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Spatial Cognition and Architectural Design in 4D Immersive Virtual Reality: Testing Cognition with a Novel Audiovisual CAVE-CAD Tool

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1. INTRODUCTION

The development of new 3D visualization technologies and novel algorithms for calculating and dynamically displaying complex structures in large-scale immersive CAVE facilities provides a transformational opportunity to designers and architects, as well as cognitive scientists interested in understanding complex tasks involved in spatial cognition. Approaches commonly in use by architectural designers to render 3D structures include a variety of computer aided design (CAD) tools that simulate 3D objects on a flat 2D computer screen. Although such screen-based visualizations are referred to as 3D models, they must be interpreted by the human brain as a 3D object, and require the viewer to imagine the egocentric experience accurately. Whereas highly trained design professionals may have greater cognitive facility with this mental transformation, clients and users are often unable to create accurate mental representations from 2D plans and elevations or indeed from "3D walkthroughs" viewed on 2D desktop screens. For the cognitive scientist, the availability of more realistic representations that involve multiple coordinated sensory modalities offers the possibility of studying spatial cognition using more natural experimental conditions.

2. CURRENT AND FUTURE HUMAN SCALE VR FACILITIES AND THEIR APPLICATIONS

The implementation of large, human scale virtual reality (VR) facilities, such as the StarCAVE at UCSD's Calit2, has introduced a novel tool for displaying and testing the user's experience and responses to life-sized design spaces. In the StarCAVE, architectural settings are back-projected on 360^{o} surround screens in a stereoscopic view that allows a single viewer or a group of up to 10 people to experience movement through the realistic, full-scale model of a building or built settings.[i] (**Figure 1**) Multiple projectors and computers drive and stitch together the stereo images that are viewed with passive polarized glasses. Moreover, the recently implemented capacity to add to the visual presentation of the design a realistic and accurate representation of the dynamic sound properties of the space has enhanced the uniqueness of these facilities for use in the creative aspects of the design process, as discussed in another section below. [ii]

Figure 1: View of the StarCAVE with the back panel opened to allow a group to experience a VR representation of a healthcare facility design.

While back-projection has some advantages and some limitations, the arrival of 3D television and large flat panels in the consumer market has enabled the virtual reality community to build novel devices at a small fraction of the cost of projector-based systems. These displays are also easier to install and maintain. The NexCAVE at Calit2 (**Figure 2**) is an example for how 3D TV displays can be mounted to form an immersive VR system. The screens may be installed in a 3x3 array, which is curved towards the user in both directions, so as to maximize the coverage of the user's field of view. A 10th display is mounted below the center column to allow viewing the floor. The screens may be configured in larger arrays for enhanced peripheral views, larger content and CAVE like enclosure.

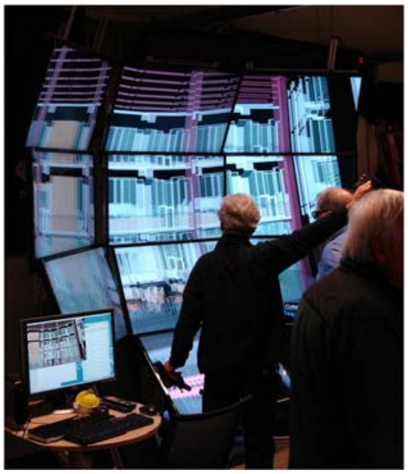

Figure 2: Next generation of flat panel 3D Immersive VR systems illustrated by the NexCAVE.

The availability of powerful consumer graphics cards has transformed VR visualization functions, enabling multiple displays to be driven by fewer computers, simplifying administration and maintenance, while reducing power consumption. The recent trend towards PC systems offer opportunities for Windows based systems rather than Linux operating systems which can be harder to administer. VR tracking systems adjust the images across the display screens, merging them into a single view of a 3D model. Hand-held input devices and infra-red head trackers with 3D interaction capabilities track the participant's location and point of view within the virtual world. Because of the availability of inexpensive high resolution cameras, optical tracking systems are now more affordable, and are in many ways superior to other tracking technologies (such as electro-magnetic, mechanical, or ultrasound based systems). [vii]

3. DEVELOPMENT OF A SOFTWARE DESIGN TOOL FOR THE IMMERSIVE VR ENVIRONMENT: CAVE-CAD™

A team of neuroscientists, clinicians, architects, designers, engineers, and visual computation research specialists created a novel software applicationcalled CAVE-CAD™ that offers a number of innovations with an intuitive user interface that allows users to experience full-scale design as they modify and move through 3D renderings. Innovations include the ability to render and change the auditory and visual environment in real-time, enabling rapid development and display of different design options.

