Pers Ubiquit Comput (2014) 18:1227–1241
DOI 10.1007/s00779-013-0731-6

ORIGINAL ARTICLE

AWE: an animated work environment for working with physical and digital tools and artifacts

Henrique Houayek · Keith Evan Green · Leo Gugerty · Ian D. Walker · James Witte

Received: 14 January 2013 / Accepted: 25 July 2013 / Published online: 18 October 2013

Abstract We discuss the design, development, and testing of animated work environment (AWE), a novel, programmable, AWE supporting everyday human activities at work, at home, or at school in an increasingly digital society. A physical example of the emerging genre of "architectural robotics," AWE features a programmable, reconfigurable "wall," three horizontal, mobile work-surfaces, and embedded information technologies. AWE is the result of an iterative design process involving surveys, task analyses, virtual and physical prototyping, and usability testing accomplished by a transdisciplinary team of engineers, architects, sociologists, and human factors psychologists. Usability testing has demonstrated AWE's potential to enhance working life: AWE adapts to variations in complex activities involving users working in one physical place with physical and digital tools and artifacts.

H. Houayek (✉) · K. E. Green
Department of Architecture, Clemson University, Clemson, SC 29634, USA
e-mail: houayek@gmail.com

K. E. Green
e-mail: kegreen@clemson.edu

L. Gugerty
Department of Psychology, Clemson University, Clemson, SC 29634, USA
e-mail: gugerty@clemson.edu

I. D. Walker
Department of ECE, Clemson University, Clemson, SC 29634, USA
e-mail: iwalker@clemson.edu

J. Witte
Department of Sociology, Clemson University, Clemson, SC 29634, USA
e-mail: jwitte@clemson.edu

Keywords Collaborative work · Robotic workstation · Physical and digital tools · Interactive environments

1 Introduction

The network of increasingly powerful and inexpensive personal computing devices is revolutionizing many aspects of human existence, connecting individuals' worldwide and making accessible to them vast amounts of information and opportunities. This increasingly digital society is nevertheless characterized during most working—and some leisure—conditions (at the office, home, or school) by the single user facing a computer screen, accessing digital information within a static physical environment. While more and more people are caught up in cyberspace, they nevertheless continue to find utility and value in physical artifacts, materials and tools [1, 2]; and they also need and desire close collaborations with others, engaging together in complex working and leisure activities unfolding in a single physical space. For example, ethnographic studies [3, 4] have shown that people performing complex, creative tasks vigorously resist the "paperless office" and find that paper affords many functions—such as annotation, reconfigurability, organizing information spatially, and shifting between storage, imminent use, and active use—that computer tools do not afford well.

In designing the animated work environment (AWE), we sought to respond to these concerns by designing a workstation to meet two key goals: (1) mixed media use—allowing users to use a range of digital and analog displays such as monitors, paper, whiteboards, and corkboards; and (2) user-programmability (reconfigurability)—allowing users to flexibly rearrange digital and analog display areas to meet changing task demands. AWE (Fig. 1) offers an alternative vision to mobile and desktop computers. A user-programmable, physical environment with embedded Information Technology (IT), AWE supports users engaged in both routine and complex tasks requiring non-trivial combinations of digital and physical artifacts, materials and tools, and peer-to-peer collaboration in one physical space.

Animated work environment is viewed as part of a growing tendency within IT research concerned with various crosscutting issues related to working life, including the use of multiple displays [5, 6], managing mixed media [7], viewing healthcare information [8], and, more broadly, practices frequently defined as *Computer-Supported Collaborative Work* (CSCW) [9]. In particular, AWE builds on prior research in intelligent environments [10] such as the *Interactive Workspaces Project* [11] and *Roomware* [12, 13]. These informative and compelling precedents, however, focus not on automated or physically reprogrammable spaces but mostly on collections of computer displays, whiteboards, and novel peripherals to create electronic meeting rooms. Technologically, AWE sits instead at the interface between computer technology, architectural design, and automation, where the physical environment (including display surfaces for paper) is also subject to manipulation.

Animated work environment seeks particularly to improve user experience, both "at work" and "at home," by adapting to work and leisure activities that employ digital and analog tools and documents. The AWE concept is inspired in part by William Mitchell's vision offered in "e-topia" [1]. Mitchell believes that "the building of the near future will function more and more like large computers" and that "our buildings will become … robots for living in" [1].

Fig. 1 AWE featuring a "smart wall" and three mobile work-surfaces

We implemented the design goals of user-programmability and reconfigurability by giving AWE the capability for robotic movement. The robotic dimension of the AWE project (Fig. 2) is enabled, in part, by recent progress in the exploration of programmable structures to create active physical environments [14]. This has been explored by the group of Kas Oosterhuis at the Technical University of Delft, which has constructed programmable, flexible "play" spaces framed by continuum structures [15]. The physical AWE prototype presented here is more complex, featuring novel surfaces supporting and enhancing purposeful human activities in an increasingly digital society. AWE has two key physical elements: a user-programmable robotic system equipped with an array of embedded sensors and IT peripherals and a collection of three horizontal work-surfaces which are themselves reconfigurable (Fig. 1).

Fig. 2 An evolution of interactive robot technology in the AWE project from a linear form (*top*) previously developed and fielded by the authors, to a smooth surface (*center*) initially conceived for AWE, and to a hybrid of these two (*bottom*) in the final AWE implementation

Overall, AWE represents a new approach to human-centered home or building automation. AWE is particularly focused on the immediate environment enabling computer-supported work, combining digital and physical media. As such, AWE may be viewed within the overall framework of Blended Interaction [16]. This paper describes the overall AWE project, including all aspects of the research. An early vision of the project was articulated in [17]. The engineering issues in the construction phase of AWE are reported in [18] and [19]. This paper presents and summarizes the subsequently completed hardware and describes resultant usability testing of it, including lessons learned.

The following section discusses methods used to motivate and define the requirements for AWE. The resulting system design and realization are described in Sect. 3. Operation of the system is discussed in Sect. 4, with usability testing and evaluation described in Sect. 5. Discussion and conclusions are presented in Sect. 6.

