An Instrumented Office Chair with a Steerable Projector for Personal Spatial Augmented Reality

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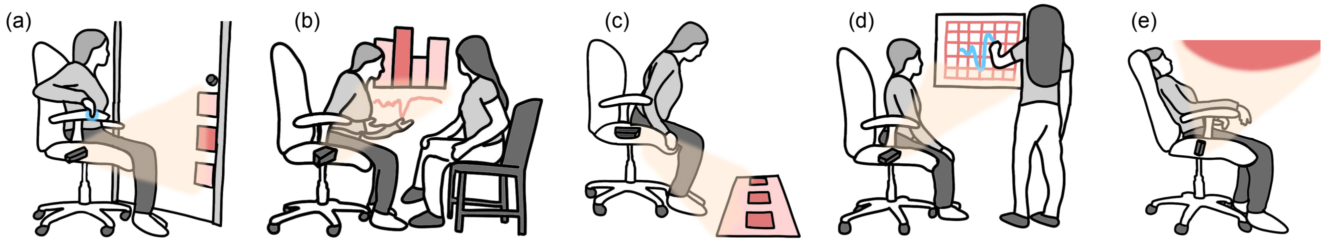

Figure 1: Example usage: (a) notifications on a door; (b) content on a wall during a meeting; (c) interacting with content on floor; (d) using a reference image to enhance whiteboard; (e) promoting work breaks with an ambient ceiling projection.

ABSTRACT

We contribute the idea of an instrumented office chair as a platform for spatial augmented reality (SAR). Seated activities are tracked through chair position, back tilt, rotation, surface sensors, and touches along the armrest. A depth camera tracks chair position using simultaneous localization and mapping and a servo-actuated pan-tilt projector mounted on the side of the chair displays content for applications. Eleven demonstration scenarios explore usage possibilities and an online survey gathers feedback. Many respondents perceive the concept as useful and comfortable, validating it as a promising direction for personal portable SAR.

CCS CONCEPTS

• **Human-centered computing → Interaction techniques**.

KEYWORDS

spatial augmented reality; contextual interfaces; augmented chairs

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1 INTRODUCTION

Many forms of augmented reality (AR) register content in 3D [3], but the term "spatial augmented reality" (SAR) has come to represent a specific type of AR that renders content on existing environment surfaces using projection mapping [50]. This enables shareable public content and even peripheral *personal* content when located near a user (e.g., [7, 31, 61]). Typical SAR systems use wall- or ceiling-mounted projectors which are expensive and difficult to move, and they require complex calibration [28], hindering deployability and portability. Steerable environment projectors enable more surfaces to be reached with less equipment [45, 60], but they are still anchored, so they are susceptible to projection occlusion and cannot support simultaneous SAR content in different locations.

Self-contained "portable" SAR systems mitigate some of these issues while enabling personal SAR experiences. Handheld projectors enable expressive input [7, 49], but can be fatiguing. Wearable SAR projectors [21, 24, 40] can be cumbersome and may not be socially-acceptable. Projectors mounted on small objects like laptops [31], and movable projector-camera units [46, 56, 61], can create portable SAR systems that are easy to deploy, personal, and socially-acceptable. However, attaching projectors, cameras, and batteries to small objects like laptops make them more bulky. Previous object-mounted projectors and projector-camera units are not steerable, limiting their flexibility and surface range.

Furniture is a class of objects that also could be instrumented for portable SAR. For example, Lightform envisioned steerable projectors integrated into lamps [27]. Wheeled task chairs, in particular, are ubiquitous in offices, and are essential for activities such as working, meeting, and even relaxing. Previous work shows people move chairs into specific formations for collaborative work [36, 55] and frequently perform chair movements like turning to face a public display or another person [38]. Office task chairs are easy to roll between rooms, and have adjustable and movable components with high degrees of freedom that can be mapped to explicit and implicit user interactions [47, 57]. While chairs have been augmented to track seated postures (e.g., [5, 11, 16, 51]), and rotations (e.g., [12, 25, 48]) and to aid in deictic pointing [2, 41], they have not been used as a platform for ubiquitous computing. We believe that the size and mobility afforded by office chairs makes them suitable for portable and personal SAR which can be controlled by sensing adjustments and chair movements as implicit and explicit input.

We contribute the idea of using an office chair as a standalone input and output device (Figure 1). A chair is instrumented to track its position, back tilt, and rotation. Force-sensitive resistors capture seated posture, and capacitive sensors enable touch input along the armrest edges. A steerable projector mounted on the side of the chair rotates to place content on different surfaces, which is achieved using a virtual representation of the room captured by the chair. Eleven demonstration applications are presented using our proof-of-concept system and results from a survey show that chair-enabled SAR was well-understood, perceived as comfortable, and many applications were perceived to be useful. Our work serves as a foundation for future research on portable, chair-enabled SAR.

2 BACKGROUND AND RELATED WORK

Our work is related to portable SAR and instrumented chairs.

Portable SAR Systems. SAR systems typically rely on multiple cameras and projectors installed into an environment at fixed positions, which can be difficult to setup, calibrate, and move to new locations. Large steerable projectors, like Everywhere Displays [45] and Beamatron [60], enable more surfaces to be reached with a single projector, but are still anchored to one room. Self-contained, or "portable" systems can mitigate these issues. Larger portable systems allow users to place a projector on different surfaces in the environment. Lightform [27] creates portable and steerable projector-camera units that look like desk and floor lamps, so they can blend into the environment. ED-Lite [46, 56] and PlayAnywhere [61] are portable projection and sensing systems that turn nearby objects, such as walls, shelves, and tables, into interactive touch displays, but they are not steerable.

Handheld projectors, like RFIG Lamp [49] and Cao and Balakrishnan's projector system [7], allow users to aim the projector at surfaces to discover and interact with interfaces. Handheld projectors offer an expressive and diverse set of user interactions but may be fatiguing to use and there is limited opportunity for implicit interactions, since the user explicitly controls the projection [53].