Until recently, facilities such as the StarCAVE were only able to display architectural models developed using standard CAD software that could only be modified by changing the original files offline. The new version must then be re-imported before it can be displaying again in the CAVE, a laborious and time-consuming approach. Changes in design using this process may incur high costs and limit the design team's ability to provide a significant number of alternative design options given the timeline or budget of the architectural design process or experimental protocol.

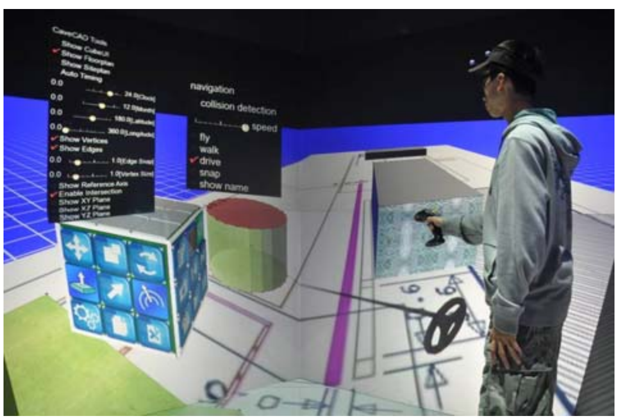

Figure 3. Using CAVE-CAD ™ software architecture can be constructed around the viewer, immediately offering an experience of the design. Shown here are some of the tools (drop-down lists, palette cube) that have been implemented in the software.

To overcome this, we have developed software, called CAVE-CAD™ that allows the design process to be carried out entirely within the StarCAVE or one of the more recently implemented portable immersive CAVE facilities.[iii] CAVE-CAD™ possesses several unique features that are particularly useful to real-time immersive 3D design. For example, instead of multiple option menus, functions are accessed through smart 3D icons that move with the designer to provide easy access to design functions, finishes and modifiable building elements (**Figure 3**). With this system, architecture can be constructed around the viewer, immediately offering an experience of the design, with sightlines within the building and through openings to exterior spaces presented with geometric accuracy. Options for adding, for example, dynamic shadows (time of day, season) and different external settings (nature scenes, cityscapes), enhance the perceived design.

4. IMPLEMENTING THE AURALIZATION OF IMMERSIVE VIRTUAL ARCHITECTURE

The augmentation of VR visual display systems by an audio component increases the sense of immersion and perceptual realism by connecting the visual scene to a coherent spatial auditory dimension. Spatial audio perception can be provided either by signals through loudspeaker arrays that surround the viewer position, or by addressing the viewer's ears individually through headphones or controlled projection of sound beams.

Enhancement of the VR experience by the addition of sound also adds relevant qualitative information to the visual experience. Our SoniCAVE™ project seeks to establish a set of tools that complement visual architectural design with auditory features accessible directly through the immersive VR display technology. In the context of CaveCAD ™, SoniCAVE ™ provides instant auditory feedback for accurate architectural acoustic prediction. Unlike previous acoustical modeling packages, changes to model geometry as well as the reflective and transmissive properties of floors and walls are continuously mirrored in corresponding changes to the audio rendering, providing coordinated access to visual + auditory simulations of the designed structure (**Figure 4**).

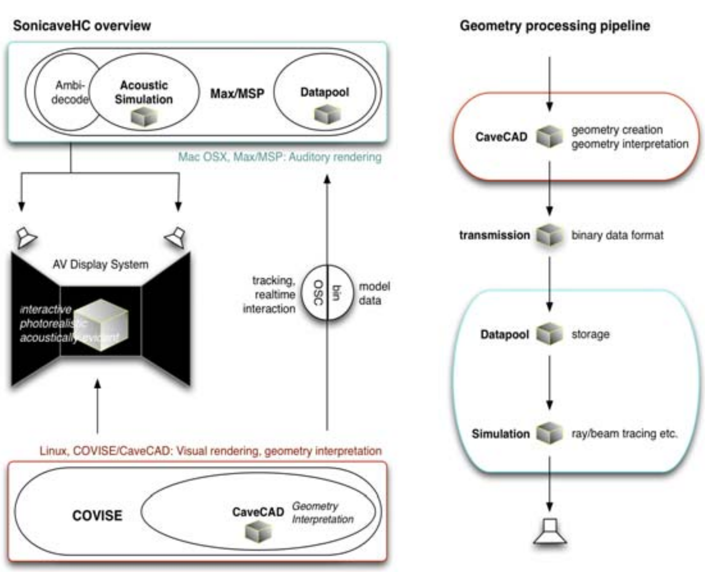

Figure 4: The SoniCAVE audio-visual system linked to CAVECAD visualization renders sound-scenes in real-time that reflect the sound profile of materials used.