2 Motivation: survey and task analysis findings

2.1 Overview of AWE design methods

The design of AWE is informed by survey and task analysis (ethnographic) studies, ergonomic standards, and workplace design precedents and theory. The surveys focused on work and leisure activities in the home, while the task analysis focused on workplace activities. It is important to note that the AWE prototype presented in this paper is not the first concept realized by the team; other prototypes were visualized, and one of these early alternatives was physically prototyped and evaluated in the course of our iterative, human-centered design approach. The final AWE prototype presented here is strongly informed by the qualitative research described in this section.

2.2 Phone survey of tech-savvy workers

The research team completed 400 phone surveys with individuals in two relatively affluent and technologically savvy communities, Cambridge, MA and Santa Monica, CA. Summaries of the findings confirm the initial assumptions that were the premises behind AWE.

Work that is done at home is often not done in standard work environments. Nearly three-quarters of the respondents doing work at home are not performing this work in a home office/study; 65 % of primary computers are not in an office/study, and 45 % of primary computers in home environments are not at desks.

Privacy is an issue for work at home. At first glance, privacy concerns are not pronounced: 52.8 % say “very much so” when asked if they have enough privacy. But this result is driven in large part by the number of one-person and two-person households in our sample. Only 30.3 % of respondents in households with three members report that privacy is “not very much” an issue. This number falls to 24.2 % in households with four or more members.

Most of the respondents (89 %) have a working computer in the home. Of those with a working computer in the home, more than half have more than one computer, though many of these computers are not networked. Asked to think about their primary computers, respondents indicated that 55 % of their primary computers are desktop computers and 45 % are laptops; 73 % of the primary computers are used for work and 88 % for recreation, 44 % for school, and 61 % for personal business. In addition, 30 % of respondents have more than one landline, and 75 % have at least one cell phone.

Respondents are doing a variety of tasks on their home computers. Of respondents, 60 % do at least some bill paying online; 55 % do at least some banking; 42 % do some credit card accounting; 55 % do some of their newspaper reading online; 70 % of respondents reported that they gift-shop online.

Respondents may use computers or analog/physical tools for the same task, but sometimes prefer the physical tools. Of the respondents who do some newspaper reading online, 50 % say they prefer printed newspapers to online ones. Of the respondents who gift-shop online, 40 % would prefer to go to an actual (physical) store.

2.3 Task analysis of work practices

A task analysis was conducted to provide a detailed look at user needs and preferences and to help generate design requirements for AWE. The task analysis involved 1.5-h interviews with workers in their everyday work settings. The participants interviewed were workers who gather and process large amounts of information and then compose new information products while doing their work. In order to assess use of information in various modalities (visual, spatial, textual, and numerical), the participants consisted of 4 architects, 4 teachers, and 4 accountants. The interview data were analyzed with the goal of understanding in detail how these workers gather, organize, store, communicate, and compose information, both electronic and paper-based, using their current work technologies. The findings are summarized here.

Most of the workers in our study used both paper and electronic information displays at every step of their work process. The workers in this study used paper for tasks such as note taking, information storage, drawing, editing, composing, and group discussion; they often printed electronic documents in order to work with them on paper; and they often categorized and laid out important paper documents near their focus of attention. This is documented for the architects in Table 1, which shows the work processes and preferences for paper versus electronic displays demonstrated by at least 75 % of the respondents. Thus, the perceived trend toward the "paperless office" [20] was not evident in our task analysis data. Our study supports and updates previous studies [3, 4] in this respect and is similar to the phone survey finding that half of those who read the newspaper online prefer a paper format.

Electronic information processing technologies were frequently used along with paper. In a common sequence,

Table 1 Task analysis of architectural work processes, showing use of electronic and paper information display

Stage	Goal, output	Info sources	Work processes with electronic (*EL*), paper (*PA*) and simultaneous (*EL* + *PA*) use
Requirements definition	*Content* site and resource constraints; space needs for each organizational function; budget *Format* document with mostly text and some site drawings or pictures	Client Work processes in client's business Site and site maps Arch. standards, precedents and local codes Prior projects	Information gathering Client conversations *PA* handwritten, dated notes *EL* notes shared by email Gathering information on site, codes, client work process *PA* reference books and prior project binders/folders *PA* handwritten notes, e.g., in notebook, on title sheet *EL* internet research Composing *EL* + *PA* document created electronically with notes and reference material on paper and on second monitor spread out nearby Info storage for active use *PA* binder with tabs for: program doc, site info, standards/codes, precedents, budget, meeting notes
Design First schematic (overview design), second design development (detailed design)	*Content* First high-level building schematics; second detailed building designs *Format* perspective, plan, and sectional drawings	Program info (e.g., in binder) Prior projects Reviewers (teammates, client)	Composing—drafting initial schematic drawings *EL* + *PA* in CAD with copying from prior CAD files; with notes and reference material on paper and on second monitor spread out nearby Reviewing—by architectural team or client Comparing multiple (e.g., 5–6) drawings *PA* drawings in close proximity Annotating (aka redlining) *PA* reviewer draws on paper drawing Editing *EL* + *PA* in CAD using annotated paper drawing Info storage for active use *PA* printed drawings stored on tabletop or hanging files
Construction documents most detailed design	*Content* final building designs *Format* perspective and plan drawings; text description	Detailed design documents	Disseminate initial info to contractors *EL* via email Reviewing—by architectural team or contractor *PA* redlining done on paper *PA* redlined suggestions shared by US mail *EL* changes made in CAD *PA* final design printed, bound and US mailed Info storage for active use *PA* bound designs guide construction

workers composed a draft work product (e.g., a design drawing or a text report) in an electronic format while looking at both paper and electronic information sources, then they printed the work product out and edited and annotated it by hand, and finally entered the edits into the electronic document. For example, Table 1 shows how the architects switched between paper and electronic (or used both simultaneously) while composing, reviewing, and editing drawings during the design stage.

Collaborative work projects were common, wherein *earlier, informal work products were communicated to other workers electronically; later, more formal work products were communicated using paper.*

Overall, the survey and task analysis underlined the need for reconfigurable work environments, suited to a wide range of tasks involving simultaneous use of mixed mode (physical and digital) materials. Multiple users and screens/computers were identified as important, and their desired configurations identified. The ability to support privacy in some situations, while allowing collaboration in others, was also identified as important.