Wearable SAR systems are more versatile as they enable implicit and explicit input. Wear Ur World [40] and OmniTouch [21] are two examples that use body-mounted projectors and cameras to turn any surface in the environment into a display. Explicit input uses mid-air gestures and touch input, while implicit input is accomplished by detecting natural gestures, like checking the time, and augmenting objects when held, like newspapers. However, body-mounted cameras may not be socially-acceptable due to privacy concerns, especially when used in public [35].

Projectors mounted to objects may provide a good balance between ease of use, social acceptability, and range of user input. Bonfire [31] uses laptop-mounted projectors to place virtual content on the top of a table. Laptop-mounted cameras track finger touches for explicit input, and detect objects placed within the projected view for implicit input.

Steerable projectors can also be mounted to objects. Knierim et al. [34] attach a projector to a quadcopter. A servo actuated mirror controls the angle of projection, effectively creating a levitating steerable projector. Hartmann et al. [22] augment an AR HMD with a steerable projector using a servo-actuated pan-tilt head, which supports sharing the user's AR view with others on nearby surfaces.

In short, previous work has focused on enabling portable SAR using projectors that are manually placed on different surfaces, held, worn, or mounted to objects. Object-mounted projectors provide a balance between range of user input, social acceptability, and ease of use, but few works have used steerable projectors. A chair-mounted steerable projector is a new way to enable portable SAR.

Instrumented Chairs. While many chairs have been instrumented to detect posture (e.g., [5, 11, 51]), few have used other chair degrees of freedom for input. Some systems focus on new interactions enabled by chairs with uncommon adjustments and movements. Probst et al. [48] explore how office chairs with bendable cylinders could integrate into different desktop computing tasks, like navigating backward and forward in a web browser. ChairIO [4] uses seat tilt, rotation, and seat bounce to explicitly control virtual environments and trigger mouse events. Others have used more common chair degrees of freedom. ChairMouse [12] uses implicit rotation to move a computer cursor across multiple external monitors, implemented using a mouse attached under the seat. VRChairRacer [59] uses an office chair as input for a racing game by mapping back tilt to virtual acceleration and rotation to steering direction. Some chairs have been instrumented with fabric controllers, allowing users to fold and touch fabric to control smart devices [6, 16]. Overall, previous work using chairs as input devices has focused on explicit interactions. There are many other implicit interactions and applications that could be enhanced, especially those outside traditional desktop computing environments.

Chairs can also function as meaningful output devices when paired with lights, haptic actuators, and speakers. BodyPods [43] are posture-sensing seats that light up in different colours to share physical presence with physically remote loved ones. Zheng and Morrell [63] instrument a chair with FSRs and vibrotactile actuators to detect and correct seated posture. The Emoti-Chair [33] turns sounds into tactile vibrations using voice coils, providing a way for those with hearing impairments to experience music. Aarnio [57] uses resistive force output to limit explicit chair input, like rotation, tilt, and movement. The resistance can relay information, such as the time until the next meeting, or enhance seated VR applications. Haptic ChairIO [15] uses visuals, audio, wind, and floor vibrations to enhance seated VR. Servo-controlled fans and vibration actuators around the chair mimic wind direction and rumbling terrain synchronized with the virtual reality environment, even as the chair rotates. Forlizzi et al. [16] explore how lounge chairs can become robotic assistants for the elderly, allowing them to remain independent in their homes. Their SenseChair prototype uses pressure sensors to track activity, and lights, vibrations, and audio remind the user to stretch, mitigate restless behaviour, and relay community information. To summarize, chairs have primarily used haptic actuators, lights, and sound for output. We are not aware of any work that uses projected output with a chair.

Asai et al. [2] augment a wheelchair with a steerable projector to help users perform deictic pointing. An arm or arrow is projected onto a nearby wall and manually controlled using a tablet, or with head movements in a later version [41]. Our work considers a wider range of chair inputs, explicit and implicit interactions, and covers a broad range of use cases for general purpose ubiquitous computing.

3 DESIGN GUIDELINES

We synthesize observations from related work to create a series of design guidelines for chair-enabled SAR using an office chair.

Prioritize Peripheral Displays. Office chairs are typically used when working at a desk and desktop activity should remain in the foreground. As such, chair-based SAR should prioritize displaying information in the background, especially when the chair is facing a desk. This demands less of the person's attention while allowing them to process information in the background [26]. However, different projection angles are ideal for different tasks and contexts of use [10]. Switching between foreground and background projections may be appropriate in certain contexts, like for displaying notifications. Layout management systems that find optimal surfaces for content [13] may be especially important, and prior work shows that people can memorize the spatial layout of different projection displays, even when they are hidden from view [9].

Consider Input and Output Holistically. Adjustments and movements of office chairs can support both explicit and implicit input. *Explicit input* refers to intentional interactions performed by someone whereas *implicit input* utilizes context to interpret interactions [53]. Ultimately, the person's intent classifies input as explicit or implicit and any degree of freedom can be used for both. However, some chair interactions may be more strongly associated with either implicit or explicit input [57].

As discussed in Section 2, previous chair interfaces have focused on interacting with content viewed at a fixed location. This is best done with explicit input since interacting with a GUI is intentional. But with chair-enabled SAR, content can be placed on any surface in the environment, so user input is also needed to select projection surfaces. This is compatible with explicit and implicit input. A person could explicitly swivel their chair to face specific surfaces they want to use for SAR; or content that otherwise would not have been seen could be shown on a convenient surface when they implicitly change postures. Although explicit input can be used to select projection surfaces and control content, some chair interactions, like rotating, may be better suited for selecting projection surfaces than interacting with SAR GUIs [47].

Leverage Context. SAR is a more pervasive form of AR, and Grubert et al. [20] note that the main use for such AR should be context-driven. There are many forms of physical and digital contexts (e.g., [20, 54]) that can be leveraged to show SAR that is relevant to the person on surfaces associated with the content. Previous work on proximate selection shows that placing SAR closer to the user may be easier to use [52], so context from the environment can also be used to select the best projection surfaces that are nearby.