Beside directionality and localization of virtual sound sources, the auralization of a 3D visual architectural model in real-time requires the development of a set of models each supporting a specific rendering strategy for the sound projection system used. The model includes several components, such as direct sound, specular and diffuse reflections, and transmitted as well as ambient sounds. Direct sound and specular reflections can be implemented with panning algorithms, such as VBAP or higher order Ambisonics, but the modeling of diffuse reflections and transmitted sound require a very direct connection between the display system layout and the sound rendering. The successful transfer of an ambient sound scene into the VR context includes the development of appropriate capturing and modeling techniques in which both the speaker layout used for sound reproduction, the microphone layout used for capturing, and the intermediate steps of processing and rendering, all need to be mutually compatible. The enhanced acoustical control adds a greater sense of realism to the display of architectural models and allows acoustic considerations to become an immediately relevant component to architectural design.

5. TRACKING GAZE AND ATTENTION: DEVELOPING AN EOG APPLICATION

The environment of the StarCAVE provides a controlled laboratory setting within which individual design features can be tested in realistic, complex virtual environments. In order to asses attention paid by subjects to visual cues and to help determine those that are most effective in navigating a built structure, we have developed the means to assay visual attention by computing 3D eye convergence using a wireless electroculography (EOG) system that is synchronized to the subjects view.[iv] Using the wireless 3D EOG system, along with additional instrumentation such as wearable EEG caps[v] and the head and movement tracking systems built into the StarCAVE, neurological and physiological responses of a freely moving human subject can be monitored in real time.

Compared to video-based eye tracking, EOG monitoring is functionally a much less complex tool. Whereas visual eye trackers must process and transmit video rate data (20Mbits/sec), EOG based trackers need only transmit low-bandwidth bio-potential signals (100kbits/sec) for processing. Physically, EOG recording can use relatively small (4-5 mm) electrodes that adhere readily to the skin around the eye, though we are currently developing dry non-contact electrodes for these purposes[xiv], and the electronic hardware can be light and easily portable. One major drawback with EOG based methods, however, is the lack of long-term accuracy due to electrode drift [xiv], necessitating our development of methodology for calibration before and during use.

In our current implementation, we use 8 adhesive electrodes placed around the eyes to record the potentials induced by the retinal dipole of each eye. Wires are held in place using the polarizing glasses used for #D visualization in the CAVE. A custom-designed wireless instrumentation system is used to amplify and transmit the EOG signals. Each channel is DC-coupled to a high-resolution 24-bit ADC to ensure accurate recording of low-frequency information in the EOG.

Signals are sampled at 500 Hz and transmitted via Bluetooth telemetry to a nearby laptop, which synchronizes stimuli and data from the CAVE. [iv]

This instrumentation allows for acquisition of eye position data simultaneously with brain EEG recordings and audiovisual stimuli, including the relative position of the viewer, which can then be analyzed by the research team to create a composite view of the subject's experience within the CAVE. Signals from the individual eyes encode azimuths and elevations, yielding information on depth, gaze and saccadic movements that can be correlated to attention and searching behaviors. Correlated with the EEG information, the underlying cognitive functions present during these behaviors may be assessed. This synchronized information is collected wirelessly, allowing the unfettered movement and more natural behaviors while performing navigation tasks within the virtual environment. These methodologies for improved calibration of EOG signals to visual targets and attention, virtual space wayfinding protocols, and dynamic multisensory environments are being implemented within the StarCAVE and other immersive environments to ascertain the effects on attention and cognition.

6. STUDYING COGNITION BY STUDYING BRAIN ACTIVITY IN THE VR ENVIRONMENT: AN APPLICATION TO WAYFINDING STUDIES BY MONITORING EEG IN REAL TIME

Immersive VR systems such as the StarCave provide controlled experimental environments in which a virtual building or an entire virtual urban city may be tested. Our initial studies enabled viewers to guide their own travel and visual experience with a remote wand as they moved through full-scale landscapes, townscapes or buildings. The first person perspective was found to offer greater engagement and more natural exploration of building models than do desktop navigation studies. Users reported that the sense of presence while navigating the environment, and in particular, the sense of being lost during wayfinding studies, were consistent with the actual experience of navigation.