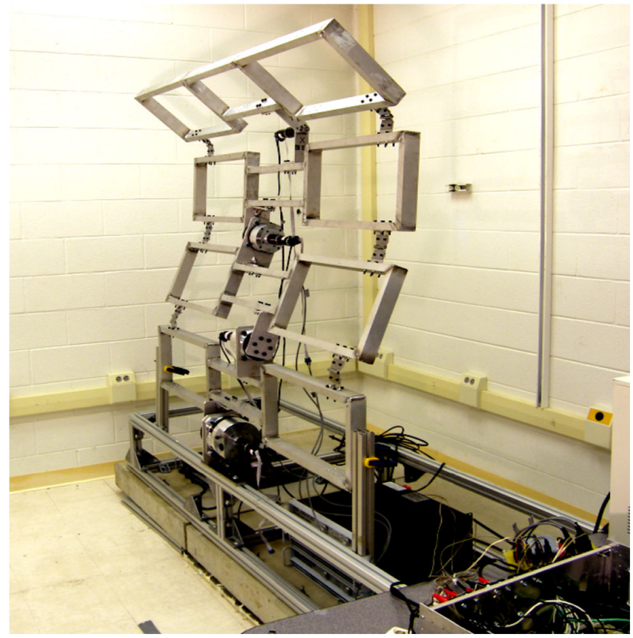

Fig. 3 Developing prototype of the robotic "wall," showing four of its eight panels

3 AWE system design and realization

Drawing from the findings of the phone and online surveys as well as the task analyses, the research team developed design guidelines that informed the development of the physical AWE prototype [18]. These guidelines, along with workplace design precedents, guided the design of our ultimate AWE prototype, particularly with respect to: (1) defining the computing environment (i.e., AWE's computer displays and CPUs, see Fig. 5) and (2) the physical configurations the robotic backbone assumes. The latter was informed, as well, by current ergonomics standards for the spatial layout of workstations drawn from the *Human Factors and Ergonomics Society*.

3.1 AWE's robotic and structural backbone

The AWE wall (Fig. 3) is a foldable surface comprised of eight five-foot-wide aluminum panels sheathed in plastic that are hinged. The hinged panels are actuated by electric motors. The motors are geared down via harmonic drives to enable the high torque loads of the worst case scenarios this system needs to handle. Exhibiting eight degrees of freedom, the AWE wall is kinematically redundant for tasks of seven or fewer degrees of freedom (i.e., all envisioned tasks for the wall). As a kinematically redundant surface, the AWE wall is a novel (i.e., unique to the best of our knowledge) robotic surface.

We placed the hinges linking the panels close to the two extremes of every panel. This allows the system of panels to move much like a typical linked, metal watchband, but at the scale of a room [19, 21].

AWE's eight panels serve as the structure for attached computer displays (three in total), lighting, audio, and other peripherals. The panels' ultimate plastic sheathing provides a "whiteboard" surface, transforming the wall into a large, configurable "easel" for writing on directly, or for displaying "annotatable" paper information, interspersed with computer displays. The center segment of each panel houses LED ambient lighting that can be switched on and off by users (Fig. 4).

AWE is a platform to be equipped with numerous, varying, and interchangeable digital and analog tools. While AWE could be equipped with such tools in a wide range of manners, we equipped AWE to support three users in close proximity as informed by our task analyses. AWE is ultimately, however, an "open chassis" for accommodating more general user preferences with respect to its equipping.

As AWE was designed for up to three users computing at once, working individually or in collaboration, we allocated three displays total for AWE (with an optional fourth display, smaller and lighter in size, mounted on the panel farthest from the base). All displays are user-adjustable and are mounted following established ergonomic specifications. As shown in Fig. 4 and in subsequent figures, the three lower screens are 19″ diagonal flat panel screens mounted on the two frames lowest to the base of the AWE backbone, and the fourth screen is specified as a 15″ diagonal. Subjects in the task analysis also expressed a

Fig. 4 AWE wall with mid-section lighting

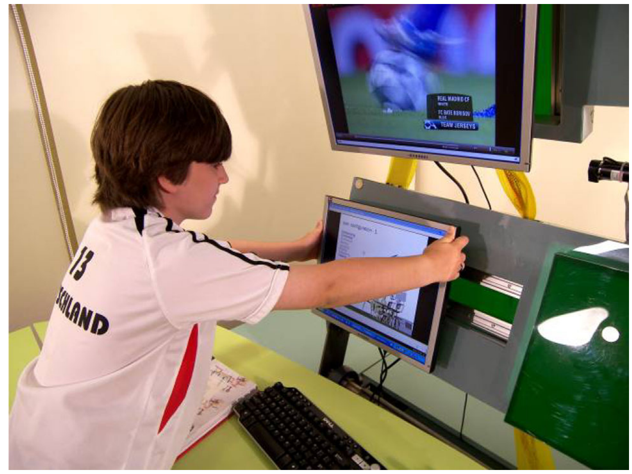

Fig. 5 AWE's three 19″ adjustable screens and base

preference for aligning multiple displays vertically and horizontally. To accommodate this preference, the mounting hardware was designed for AWE to allow the two screens in the frame closest to AWE's base to slide horizontally. See Fig. 5. If these two screens are slid apart, they better accommodate two users working side-by-side; if they are slid together so their sides abut, these two screens can be used by a single user. The mounting hardware for the screen just above these two sliding screens allows this screen to be aligned over the left-most screen below it. All the screens are mounted with a ball joint to allow them to be angled to achieve a "wrap-around" configuration to best suit the user(s).

In locations on the eight frames where no computer displays are mounted, magnets are mounted, affording the attachment of printed documents. AWE's mix of vertical and horizontal surfaces for the digital display of documents, for hand-written notes, and for the display of printed documents is again an attribute of work environments much valued and desired by participants in the task analysis.

3.2 AWE's three mobile work-surfaces

In addition to the robotic backbone, AWE comprises three horizontal, mobile work-surfaces which collectively afford various working and leisure activities. By spinning and combing these three "programmable" units, different modes for working are made possible: a *U*-shaped composing mode, an intimate meeting mode, and a formal conferencing mode (Figs. 6, 7). The three units together provide ample horizontal surface area for teamwork as well as the handling and organization of paper documents and three-dimensional physical models of various sizes.