Previous work also shows that contextual information can be inferred from chair location and surrounding objects [25, 38, 55]. For example, when the chair is facing a workbench, the usage context is likely working with tools, but when arranged in a circle with other chairs, the context is likely a meeting or collaborative work. Implicit seated interactions can reveal information about a person's current state: people slump or fidget when frustrated or bored and lean forward when engaged in a task [32], or are interested in a subject [58]. Combining these contextual cues could lead to even more compelling user experiences. For example, if someone leans back in their chair, they may be stressed or taking a short work break. In that case, placing a deep-breathing exercise on the ceiling may make sense, since the person is looking up and leaning back.

Focus on Personal Use. Chairs are ubiquitous and essential for many daily activities. People usually have a preferred, "primary chair" that they interact with throughout the day [19]. This primary chair often becomes a "command centre" and is conveniently placed in a room so most activities can take place around it [16], and objects needed throughout the day are placed nearby [25]. Prior work also shows that office workers spend at least 6 to 9 hours per day on average sitting [16, 39], so it is highly likely that one's primary chair is their personal office chair. The idea of primary chairs suggests that chair-enabled SAR interfaces may be most suitable for personal use. Chairs serving as personal command centres further motivates chair-based SAR; a wide range of information can be shown as needed, while anchored to one, central, user-focused location.

Office chairs are often located in shared work environments. Like traditional SAR, shared projected views can improve collaboration, and the portability of chairs could lead to more ad hoc SAR. In open-concept work environments, it is common for colleagues to roll their chairs to a colleague's desk to work on a task together [36, 55], and chair-enabled SAR could enhance these unplanned work activities. Maintaining the chair user's privacy is also important, especially if they use the chair as an information command centre. People could interact with the chair to hide content, like explicitly shifting their weight to discreetly hide private content.

We envision a future in which chairs can use context to automatically place personal content in the periphery that can be interacted with and revealed using chair-based implicit and explicit input. We realize this idea through our prototype system and applications.

4 PROOF-OF-CONCEPT SYSTEM

Our proof-of-concept system is composed of a standard office chair outfitted with sensors and a steerable projector (Figure 2), and a software toolkit in Unity3D for creating applications (Figure 3). Our aim is to exploit multiple degrees of freedom of the chair to be used for explicit and implicit input. Office chairs also have physical characteristics that are desirable for use as a portable SAR system. Unlike small objects, chairs can handle a significant amount of weight and there is usually substantial free space underneath the seat. This is ideal, as circuit boards and power sources can be large in size or heavy. Office chairs have a well-defined front, making it clear where a projector and camera should face. Armrests have space for mounting a front-facing camera and a projector in a way that mitigates possible privacy concerns. Office chairs typically exist in environments with excellent wireless connectivity, enabling the creation of a completely wireless system. When network conditions are poor, chairs can be connected to personal computers, which are usually nearby in office environments.

Our proof-of-concept chair is a self-contained, fully portable system. A custom printed circuit board connects all sensors, servos, and actuators to an Arduino Mega using purpose-made connectors (Figure 2c). The Arduino and an Intel RealSense D435i RGBD camera are connected to a Raspberry Pi 4 through USB ports (Figure 2d). The Arduino streams raw sensor data to a serial port on the Pi at 115200 baud. The Pi is powered by a standard 5V, 27000mAh power bank (Figure 2g). The Pi is also connected to a local wireless network, and streams sensor data and images to a Windows 10 i7-7820X desktop computer using a custom Google gRPC server. The chair can be plugged directly into the desktop computer's USB port for testing or if full, untethered usage is not required. A custom, dynamic-linked library installed as a Unity plugin acts as a client to the gRPC server to retrieve images and sensor data. Data obtained from the chair is used to locate its position, rotation, and tilt; detect the posture of the person seated in the chair; and detect touches along the armrest edges. This data is visualized using the software toolkit (Figure 3). In addition, the toolkit is used to calibrate the room and customize SAR views.

4.1 Camera Pose Estimation

The Intel RealSense D435i RGBD camera is mounted underneath the right armrest (Figure 2e). The camera is mounted 14.5 cm away from the armrest and has a slight downward angle. We tried orienting the camera to face the floor, but this did not provide enough feature points; placing the camera on the side of the armrest strikes the best balance between providing a good view of the environment and ensuring that the privacy of the seated person and other people in the environment is maintained. The camera automatically captures RGB and depth images at 30 FPS. Rectified depth images and UV maps are created using the RealSense API (all 640 × 480px). These images are used to sense the chair's position and rotation, and create 3D meshes of the room.

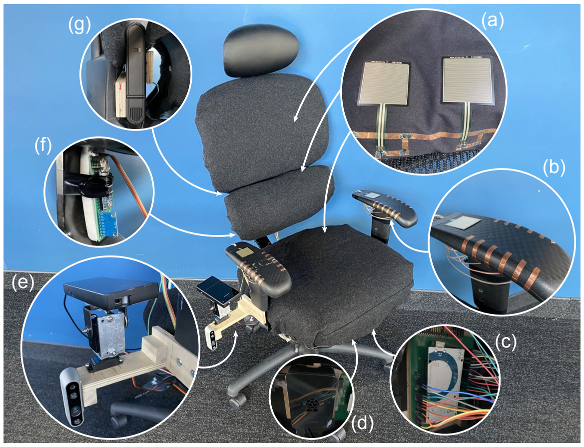

Figure 2: Chair sensors and projector actuation: (a) FSRs on back and seat for posture sensing; (b) copper tape on armrest edges for touch input; (c) circuit board and Arduino under seat; (d) Raspberry Pi under seat; (e) custom mount under right armrest to support depth camera and steerable pico projector; (f) IMU on back tracks tilt; (g) battery bank.

To track the chair's position and rotation, we use Mur-Artal and Tardós' open-source ORB-SLAM2 simultaneous localization and mapping library [42]. Relative movement is captured, but our software toolkit logs the last position of the chair upon exiting the program so an absolute position can be saved. If the chair is moved when the program is not running, a single ArUco marker [18] placed underneath the user's desk is used to re-position the virtual chair within the reconstructed environment. The coordinate systems of ORB-SLAM2 and Unity do not align, as the y-axis of ORB-SLAM2 is inverted and all images were rotated 90° due to the mount placement, so manual tuning was done to align the two coordinate systems. The 1€ filter [8] is used to remove noise from ORB-SLAM2's transformation matrix.