The use of VR in combination with electroencephalographic (EEG) brain imaging allows for systematic investigation the brain dynamics underlying spatial cognition during movement. Synchronized with motion capture of the participants head movements and perceptual location of the subject in the VR CAVE model, EEG brain dynamics can be recorded with high temporal resolution and analyzed with respect to the first-person perspective of the subject’s view within the CAVE. This is in contrast to brain imaging methods that do not allow for movement, are too heavy to accurately follow the participant’s movements, or have insufficient temporal resolution to track the sub-second time course of brain activity accompanying cognitive processes.
Previously, brain imaging methods have used desktop-based VR studies with highly restrictive experimental protocols in which participants navigate in 2D virtual environments displayed on a flat computer screen. Subjects must sit still and restrict eye movements while navigating in order avoid interference with the

cortical brainwave data of interest from muscular potentials, or inaccuracies from sensors too heavy to follow participant movements (e.g., fMRI, MEG).[vi]

The absence of any natural movement, however poses a serious problem for the navigator. Idiothetic information that is needed to update egocentric and allocentric spatial representations is missing. In other words, an embodied process of spatial orientation in the natural world becomes dis-embodied in a desktop virtual world. [vii] A more natural spatial orientation approach in the immersive StarCave is based on participants' ability to freely move in the virtual environment including orienting movements of the head and the eyes during exploration. As a consequence, idiothetic information stemming from the vestibular as well as the proprioceptive systems provide the user with a wider range of sensory information approximating information processing during natural navigation. [viii] Riecke et al., (2010) suggest that the absence of translational body movements due to the restrictions of the physical space in VR environments such as the starCave might have little impact on results. [ix]
Advanced data driven analyses methods such as independent component analyses (ICA) have been shown in earlier experiments (Gramann et al., 2010; Gwin et al. 2010, 2011; Makeig et al., 2009) using mobile brain imaging methods (MoBI) developed at the Swartz Center for Computational Neuroscience, UCSD to successfully dissociate brain activity accompanying spatial cognitive process from non-brain related electrical activity (e.g., neck muscle and eye movement activity). [x,xi]

Our initial recordings using MoBI in the StarCave revealed a wide-spread cortical network to be involved in navigation from a first person perspective. The virtual reality experimental setting comprised completely ambiguous corridors with no visible spatial cues as well as hallways with a number of salient objects that could be used as landmarks to guide orientation within the same building. Brain dynamics revealed a wide-spread cortical network to be active during both ambiguous and non-ambiguous surroundings including occipital, occipito-temporal, parietal, and frontal brain regions. In particular, the parietal cortex, an area that subserves the integration of multisensory information embedded in distinct spatial reference frames, revealed differences between oriented and disoriented trials (**Figure 5**).

The differences were most pronounced for the lower alpha (8-10Hz) and the theta band (4-8 Hz). The desynchronization of alpha activity in or near the parietal cortex during orientation in ambiguous environments indexes increased activity of this cortical area underlying cognitive processing. As compared to orientation in unambiguous environments, in ambiguous environments participants have to search for any information that might possibly inform on their current location and orientation with respect to the overall structure of the environment. This increased demand for attention and integration of multisensory information received during orienting movements, i.e., vestibular and kinesthetic information, reflects the cognitive state of being disoriented in a featureless environment. [xii]

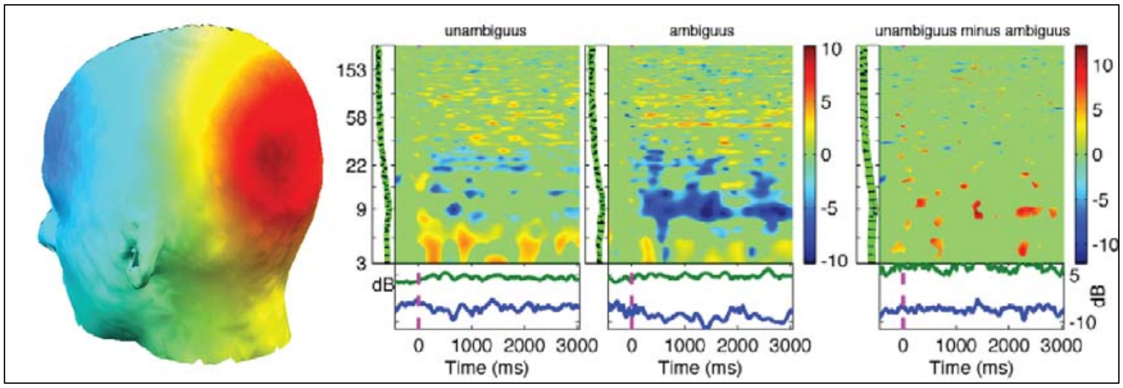

Figure 5: A 256 electrode array reveals different EEG frequency responses in unambiguous spaces with no visual cues compared to ambiguous virtual reality spaces devoid of wayfinding cues. [xii]