The horizontal work-surfaces are not actuated (although they could be, in which case they would in effect become mobile robots, and could exploit the extensive body of knowledge and algorithms established in the mobile robot field). The horizontal work-surfaces are mechanically decoupled from the wall and each other. They were designed with embedded (IR proximity) sensors installed in the sides of the tables, just below the table top. Placement of these horizontal sensing sensors was selected to guide and confirm "docking" of the work-surfaces to each other and to the vertical component of AWE. The original plan was for the overall AWE controller to receive (via wireless) the sensor information from the horizontal surfaces, though this was not implemented in the final version of AWE.

Taken together, AWE's three work-surfaces, its white and pinup boards and its computer array provide users the ability to effectively combine tasks involving printed and electronic information—work activities most prevalent among subjects of our human-centered investigations. The six physical configurations AWE assumes in supporting work (and play) activities are described in the following section.

4 AWE's six configurations and implementation

4.1 Six configurations

We have designed for six standard physical configurations in support of individual and collaborative human activities

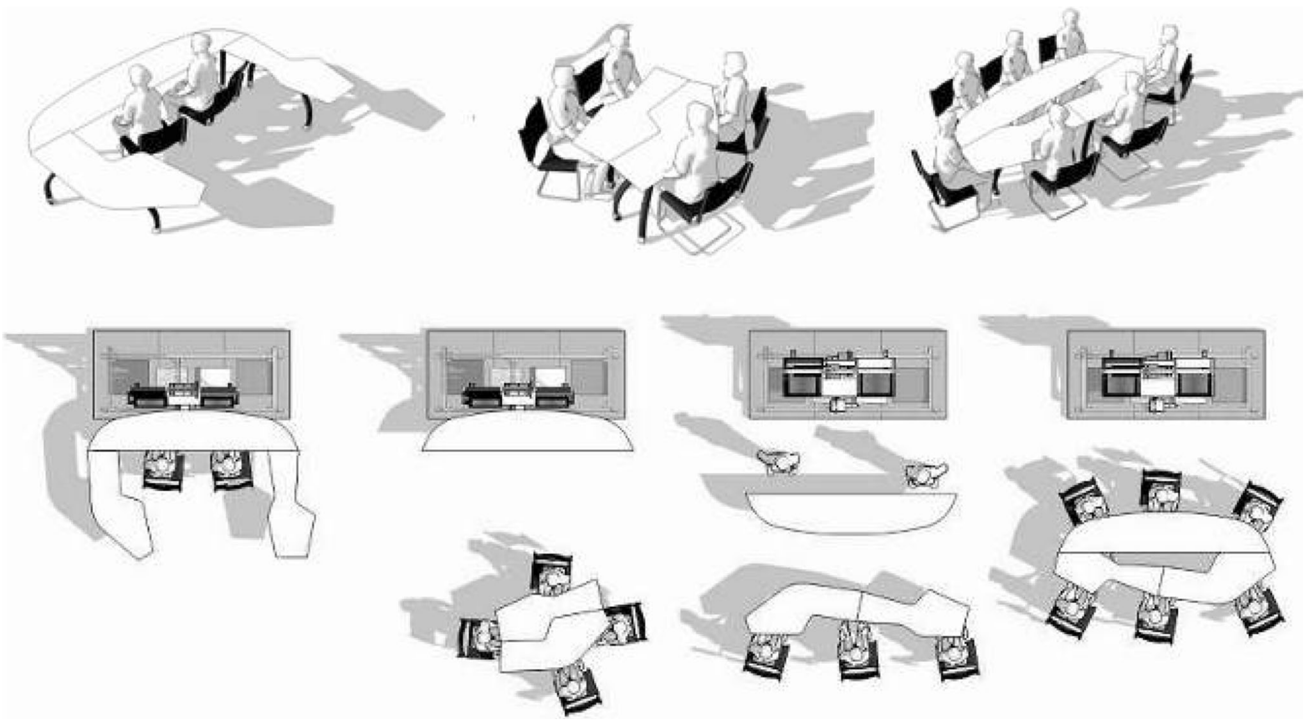

Fig. 6 Configurations of AWE's three programmable work-surfaces. *Top row*, left to right: three work-surface configuration for collaboration; two smaller work-surfaces for small conference; three work-surface combinations for larger conference. *Second row* (combining work-surfaces with AWE main body), left to right: three work-surface configurations for collaboration; (two variants of) two smaller work-surfaces for small conference; three work-surface combinations for larger conference

Fig. 7 AWE tables in conferencing mode

afforded by AWE, including those defined more by work (e.g., composing and presenting) to those defined more by leisure (e.g., gaming and viewing). These six configurations (Figs. 8, 9) were informed by the findings of the surveys and task analyses. To call-up a particular configuration, users could select one of six numbered buttons located just below the first frame from the base. Fine adjustments by the user (Fig. 10) are made possible by touch sensors located at the ends of three of AWE's panels (this is discussed further at the end of this subsection). Such user adjustments can be saved and later recalled.

Configuration-1 Configuration-1 affords intensive composing and viewing of electronic and printed information by one or two users. The focus in configuration-1 is on the three lowest screens which can be positioned so that either: (1) one or two users can focus on the same set of displays, with all three screens positioned closest to center; or (2) two users can work separately side-by-side with the two lower screens set apart, as shown in the figure.

Configuration-2 Configuration-2 affords intensive computing by a single user who might elect to position the two lower screens toward the vertical-center as shown in Fig. 8. A privacy screen can be pulled toward the floor to block visual access from behind the user. As well, the leaf in the foreground of the figure can be folded upwards to provide partial visual access from the side, presuming that AWE is set with its other side near a wall, as shown in the figure.

Should AWE be placed in a room where the wall is to the right of the user, the two outer work-surfaces, both on casters, are easily repositioned to offer the same measures of privacy.