4.2 Posture and Touch Sensing

The Arduino Mega is placed underneath the chair (Figure 2c). It is used to track the chair's back tilt, seated posture, and touch input along the armrests. The pitch values of an inertial measurement unit (MPU 6050) attached to the chair's backrest (Figure 2f) are used to measure the back tilt angle in degrees (163° in a neutral position to 143° when leaning back).

Posture. Posture is detected using force-sensitive resistors (FSRs) placed on six different parts of the chair: the upper back, lower back, seat, and the two armrests. Previous work has shown that using FSRs, electrodes, and other pressure sensors (e.g., [5, 16, 51, 63]) is an effective way to accurately sense seated posture. Each FSR (FSR406 from Interlink Electronics) has a sensing area of 38 × 38mm and a minimum actuation force of 0.1N and a sensitivity of 10N. The FSRs change their resistance proportionally to the applied force, so a voltage divider circuit interfaced with the analog ports of the microcontroller is used to sense pressure values. For the seat and upper and lower back, the FSRs are affixed to thin, black, cotton fabric and connected using copper tape (Figure 2a). This effectively creates three pressure sensing 'mats' that are then placed on the chair. The upper back, lower back, and seat have 5 FSRs each. A single FSR is placed on each armrest. By combining the pressure values derived from each part of the chair, the system can estimate the overall posture of the person when seated using different heuristic rules and thresholds (e.g., if one side of the seat has more pressure than the other, the user is likely sitting with their legs crossed). The thresholds were determined through initial tests and can easily be tuned for specific users.

Touch Input. The edges of the armrests are instrumented with touch sensing capabilities. We considered using other areas of the chair for explicit touch input, like the base and the area under the seat, but felt the armrests were better due to surface availability and size. Previous work explored touching the side of armrests using fabric controllers [6], but the side of the right armrest is unavailable due to the mount, which may disadvantage right-handed people. The top surface of armrests have also been instrumented with click wheels [16], but previous work also shows that people naturally place their arms on this area [57], which could cause accidental

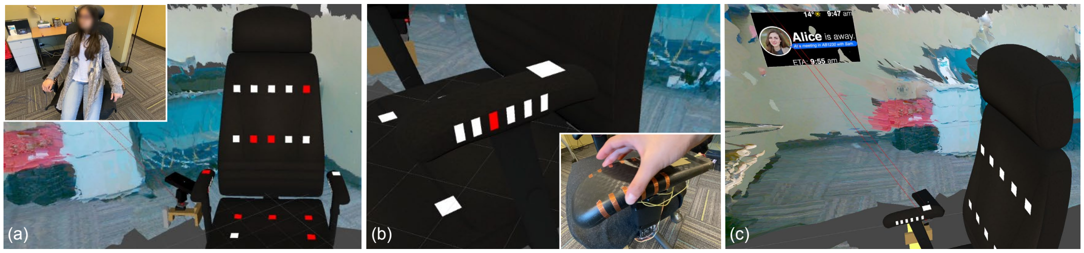

Figure 3: Chair state visualization: (a) virtual chair representation in Unity showing active sensors; (b) chair inputs, like armrest touch, can be mapped to application commands; (c) application displays placed within reconstructed environment.

input. Instrumenting the edge is ideal, as it is close to the the user's hands but away from the area they usually place their arms on.

Twelve parallel bands of 6mm wide copper tape are wrapped around the outer and inner edges of the right and left armrests (Figure 2b). A MPR121 capacitive controller board is connected to each strip of copper tape. This enables low resolution touch input through swipes and similar approaches have been used to detect touch input on the side of mobile phones [62]. Individual edges can be swiped independently, or both can be swiped at once. Restricting input to swipes along the armrest edges avoids unintentional input when gripping to get up or move the chair, and a designer can tune input mappings in the toolkit if there are false positives.

4.3 Projector Output

Similar to the AAR system [22], a pico projector is mounted to a pan-tilt mechanism using two 180° high-torque servo motors (DS3235, 35kg torque). This is mounted on the right-side of the chair, 8cm below from the armrest bracket, and 10cm out from the chair (Figure 2e). The projector faces forward when the top "tilt" servo is at 70° and the bottom "pan" servo at 130°. To prevent the projector from contacting the mount or chair, the tilt servo range is adjusted based on pan servo position: $[0°, 170°]$ when panning forward ($\approx 130°$); $[0°, 100°]$ when panning away from the chair ($\geq 170°$); and $[40°, 100°]$ when panning towards the camera ($\leq 30°$). Even when the chair is at a desk, the projector can display on the floor, ceiling, walls, table edge, and objects to the right such as a cabinet (Figure 4). We considered mounting the projector above the headrest to project on tabletops, but this is less stable, more more likely to shine bright light into people's eyes, and such a conspicuous position would really change the look and feel of the chair which could affect user impressions.

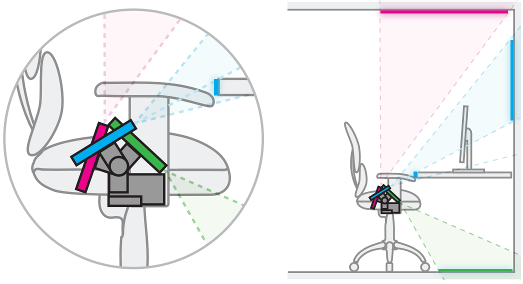

Figure 4: Reachable projection surfaces at a desk with pan servo forward: (pink) ceiling near 0° tilt; (blue) wall behind desk and desk edge at 50°; (green) floor under desk at 100°.

The projector (Cellulon picobit) uses laser optics at 1280 × 720 resolution and 63 ANSI lumens. It features a built-in battery and the ability to display a video source over Miracast, where the projector is treated as a wireless display to the main computer. This simplifies our hardware system. The projected image is somewhat dim in a bright room, but high contrast imagery can improve readability and laser optics create a very large depth of focus so the projection appears reasonably sharp at different distances.