These first very promising results demonstrate the potential of combining the StarCAVE with neuroimaging methods such as MoBI to provide new insights into the neural foundation of spatial cognitive processing during active exploratory behavior. [vi]

7. APPLICATION TO HEALTHCARE FACILITY DESIGN

The impact of being lost in a healthcare setting may be of great consequence. In a 2004 study of a 300 bed hospital, it was revealed that staff spent 4500 hours a year helping patients and visitors find their way, associated with lost staff time equivalent to US$220,000 a year. [xiii] Serious adverse events may result from delay in the provision of care, increased stress levels, or unintended transmission of infection from lost patients.

Although a great deal is spent each year on wayfinding signage systems, many are of limited value. Individual features of design may be assessed in virtual settings to understand their specific influences on memory and wayfinding performance (**Figure 6**). The medical and psychological condition of users may affect the rate of learning, persistence of memory, and ability to understand wayfinding cues. In addition, navigation memory strategies are susceptible to stress and fatigue, and thus likely to influence visitors and staff as well as patients. A greater understanding of the cognitive processes used in memory formation, retrieval and successful navigation holds the potential to inform designers about the salient characteristics of environments that support effective spatial cognition.

Immersive virtual reality studies synchronized with cortical EEG recordings offer the opportunity to test healthcare wayfinding systems based on our knowledge of cognitive navigation strategies in both healthy and patient populations, with 3D EOG used to confirm visual attention to design cues proposed.

Figure 6: A first-person perspective in an immersive CAVE representation of patient rooms reveals sight-lines between clinical and patient avatars and provides a test environment for optimizing design features that may reduce serious adverse events. Two adjacent rooms are shown here from the point of view of an external nurses' station, allowing visual and auditory monitoring of both rooms.

8. CONCLUSIONS: NEW APPROACHES TO STUDY SPATIAL COGNITION IN ARCHITECTURAL DESIGN

A number of studies demonstrate enhancement of performance and reaction time when multiple sensory modalities are used. With the combination of CAVE-CAD^{TM} and SoniCAVE^{TM} as well as neurological and physiological monitoring described here (**Figure 7**), a more realistic range of audiovisual stimuli and architectural features will be under the control of the designer, who can test the response to alternatives and modifications in real time. The design team and their clients can thus request and immediately experience the consequences of design modifications. Further, researchers can rapidly create and test new designs and environments to reveal effective wayfinding cues and cognitive navigation strategies for built settings that range from small to large places. The creation of this virtual immersion design laboratory supports our ongoing studies to explore the strategies used in spatial cognition.

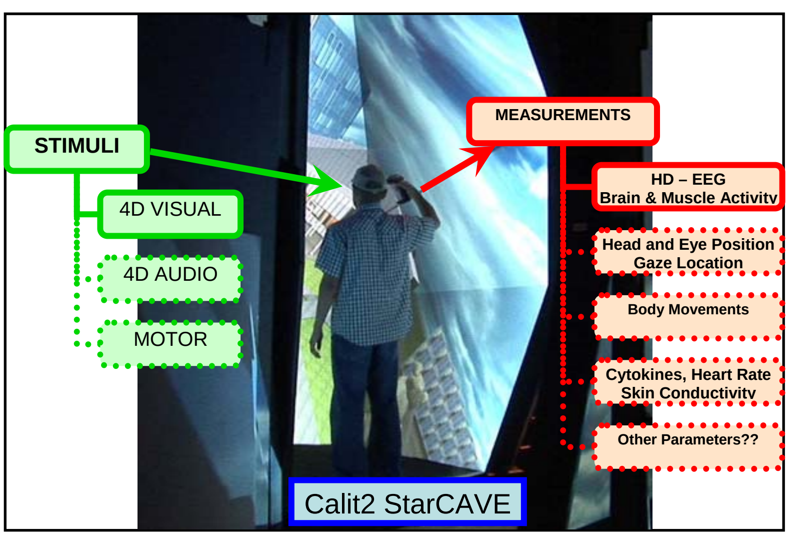

Figure 7. Summary of current and planned features of our approach to audiovisual VR instrumentation and human response monitoring for testing architectural designs. Dotted lines indicate features currently under implementation or development.

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