Configuration-3 Configuration-3 affords composing by two individuals engaging in activities that do not require that they share the same intimate space. This might be the

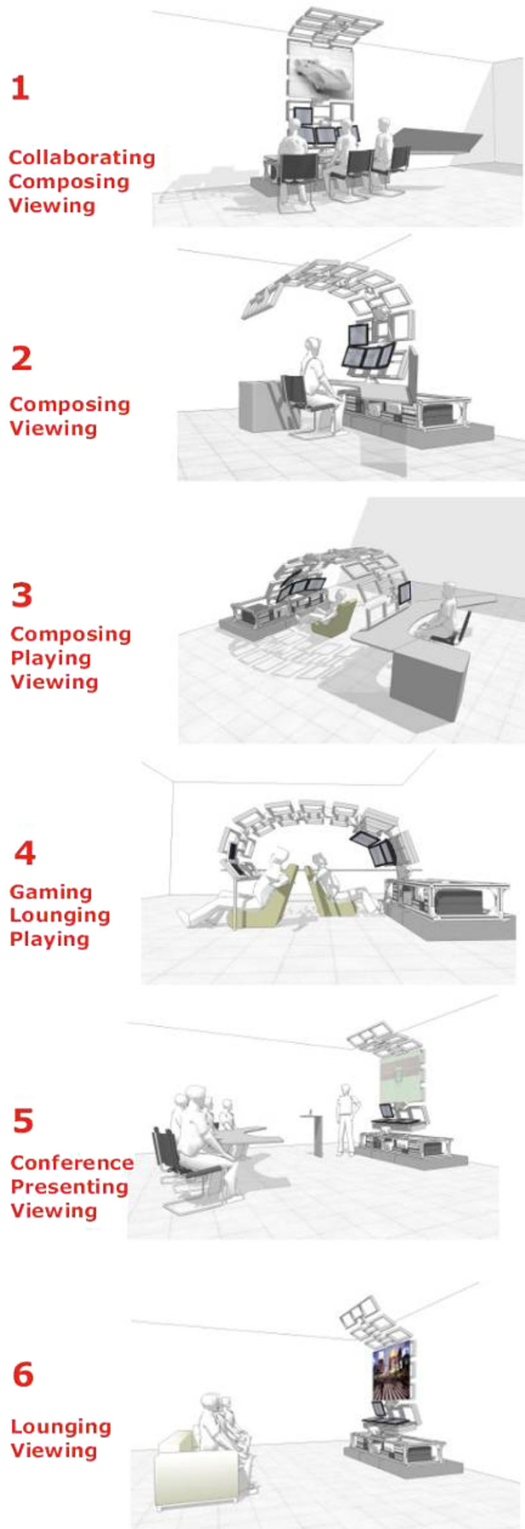

Fig. 8 AWE's 6 user-selected configurations

case where the two users are working alone on different pursuits or different aspects of the same pursuit and welcome the modest distance this spatial relationship creates between them.

Fig. 9 AWE in lounging/viewing mode (configuration 6)

Fig. 10 Users fine-tuning AWE via IR sensors

Configuration-4 Configuration-4 affords two users to work in the same intimate space, but back-to-back. This configuration suits two people gaming. It is also suited to working collaboratively; but unlike the side-by-side collaboration of Configuration-1, this configuration better supports a scenario in which the collaborating individuals are working on different but related documents (say, pertaining to a single project) or are working on different aspects of a single document.

Configuration-5 Configuration-5 affords, most particularly, formal presentations requiring a projection screen. The work-surfaces of AWE are repositioned and rotated 180° to allow room for the presenter, a podium, and a pedestal supporting physical artifacts as part of the presentation. Lighting integral to AWE's panels is programmed to focus light onto the physical objects displayed.

Configuration-6 Configuration-6 affords leisurely viewing of videos or slide shows presented on the projection screen.

This configuration suits the playback of movies, satellite television, and other longer time-based media. See Fig. 9.

Lighting is particularly important in presentation mode (see Fig. 8-5), when gaming (see Fig. 8-4), and when needing more privacy, but still wanting a lot of light (see Fig. 8-3).

The AWE wall automatically responds safely to unanticipated and unexpected movements of its users by exploiting an array of IR sensors integrated with its panels. Each panel features two IR sensors. This provides programmable functionality of the wall in response to sensed real-time proximity data. We have found an arrangement of "reflexive columns" of sensors, repelling the wall from suddenly approaching users, to be particularly intuitive and effective. In addition, the sensors can be configured in columns set to "attract/repel" modes to allow users to fine-tune the configuration of the wall about the six basic modes. In effect, this allows users to program the wall shape according to their particular needs. New configurations of the system can be "saved" for future recall.

4.2 Trajectory (shape) planning

In realizing the six configurations and movements between them, real-time trajectory planning of AWE's panels follows the resolved rate approach [22–24] based on an AWE-specific Jacobian-based model [19]. We implement the Jacobian-based model:

$$\dot{\mathbf{x}} = [J(\mathbf{q})]\dot{\mathbf{q}} \tag{1}$$

where $\mathbf{q}$ is the 8×1 vector of joint (panel) angles, $\dot{\mathbf{q}}$ their time velocity, $\dot{\mathbf{x}}$ is a (given) $m \times 1$ task space velocity ($\mathbf{x}$ defined variously for different AWE modes of operation, as discussed below), and $[J]$ is the corresponding AWE Jacobian (defined below).

The key novelty of the AWE redundancy resolution problem is in the nature of the task spaces and tasks required of the "robot wall" [i.e., $(\mathbf{x}, \dot{\mathbf{x}})$] rather than the structure of $[J]$. Note that the unconstrained structure behaves, kinematically, as a planar serial rigid-link mechanism. Therefore, elements of the columns of $[J]$ corresponding to the task space of the kth panel $\mathbf{x}_k = [x_k, y_k, \phi_k]^{\mathrm{T}}$ are easily established as

$$J_{1i}(\mathbf{q}) = -\sum_{j=1}^{k-i+1} a_j \sin\left(\sum_{k=1}^{j} q_k\right)$$

$$J_{2i}(\mathbf{q}) = \sum_{j=1}^{k-i+1} a_j \cos\left(\sum_{k=1}^{j} q_k\right)$$

$$J_{3i}(\mathbf{q}) = 1 \quad (i = 1, .., k)$$

In the above, the variables x_k, y_k are the coordinates of the tip of the kth panel, in a coordinate frame (fixed at the base of the AWE wall) having its z axis aligned with the panels and its y axis vertical. The variable ϕ_k represents the orientation of the kth AWE panel [defined in the (x, y) plane perpendicular to the AWE panels and measured counterclockwise from the horizontal x axis of the above fixed frame]. The parameter a_j is the known side height (vertical dimension) of the jth AWE panel.