We create a virtual representation of the real projector in Unity using the projector intrinsics and dimensions for projection mapping. The virtual projector position is tracked using matrices obtained by ORB-SLAM2, offset by the distance between the camera and the projector in the real world. This offset is set manually, but could be determined automatically using a method similar to the camera to projector calibration used in AAR.

4.4 Software Toolkit

A corresponding software toolkit for Unity (Figure 3) is used to visualize the chair state, create applications, and reconstruct rooms.[1] For testing and debugging, a virtual representation of the physical chair visualizes which sensors are being used (Figure 3a). The virtual chair position and rotation is synced to the physical chair. The toolkit is general purpose and acts as a template Unity project that users can build on to create their own chair-based SAR experiences.

Raw data from the chair sensors is processed to create an interaction vocabulary of 33 different chair- and context-based interactions. The interactions consist of: digital contexts, like elapsed time; applying pressure on individual regions of the chair, like the right and left armrests; different postures that make use of multiple regions of the chair, like leaning forward, backward, left or right; whether the chair is close to or facing specific areas of the room; and touch events along two armrests, using the outer or inner edges in upward and downward motions (Figure 3b). Interactions defined in the interaction vocabulary can be layered or used individually to control the visibility of the projected content, and to interact with the content itself, like navigating to and selecting menu items.

Placing Content. Surface-mapped virtual displays are manually created in Unity and placed on various surfaces within the reconstructed room (Figure 3c). Future work could explore ways to automatically place displays in ideal locations [14, 17]. Once the system decides that content should become visible to the user (which depends on the specific application), the virtual projector will move to point toward that virtual display. The virtual movement is used to

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[1] Source code available at https://github.com/exii-uw/sar-chair

Hey Alice,
Are we still good for 10am? I wanted to ask you about the upcoming presentation but we might need a little more time.
Hope this works for you.
- Bob

Figure 5: Notifications: (a) a summary view on a wall rotates to the floor when the chair is moved away from the desk; (b) ambient light highlights different objects in the room; (c) "be back soon" messages for others to view appear on a nearby wall; (d) a notification tray appears on a door and individual notifications can be viewed by rotating the chair to face a larger surface.

calculate the new angle the two servos should move to. The servos will only move if the chair is stationary (acceleration < 0.02 m/s^2) to avoid unnecessary movements.

Room Reconstruction. When first setting up the chair in a new environment, the user performs a room reconstruction to capture the 3D geometry of furniture and surfaces. Standing behind the chair, they push it to different parts of the room to capture its geometry from different angles. A single 3D mesh, representing the camera's current view, is generated using the colour, depth, and UV images, as well as the camera extrinsics. Multiple meshes are combined to create a full representation of a single room. Depending on the size of the room, the reconstruction could take 5 to 20 minutes. After reconstruction, the meshes are automatically saved to disk. The current system loads different rooms manually, but this could be automated by finding the room mesh with the highest correspondence using temporal smoothing.

5 DEMONSTRATION APPLICATIONS

Eleven applications demonstrate the potential of chair-enabled SAR. These serve as a form an evaluation by showing how technical components work together to validate the overall idea [37] and as source material for a survey described later to gain insights into people's impressions of chair-enabled SAR. Not all applications are novel, our goal is to also show how applications enabled by large systems, like Beamatron [60], are achievable with smaller portable chair-based SAR. The applications also explore a wide range of surfaces and chair interactions with an emphasis on contextual uses for portable SAR, rather than focusing on what might be most useful or suitable for everyday use. All demonstrations were implemented using the Unity3D software toolkit and proof-of-concept system described earlier. The system does not have general purpose context-sensing or automatic projection surface selection, nor is it integrated into real applications: predetermined locations and mock-up content are used. The associated video has full demos.

5.1 Notifications

Day in a Glance — A summary of the user's day, including their upcoming calendar events and pending todos, is projected on a wall above the user's computer (Figure 5a). When the chair is pulled away from their desk, the projector rotates to move the summary to the floor. The user, standing behind the chair, can view this information before sitting down. The projector hides the summary view when the user sits down and pulls their chair toward their desk. The implicit interaction of moving the chair is used to infer where the user is likely facing, so the content can remain in sight.

Ambient Notifications — Nearby objects can serve as memory aids [44]. The projector can automatically rotate to spotlight different objects in the environment to remind the user of different things. For example, a small, pink circle can appear on a calendar or a plant (Figure 5b). The subtle visualization allows information to remain in the periphery, but transitioning between background and foreground displays can ensure that important information, like upcoming deadlines or reminders, are shown to the user.

Be Back Soon — When the user stands up from the chair and pushes it away from their desk, a sign showing the user's name, photo, and a "be back soon" message appears on a nearby wall (Figure 5c). This sign can notify others who are looking for the user that they are temporarily away from their desk, and their estimated return time. The implicit input of standing and moving the chair away from the desk is paired with digital contexts, like a calendar.

Notification Tray — A notification tray showing the user's emails, social media feed, calendar events, and weather alerts, is projected along a nearby door (Figure 5d). The user can navigate to specific notifications by swiping along the inner and outer edges of the armrest. Applying pressure on the left armrest shows a short, one-sentence summary of the notification. Applying pressure on the right armrest causes the notification tray to reappear. If the user rotates the chair to face a nearby wall, the projector rotates to face it and displays the full notification. The user can discreetly hide

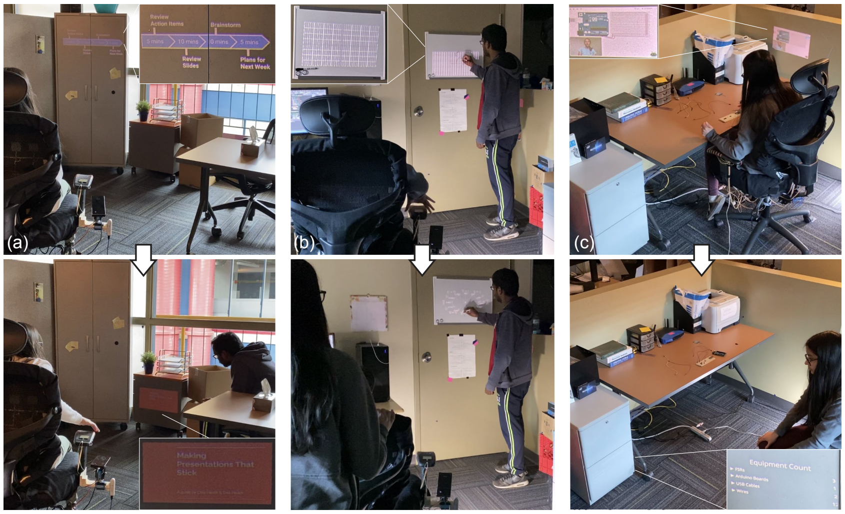

Figure 6: Work-Related Tasks: (a) an agenda is shown on cabinet and leaning forward shows slides on a set of drawers; (b) drawing surfaces are augmented with supporting images that can be changed by swiping the armrest or tilting the back; (c) tutorial videos are shown on a wall and can be paused/played using the armrests, facing a set of drawers shows a list of supplies.

