2000 about olfaction and about technologies that, in principle, can support olfactory displays. A more recent review is that of Gutierrez-Osuna (2004). Myron W. Krueger (1995) specifically worked on the issue of mixing odorants to achieve specific scents in the context of medical simulation.

The Sensorama (Heilig, 1962) included a fan and a container that enclosed an odor-producing chemical and a device to open the container at a time that corresponded to visual images congruent with the odor produced by the container's contents. This system is likely the earliest example of an olfactory display integrated with other display devices.

Heilig's (1962) approach to producing smells on demand has not been significantly improved upon in the intervening years. At issue is the ability to (1) produce a specific smell when needed, (2) deliver the smell to the nose(s) of the user(s), and (3) dissipate the smell when it is no longer required. Each of these three elements presents serious technical challenges. Producing a specific smell is, in many cases, beyond current technical capabilities. Some smells are associated with chemicals or chemical reactions and may be producible on demand (see, for example, Krueger, 1995). Rakow and Suslick (2000) have developd technology to detect odors and have proposed the creation of a "scent camera," but their company, ChemSensing, Inc., has not yet marketed such a device. In 2000 a Korean company, E-One, proposed developing such a device as well (see http://transcripts.cnn.com/TRANSCRIPTS/0005/04/nr.00.html), but, again, nothing has reached the market. Delivery mechanisms are another area of concern. Just as in Heilig's (1962) approach, most devices depend on a fan to deliver the scent to the user or users. The Institute for Creative Technologies at the University of Southern California has developed a neck-worn system that places the source close to the user's nose (see http://ict.usc.edu/projects/sensory_environments_evaluation/). A good summary of past and current commercially available olfactory displays has been compiled by Washburn and Jones (2004). It is noteworthy that many commercial enterprises established to develop and market olfactory displays have not survived. An additional review is included in Davide, Holmberg, and Lundström (2001).

Training Applications

Although their potential has been recognized, few have attempted to incorporate olfactory displays in training applications. One of the first was developed at the Southwest Research Institute (Cater, 1994)—a virtual environment for training fire fighters that provided both olfactory stimulation as well as thermal, visual, and auditory displays. Researchers in the U.S. Army have investigated the use of olfactory displays to provide the smell of blood, cordite, and other scents of the battlefield (Washburn, Jones, Satya, Bowers, & Cortes, 2003). In spite of these efforts, no virtual environment training applications have been deployed (as of this writing) that incorporate an olfactory display.

Challenges

Challenges abound as noted earlier. The most difficult is probably in the area of producing, on demand, a specific smell that fits the context of the training application. The solution to the problem will be a mixture of both science and art. The challenge of delivering the smell to the user(s) and dissipating it, while complex, is fairly straightforward and will likely have a variety of solutions depending on the training application's objectives and its physical relationship to the user(s). In spite of these issues, it must be recognized that there are human variables that will be beyond the control of the application and its users/operators. These variables include transitory (for example, the common cold) and permanent inability, on the part of the user, to actually detect a delivered scent.

GUSTATORY DISPLAYS

Technology

While gustatory (taste) displays have been discussed in the literature, no system has yet emerged that can be evaluated. Beidler (1971) provides a compendium of knowledge of the basis for the sense of taste in his handbook. Much more recently Maynes-Aminzade (2005) offered a light-hearted suggestion for "edible user interfaces" at CHI 2005. Food science does provide a basis for the development of gustatory displays. For example, handbooks (see, for example, Deibler & Delwiche, 2003) provide access to the literature of "taste" from a variety of perspectives. Thus, it can be said that we do know a great deal about how the sense of taste "works" and how to produce, chemically, some specific tastes. Just as in olfaction, however, translating this knowledge into a practical application will be quite difficult.

Challenges

Again, just as in the case of olfaction, there are the usual challenges of producing a specific taste on demand, delivering the taste sensation to the user(s), and them eliminating the taste as required. Beyond these problems we have the additional issues of the strong relationship between taste and smell (Ohloff & Thomas, 1971) and of large human variability in the abilities to discern a specific taste and, collectively, agree on a characterization of that taste.

VESTIBULAR DISPLAYS

Vestibular displays provide the senses of acceleration and orientation to the user. Obviously (see the illustration in Figure 5.4 above of an early flight simulator, *circa* 1910), these "displays" are often mechanical in nature and provide a straightforward means of subjecting the user to the movements (accelerations) and orientations necessary for effective training. This recognition, over a hundred years ago, led to a robust industry dedicated to motion based platforms on which users are placed. Such platforms are found in many high performance flight simulators that routinely train pilots to operate aircraft and spacecraft (see, for example, Rolfe & Staples, 1988). Flight simulators certainly represent one "class" of virtual environments used for training (Brooks, 1999), but there are others that should be mentioned. Submarine simulators (for example, that are operated by the U.S. Navy at Pearl Harbor, Hawaii) typically incorporate motion bases for orientation. During a steep dive or an emergency surfacing operation, these simulators provide the users with the direct experience of trying to stay at or get to their stations in spite of a steeply sloping deck.

Technology

The technology of vestibular displays as represented by motion based platforms was reviewed thoroughly in Stanney (2002) and that source remains

Figure 5.4. This is a picture of an early (1910) flight simulator.

current as of this writing. Two specific points will be made here, however. The first is that low cost, "personal" motion based platforms are available and may be integrated with a virtual environment designed for training (see, for example, Sterling, Magee, & Wallace, 2000). This integration is very simple, assuming that the necessary control software is available for a specific motion base. A second and rather interesting technique is to directly stimulate the human vestibular system. Cress and his colleagues have demonstrated that electrodes can be used to create the sensation of acceleration in a subject (Cress et al., 1997). Obviously, this technology may not find widespread acceptance and has not been studied in a large population to determine its degree of safety.

Training Applications

Given the literature references made above, we will not try to exhaustively address vestibular displays as a part of virtual environments for training in a global sense. Rather, here we will consider only the typical virtual environments (goggles and gloves) that have been developed for training purposes. The system described by Sterling et al. (2000) is, perhaps, the best example. In this case, the authors examined a "low cost" helicopter landing simulator using a small motion base, minimum controls, and a head-mounted display in comparison to a high-cost, large-scale helicopter simulator. The results of their research suggest that the low cost system's effectiveness in training was comparable to that of the high-end system.

Challenges

With the availability of low cost motion based platforms, the ability to integrate these into virtual environments designed for training is at hand. What is lacking is the requirement to do so. One possible explanation for this lack of applications is the dominance of the visual sense. For example, ship bridge simulators almost never incorporate motion based platforms. Yet, as anyone who has used such a simulator can attest, it is easy to get seasick if the visual displays provide scenes that incorporate only visual motion.

SUMMARY

Multimodal displays are an essential component of virtual environments used for training. Such displays offer the potential to provide sensory channels that are essential for some training applications. If virtual environments were limited strictly to visual and auditory displays, a significant fraction of the human sensory spectrum would be ignored. In some cases this could lead to less effective training or even to negative training.

This chapter addresses displays for the haptic, olfactory, gustatory, and vestibular sensory channels. Haptic displays, while limited, do offer significant technical maturity in some applications and have been demonstrated to add effectiveness to some training applications. Olfactory and gustatory displays are largely not available and have not yet been incorporated into fielded virtual environments for training. Vestibular displays are widely used in many virtual environments designed for training in aircraft and spacecraft piloting. The use of lower-cost versions of these displays is now possible, and it is anticipated that they will find their way into more widely deployed applications. In all cases, significant challenges remain before these display modalities will become as common on visual and auditory displays, yet the need to deliver highly effective training demands that these technologies be available.

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