Therefore, the Jacobian elements corresponding to tasks described in any of the AWE panel coordinates $\mathbf{x}_k$ are readily available and easily computable. The key issue is how to exploit this information to achieve the desired motion of AWE for its various tasks.

An unusual aspect of the AWE application is that complete regulation of the "end effector" (tip of the AWE wall) position/orientation is rarely the primary consideration. More typically, positioning/orienting of screens more proximal to the base represents the primary task, and only orientation of the tip (to, for example, direct lighting on to screens or users) is of primary concern at the tip. Positioning of the final (and other) panel(s) therefore becomes a subtask in the redundancy resolution. This is in contrast to the usual serial-link redundancy resolution problem in the literature, where the end effector (tip) task is primary, and the body motion secondary, to the problem.

To encode these requirements in a consistent form, the task space vector $\mathbf{x}$ in (1) is selected as (the nonzero elements of)

$$\mathbf{x} = [S]\tilde{\mathbf{x}}$$

where $\tilde{\mathbf{x}} = [\mathbf{x}_{1,} \ldots \mathbf{x}_8]$ and the (24×24) matrix $[S] = \mathrm{diag}(s_i)$. The task selection matrix $[S]$ encodes the different modes of AWE operation and transitions between them. A nonzero element s_i in $[S]$ indicates a specific primary task requirement for the corresponding element of $\tilde{\mathbf{x}}$ in the current AWE mode. For example, for the "Presentation" mode (Fig. 8), the nonzero elements of $[S]$ will include $\{s_4, s_5\}$ (representing tip position of panel 2, the "base" of the screen) and $\{s_9, s_{12}, s_{15}\}$ (representing the orientation constraints on panels $\{3, 4, 5\}$, required to keep the screen vertical). Transitions between AWE modes are accommodated by smooth (time) trajectories of the s_i, to and around zero. Note that this enables smooth transition between the structural changes in (1) required as the task space of AWE changes between modes.

Given a selection of $\mathbf{x}$ as above, real-time trajectory planning is achieved via iteratively updating the nominal panel joint velocities $\dot{\mathbf{q}}$ (and hence the controlled input positions $\mathbf{q}$ via numerical integration) in (1) based on the iterative algorithm

$$\dot{\mathbf{q}} = [J(\mathbf{q})]^{+}\dot{\mathbf{x}} + [I - J^{+}J]\varepsilon \tag{2}$$

where $[J]^{+}$ is a (right-sided) generalized inverse of $[J]$ (for example $[J]^{+} = [J]^{\mathrm{T}} \; ([J][J]^{\mathrm{T}})^{-1}$, the Moore–Penrose inverse), and the 8×1 vector $\boldsymbol{\varepsilon}$ is arbitrary, to be selected according to the particular redundancy resolution scheme adopted (see below). The vector $\boldsymbol{\varepsilon}$ tunes the "self-motion" term $[I - J^{+}J]\boldsymbol{\varepsilon}$ which exploits the redundant degrees of freedom for subtask performance after satisfying the primary task given by $\dot{\mathbf{x}}$.

In our trajectory planning for moving between the six reference configurations, we adopt the gradient projection approach introduced by Yoshikawa (where $\boldsymbol{\varepsilon}$ is chosen as the scaled gradient of a cost function selected so that its minimum corresponds to the system matching a fixed, preselected configuration [25]). This was done to configure AWE closest to pre-assigned desired reference, or *guiding*, configurations (discussed in following paragraph), subject to satisfying the primary task constraints.

We explored different guiding configurations to improve path choice from one configuration to another. Eight different guiding modes were selected, inspired by the cobra, sequoia ostrich, an elephant's trunk, and the shape of a football to reflect the perceived "organic" nature of the wall. The function of a guiding configuration is to resolve the redundancy by providing a "guide" for the wall to be "closest to" during a given movement under the motion planning strategy in (2). So, the wall in some sense is expected to exhibit the "nature" of the selected guiding configuration during the motion.

Figure 11 illustrates the results of the approach, comparing two alternatives for moving from composing mode 2 to presenting mode 5. The wall is viewed from the side. Each image (left and right) represents the moving wall section by green intermediate segments. The segments begin at the composing configuration on the left/lower and move to the final presenting configuration (shown as a red line) at the right/upper of each sequence, the green growing lighter as time evolves. The two sequences differ in the guiding configuration, shown in blue: the elephant's trunk in Fig. 11, (left), and football in Fig. 11, (right). Thus, the beginning and ending configurations (composing and presenting) are the same, but the way the wall transitions between them is quite different.

In the more favorable condition (Fig. 11, left), the elephant guiding mode allows the top and middle joints to move into position fairly rapidly, reducing the torque on the bottom motors; whereas, in the less favorable condition (Fig. 11, right), the top joints take longer to move into position, placing more torque on the bottom motors. The configuration show on the left is therefore most favorable, serving as the model for the wall trajectory [18].

In addition to the above trajectory planning for moving between the six configurations (as selected a priori by the user), we implemented scenarios where AWE directly senses and adapts to user behavior. In one such experiment, the AWE wall, in configuration-5, maintains the orientation of the projection screen (so the audience is not distracted) and, at the same time, moves its other panels to allow a spotlight to track the movements of a speaker [19].

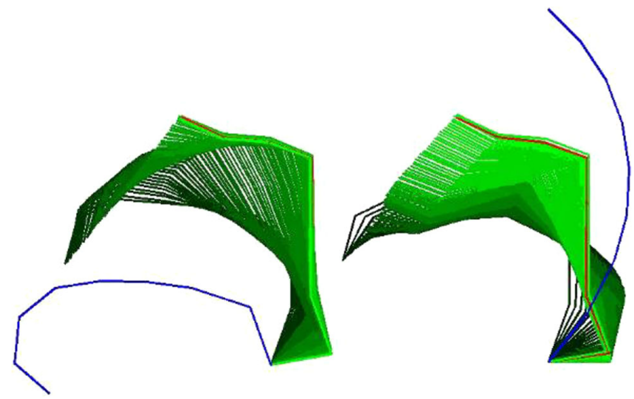

Fig. 11 Trajectory planning from configuration-2 to configuration-5 using two different guiding modes; the condition on the left is more desirable

4.3 Example scenario

An exemplary scenario illustrates the use of AWE. Martha approaches AWE, currently in standby mode. She inserts her USB drive into the slot in one of AWE's PC's, transitioning AWE into standby mode. The USB drive contains a "saved" AWE configuration. AWE's software recognizes this and moves to the saved configuration (configuration 1, composing/viewing).