their notifications by crossing their legs. The notification tray is a personal display that requires explicit input, but discreet commands are used to preserve privacy in public environments.

5.2 Enhancing Work-Related Tasks

Enhancing a Meeting — During a meeting, the projector rotates to place a meeting agenda on a nearby cabinet (Figure 6a). When people are engaged in a task, they usually lean forward [32, 58]. The chair uses this implicit input to show content the user may want to focus on, such as a slideshow. If the user leans forward during the meeting, the projector automatically rotates down to place slides on a convenient surface, like a set of drawers. The user can move to next and previous slides by swiping along the outer edge of the right armrest. When the user leans back to a neutral seated posture, the projector rotates back up to the cabinet and shows the meeting agenda once again. The implicit interaction of leaning forward is used to show information in the moment, that may have otherwise not been seen.

Augmenting Physical Drawing Surfaces — Brainstorming sessions between colleagues often involve drawing on physical surfaces, like a whiteboard. To augment sketching, if the chair is facing a whiteboard, supporting images, like grid paper and circuit diagrams, are shown on the whiteboard (Figure 6b). The seated user can switch between different supporting images by swiping up and down along the right armrest. If the user is standing behind the chair, they can pull the back toward them to navigate to the next supporting image. Impromptu meetings can leverage such ad hoc SAR to improve collaboration when both sitting and standing.

Supporting Physical Tasks — People often associate certain physical tasks with areas and objects within a room, for example, a workbench to use fabrication tools. When the chair moves toward a specialized work area, the projector moves to display content related to specific tasks, like video tutorials, on a nearby wall (Figure 6c). Applying pressure to the left and right armrests triggers the video to pause and play. When the user moves the chair away from the office workbench and faces a nearby set of drawers, the projector automatically moves down to show an inventory of equipment on the drawers. Explicit input is used for content control while implicitly moving to face the cabinet is used for surface selection.

5.3 Encouraging Work Breaks and Relaxation

"20-20-20" Rule — This is a recommended guideline to reduce eye strain by varying the distance and position of text while reading [1]. To encourage users to follow this, the chair can smoothly move content from a desktop to surfaces further away (Figure 7a). For example, the user can rotate their chair, and the website they were looking at on their computer is projected on a wall. The user can scroll through the content using the outer edge of the right armrest. After some time, the projector automatically rotates to another wall placed further away, encouraging the user to continue reading from a distance. Different digital contexts, like an article and time spent reading, are paired with physical contexts, like nearby objects and their distance from the user, using the chair.

Deep-Breathing Exercises — If the user leans back, as though relaxing or thinking, the projector automatically rotates to place a deep-breathing exercise on the ceiling. A visualization with text encourages a brief moment of relaxation and meditation while the user is leaning back (Figure 7b). The deep-breathing exercise stops once the user returns to a neutral seated position. Implicitly leaning back is used to infer the person's emotion or mental state, which is used to show content of interest.

Mood Lighting for Video Games — Ambient lights are projected above the user's monitor as they play a video game [29] (Figure 7c). The lights become red and green as the player loses and gains health in-game. The chair pairs relevant digital and physical contexts.

Games — Games can be expanded to larger surfaces, like the floor or a nearby wall. For example, inspired by large, 'life-sized' chess boards, we create a multiplayer chess game. A chess board

Figure 7: Relaxation: (a) articles on a computer appear on surfaces further away; (b) leaning back triggers deep-breathing exercises on the ceiling; (c) mood lighting for video games appears above a monitor; (d) a large chess board shown on the floor.

is displayed on the floor (Figure 7d). One or two users can play by moving pieces on their mobile phones. The projected board updates in real-time, providing a frame of reference for the two players as well as other observers in public locations. The chair creates a frame of reference for multiple players, and shows how other input devices can be used when 1D touch input is insufficient.

6 SURVEY

We conducted a survey to understand existing habits with chairs and use cases for chair-enabled SAR.[2] A survey enabled a broad set of respondents and conformed to our institution's restrictions for in-person research due to the COVID-19 pandemic. It was disseminated online through social media and to our institution's graduate student mailing list. Respondents typically spent 25 minutes and they could opt into a prize draw for 1 of 10 $35 gift cards.

The survey was split into three parts. The first part used Likert questions to understand how people use office chairs, such as the frequency of movement, rotation, and specific postures. Respondents were told to consider their behaviours both before and during the COVID-19 pandemic. The second part gathered feedback about the demonstration applications described in the previous section. Respondents watched a short video of each demo (10s to 30s each), answering Likert questions after each one about how well they understood the applications, how useful it would be, and how comfortable it would make them feel. Demos were presented using the thematic groupings in Section 4.4. After watching all demos in a theme, respondents commented on chair-enabled SAR considering the whole thematic grouping in a free-form text box. Finally, the third part of the survey presented Likert questions on overall understanding, usefulness, and comfort, and free-form text for comments about other scenarios in which chair-enabled SAR could be used. All Likert questions used the same 5-item scale with standard anchors (see Figure 8 and Figure 9 legend).

6.1 Respondents

We received 41 responses in total (26 male, 15 female; ages 22-49, M=27.4, SD=5.7). All but 2 reported familiarity with AR: 16 were slightly familiar, 15 were moderately familiar, 7 were very familiar, and 1 was extremely familiar. Twelve had never interacted with AR before, 23 had tried it, and 6 use it sometimes or frequently.