Martha opens a partly finished presentation (an upcoming conference talk she will give next week) on one screen and the corresponding conference paper on another. She takes her notes outlining her planned modifications to the talk from her bag and spreads them on the horizontal surfaces. She begins to work on her presentation, using both the digital and hard copy information.

Martha realizes she is not being very productive and feels she would concentrate better in a closer, more intimate environment. So, in the AWE control window, she toggles Configuration 2, composing/viewing. AWE's surfaces fold to create a more confined space (see 0.49–1.06 in the video [21] for the geometry and timing of this movement). Still not completely happy, Martha puts AWE into fine-tuning mode and stands to draw some of AWE's panels closer to her, until she has AWE in the shape she imagines (see time interval 2.03–2.15 in the video [21] for an example of this tuning of AWE). She continues her work, and her progress is much faster.

Suddenly, Martha remembers that she forgot to lock her car outside. She stands up quickly, grabbing her things to go outside to her car. AWE's proximity sensors detect this unexpected activity and move AWE's panels away from

Martha to allow her to leave easily (see this action in the video [21], time interval 2.16–2.25). After several minutes of inactivity, AWE transitions back into standby mode.

5 Usability evaluation

We evaluated AWE by conducting two usability tests, in which users performed representative work tasks using AWE while analysts observed and recorded their behavior. However, the representative tasks for these usability tests were different from typical usability tests, since AWE was designed to facilitate long-term work tasks where users access large amounts of multimodal information and then integrate this information into a creative product. Therefore, we had users perform only one 2-h task (involving architectural design or accounting) during each test session, while verbalizing their thoughts. Using videotaping and a real-time coding program, we recorded user's focus of attention within the AWE workspace throughout the test session. Data analysis focused on spatial and temporal components of how users used the paper and computer displays of AWE.

In the following, we present the results for usability evaluations of configuration 2—composing mode—for two tasks. In the first usability test, advanced undergraduate and graduate architecture students created preliminary designs of a multifamily residence. In the second test, participants with tax preparation experience completed a complex tax return.

5.1 Usability test methods

For the architectural task, the 8 participants (age range 19–27; 4 females) were students in an architecture program at Clemson University. All participants were in the third year or higher-level in the program, had previous experience in designing, and were familiar with the architectural software required for the design task. For the tax task, the 4 participants (age range 20–50; all males) each had between 1 and 15 year's experience preparing and submitting tax forms to the US Internal Revenue Service (IRS).

The first part of the architectural design task required participants to develop two preliminary design studies for a multifamily residence on a specific site. The second part of the design task (the final design study) required participants to pick one of their preliminary design studies and develop it further by creating a 3D model using CAD software and then including images from the 3D model (e.g., front and back view, perspective) in a Photoshop document. For the tax task, participants were presented with detailed financial documents for a hypothetical friend and then completed the IRS tax forms for this person. This required completing the main tax form (IRS 1040) and four auxiliary forms. Some tax instructions and blank tax forms were given to the participants on paper; others were available on the web. The tasks each took about 2 h.

5.2 Usability test findings

5.2.1 Overall use of AWE workspace: architectural task

The constraints of the architectural task required many of the subtasks to be done on the computer and allowed the others to be done either on the computer or paper. Given this, an extreme computer-phile could avoid using paper altogether, while an extreme computer-phobe could use paper about 50 % of the time. The young age and high computer skills of our users led us to expect relatively low paper use. However, the affordances of paper for creative, knowledge-intensive tasks mentioned earlier led us to expect a moderate amount of paper use. On average, our participants used the three computer monitors for 71 % of their design work and the paper display areas for 29 %. Participants showed considerable variability in their frequency of using the computer versus paper, falling into three levels of preference for paper: 2 users who used paper for 14 % of their work (on average); 5 who used paper about 32 % of the time; and 1 who used paper 44 % of the time. Thus, even though task constraints and users' high computer skills might have minimized use of paper on this task, we found evidence of moderate paper use in most of our users. These findings provide further evidence that paper is a key part of knowledge-intensive tasks and support our design goal for AWE of allowing users to integrate paper and computer displays.

We investigated the extent to which our users spread out paper across the AWE workspace. As Fig. 12 shows, in composing mode, AWE contained 5 locations for electronic equipment: 3 monitors, a scanner, and a printer. It also contained 4 areas for paper display: the vertical area (with 3 locations), the center table (with 5 locations), the left table (with 2 locations), and the right table (with 3 locations). We classified 3 of our users who used all 4 areas and 8–11 locations as very high paper spreaders, 2 users who used 3 areas and 7–9 areas as high spreaders, 2 users who used 2 areas and 6–7 areas as low spreaders, and 1 user who used 2 areas and 3 locations as a very low spreader. Thus, 5 of our 8 users (the high and very high spreaders) made extensive use of AWE's capability for displaying paper. Figure 12 shows how the AWE workspace was used by one of the very high paper spreaders; Fig. 13 shows the same information for one of the low paper spreaders. As might be expected, users who used paper more often tended to spread out paper more, as shown by a 0.75 correlation between the percentage of paper use and the number of paper display areas used.