6.2 Results

Chair Behaviours. The goal of this part of the survey is to learn which implicit and explicit behaviours are most common, and to validate the idea of using chair behaviours for interaction. We examine the central tendency of responses (Figure 8).

When considering frequent behaviours ("often" or "always" selected), small seated movements (75.6%), small posture changes while seated (68.3%), leaning forward, leaning backward (both 56.1%), a neutral seated posture (53.7%), and rotating while seated (51.2%) were frequent for majority of respondents. Placing arms or elbows on a chair's armrests while seated was also frequent (48.8%). However, moving a chair between rooms (2.4%) and tilting the seat back while standing (9.8%) are less likely to be frequent behaviours.

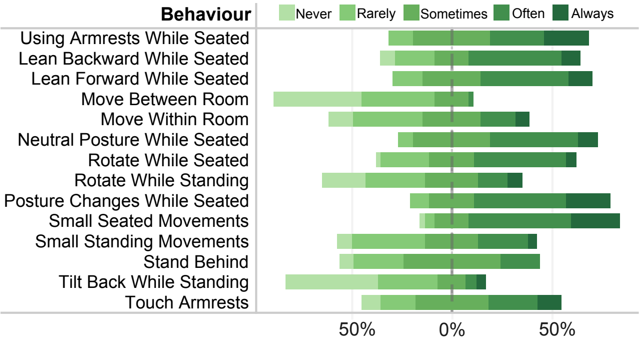

Figure 8: Chair behaviour Likert response frequency.

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[2] The full survey is available in the supplementary materials.

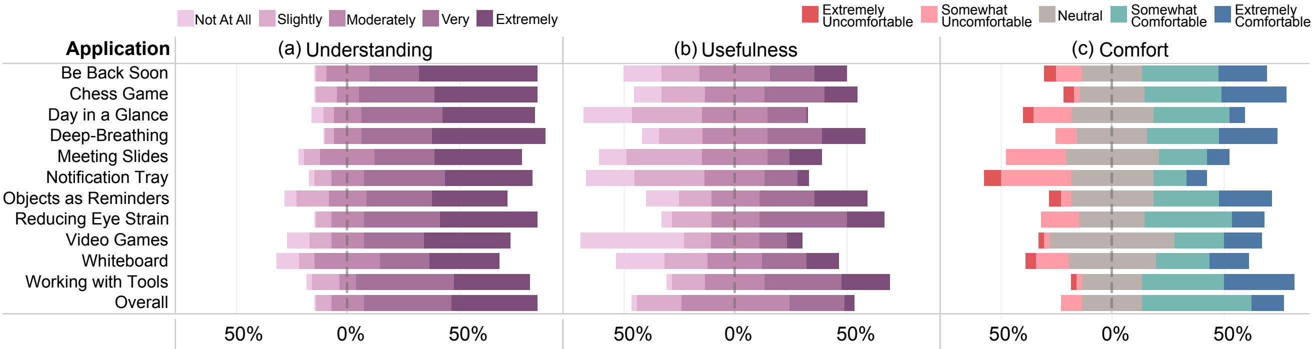

Figure 9: Demonstration video Likert response frequencies for: (a) understanding; (b) usefulness; and (c) comfort.

Moving a chair within a room (24.4%) is more likely to be a frequent behaviour than moving between rooms.

Understanding, Usefulness, and Comfort. The goal of this part of the survey is to better understand the ideal use cases for chair-enabled SAR. We examine the central tendency of responses for understanding, usefulness, and comfort (Figure 9).

Respondents indicated a high level of understanding ("very" or "extremely" selected) of chair-enabled SAR (78%; Figure 9a). There was a high level of understanding of all demonstration applications (all >50%), with deep-breathing exercises being the most well-understood (82.9%).

Respondents were split on the perceived usefulness of chair-enabled SAR, with 29.3% indicating high usefulness ("very" or "extremely" selected; Figure 9b). Almost half of the respondents indicated moderate usefulness (48.8%). When considering individual applications, it is clear some were perceived as more useful than others. Working with tools and reducing eye strain had high perceived usefulness for a majority of respondents (both 56.1%). Other useful applications include using objects as reminders (48.8%), deep-breathing exercises (43.9%), and a public chess game (41.5%). Meanwhile, a day in a glance (17.1%), a notification tray (19.5%), and ambient lighting for video games (19.5%) were less likely to be perceived as highly useful.

A majority of respondents (63.4%) indicated they would feel comfortable with chair-enabled SAR ("somewhat comfortable" or "extremely comfortable" selected; Figure 9c). When considering specific applications, most were perceived as comfortable. Working with tools (68.3%), a public chess game (63.4%), deep-breathing exercises (58.5%), the "be back soon" message (56.1%), using objects as reminders (53.7%), and reducing eye strain (53.7%) were all perceived as comfortable by a majority of respondents. The notification tray was less likely to be perceived as comfortable (24.4%).

6.3 Discussion

Overall, the survey results provide valuable insights into chair-enabled SAR. Results indicate that moving a chair between or within rooms are not frequent behaviours. However, there are still times when people will move a chair between rooms at least sometimes (19.5%), and moving within a room is something that happens at least sometimes for a majority of respondents (53.7%). This suggests that moving a chair in the context of portable SAR would not be too inconvenient or inconsistent with current behaviour. Infrequent chair behaviours, like tilting the seat back while standing, are good candidates for explicit input but designers need to be more mindful of frequent chair behaviours as they may be more strongly associated with implicit input.

The applications were well-understood and perceived as comfortable. However, the perceived usefulness was less decisive. This may be in part due to individual interests of the respondents (e.g., non-gamers seeing little value in augmenting video games). Detailed notifications (notification tray) were viewed less favourably, but less detailed notifications (using objects as reminders), supporting physical tasks (working with tools), and encouraging breaks (reducing eye strain, deep breathing exercises, chess game) were viewed more favourably. Free-form comments provide insight into ways chair-enabled SAR could be even more useful. Many respondents discussed general SAR factors like projector image quality, and lighting. We focus our discussion on comments related to the demonstration applications and chair-enabled SAR. We grouped the comments that discussed the demonstration applications and chair-enabled SAR into themes using inductive coding.

Privacy. Privacy was an important consideration, especially for displaying detailed notifications. While this application uses an explicit rotation to reveal the detailed view, some noted that *"not all people have the same postures/user experience with [chairs]"* [R15]. People who naturally fidget, for example, may have trouble distinguishing between explicit and implicit movements: *"it might be cumbersome to calibrate the display to turn on/off with specific movement (maybe you fidget a lot in your chair and want to turn the rotation sensitivity down)"* [R12]. As such, relying solely on chair input to preserve privacy may be inadequate. Other techniques, like modifying the display's level of abstraction [30], may be necessary as well.

One respondent noted that there was an intuitive mapping for leaning back in a chair to initiate deep-breathing exercises: *"it is easy to start and the lean-back gesture matches the purpose of [relaxation] well"* [R16]. However, another noted that given this strong mapping, a display would draw even more attention to the user when they are in a vulnerable mental state: *"my fears are about judgment and people having the information that I need to meditate and take some time out at work, which might show I am having anxiety and stress"* [R25]. This raises an important design consideration regarding the privacy of an interaction, not just privacy of the display content. More discreet interaction alternatives may be valuable, giving users the choice of which interaction to perform in different contexts.

Customization. Outside of privacy reasons, many noted that chair input should be customizable and tuned to fit their own habits: *"I would like to integrate more personal habits about sitting on the chair into the system, such as sitting cross-legged, tapping my foot, leaning on one side of the chair arm, and enable some semantic functions. For example, when I lean on one side of chair arm, I mostly thinking, so the system can pause the playing music, or show my status to prevent other people from interrupting"* [R3]. This could also prevent feature bloat by allowing users to target specific interactions they are aware of and reduce the chances of accidental input.

Permanence of Content. Many were concerned by the permanence of content. When tied to specific postures, respondents noted how it could be difficult or uncomfortable to maintain specific postures to view content. This is especially true when working: *"I liked the slide projections but I didn't like how we would have to lean forward for the slides. If I'm going through slides I'll take more time with them, so leaning forward for a long period of time would be uncomfortable"* [R1]. This suggests that chair interactions for showing content should not always be the same for hiding or even maintaining content. For example, leaning forward could reveal content, but this content could continue to exist in the environment until a different action is performed, like swiping the armrest.

As a concept, several respondents commented on the ease of integrating SAR into the environment using a chair due to their ubiquity. Many also appreciated how a display could be integrated into existing furniture rather than a new device.

7 GENERAL DISCUSSION AND LIMITATIONS

Our proof-of-concept system and applications show the possibilities for chair-enabled SAR. Our survey results show that many applications are perceived as useful and comfortable. Our work is the first to use explicit and implicit chair input and an object-mounted projector for portable SAR on diverse surfaces. We discuss limitations of our technique and possibilities for future work.

Projector Stability. Stability remains a challenge for portable SAR systems. Our proof-of-concept system stabilizes larger and slower movements by adjusting the pan and tilt servos using the virtual representation of the space in Unity without much latency. However, smaller oscillations are more challenging due to hardware limitations. We used servos commonly used by hobbyists, which are readily available but are slower and less accurate. Using high quality servos would further reduce the effects of small movements while seated. Note that body-mounted systems, such as AAR [22], are likely less stable than a projector mounted on a chair.

Alternative Output Technologies. It may be possible to integrate implicit and explicit chair inputs with other forms of output, like HMDs or environment-mounted projectors. Preserving privacy is easier with HMDs [22]. Small chair movements can affect image stability, but this can be avoided with HMDs as content can be rendered mid-air. However, we believe a chair-mounted projector has many advantages over HMDs and simplifies the implementation. A projector makes it easier to share AR with multiple people; there is no instrumentation of the user; and it is less explicit than wearing an HMD, enabling more ad hoc, peripheral interactions. Placing a projector on a chair is more portable than environment-mounted projectors; it is easier to deploy and scale personal SAR to multiple users; and there is no risk of occlusion. Understanding the trade-offs between output technologies would be beneficial for future research on chair-based interfaces.

Conflicting Interactions and Applications. Some implicit interactions may conflict; if someone facing their desk while leaning back swivels the chair to face another region, it is unclear what interaction should be prioritized for input. Likewise, if multiple applications are associated with the same regions of the room, they may conflict. Other forms of context, including digital contexts, nearby objects and environmental cues [23], or the person's perceived emotional state, could be especially important to manage these conflicts, and future work could develop models to detect the user's intent using context and chair interactions. Similarly, using common implicit chair interactions may lead to unintended input. From our experience, unintentional input did not occur often, which can largely be attributed to the learning that happens when SAR experiences are created and customized in the software toolkit. Users may also learn to adopt their implicit movements for explicit interaction over time. Future work could leverage feedforward to reduce accidental input with more awareness of what chair interactions will trigger.

Dynamic Environment Reconstruction. Our room reconstruction process is not unreasonable in terms of time, but it does not account for dynamic environments, such as moving furniture. Users must re-scan to update the room reconstruction. While furniture in typical office environments tends to be fixed, future work could use an iterative scanning method while the system is running, or detect if the saved room geometry does not match that of the live view and update it as needed. The meshes of objects that move in expected ways, like cabinet drawers, could be updated automatically.

Extension to Wheelchairs. Wheelchairs may be even more suited to chair-enabled SAR as they travel everywhere with a person. Our work extend that of Sato and colleagues [2, 41] to provide even more compelling portable SAR experiences.

8 CONCLUSION

We contribute the idea of using an office chair for portable SAR. We present design guidelines for how context from the environment and chair degrees of freedom could be used to manipulate projector output. To explore and test this idea, we developed a proof-of-concept system and created eleven demonstration applications to further highlight the potential of chair-enabled SAR. Results from a survey show that many applications of chair-enabled SAR are perceived to be useful and comfortable. Our work provides a new solution for creating portable SAR systems that are easier to deploy and may better integrate into everyday life.

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