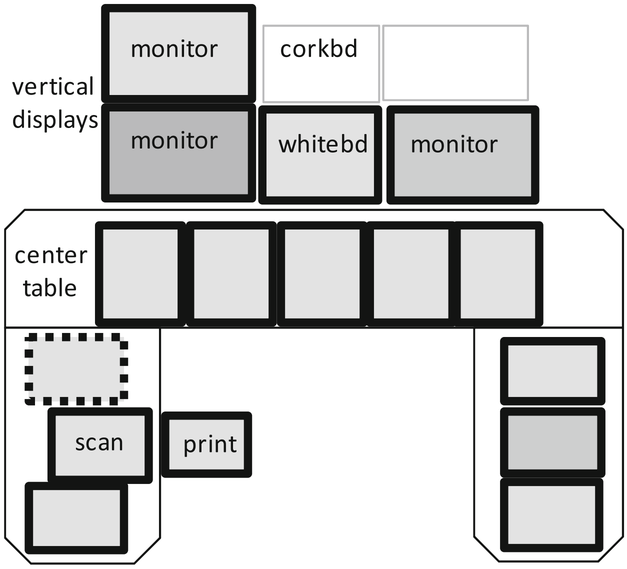

Fig. 12 Frequency of use of AWE paper and computer display locations for a VERY HIGH paper spreader who used all 4 of AWE's paper display areas (*vertical*, *center* table, *left* table, *right* table). *Darker fill* color indicates more use; *white* means no use. Heavier, *solid border* indicates more active use; *dashed border* indicates storage use

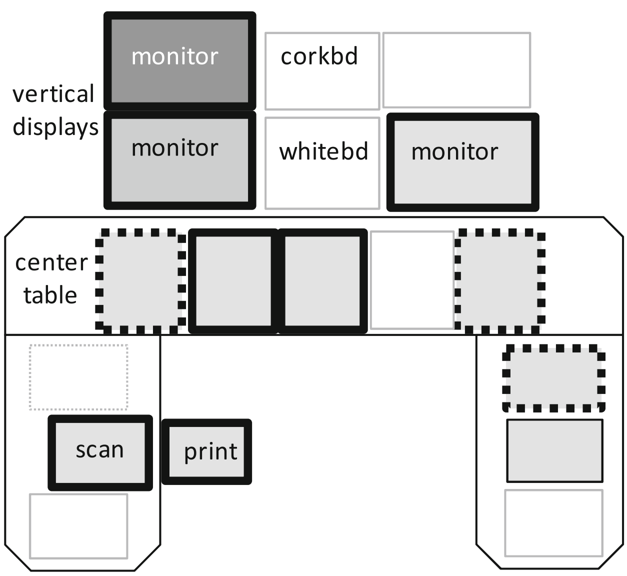

Fig. 13 Frequency of use of AWE paper and computer display locations for a LOW paper spreader who used only 2 of 4 paper display areas (*center* and *right* tables). *Darker fill* color indicates more use; *white* means no use. Heavier, *solid border* indicates more active use; *dashed border* indicates storage use

5.2.2 *Temporal patterns in using AWE: architectural task*

Users varied how they used AWE's workspaces over time, sometimes using only paper displays for long periods (e.g., perusing paper reference materials or sketching ideas), sometimes using only computer displays for long periods (e.g., working in CAD or Photoshop), and sometimes using paper and computer displays together (e.g., creating a CAD model while using a paper sketch as a reference). To help understand these changes, we coded whether each participant used paper only, computer only, or paper and computer together for each of the design subtasks throughout the design session.

The left side of Fig. 14 shows a participant who initially used only paper for examining reference pictures and for sketching design ideas, then used paper and computer together when using the CAD program with a paper sketch as a reference, and finally completed a variety of other design tasks solely on the computer. This pattern of using paper only, then computer and paper together, and then computer only was seen in 5 of the 8 users. The right side of Fig. 13 shows another of these 5 users, who repeated the "paper-both-computer" pattern three times during the session. The other 3 of the 8 users did not follow the "paper-both-computer" pattern. These users showed little use of paper alone and tended to switch between using only the computer and using paper and computer together.

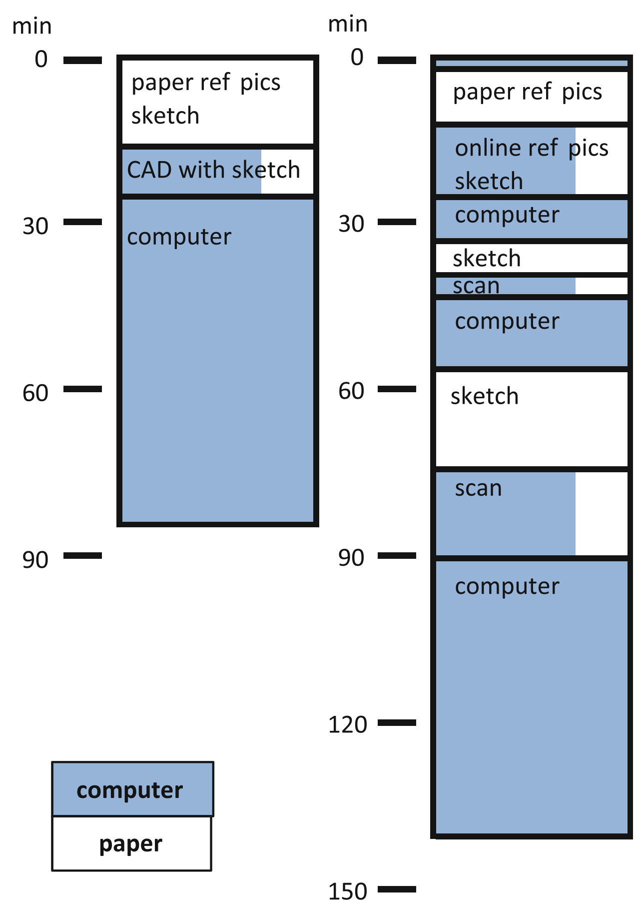

Fig. 14 Time course of using paper and computer displays for two users. *Left column* user 1. *Right column* user 2

This temporal look at patterns of using AWE supports the conclusion from the spatial analysis—that people performing creative, knowledge-intensive tasks regularly switch between paper and computer displays depending on personal preferences and the demands of particular subtasks.

5.2.3 *Use of individual parts of AWE: both tasks*

The final usability data we present deals with how participants used the 4 areas for paper display and the 1 area for electronic displays of the AWE system. For the architectural task usability test (with 8 participants), Table 2 documents usage in terms of the number of participants who used each area and the average percentage of time participants used each area. It also shows whether each area was used primarily for active use, information storage, or both. For the tax task (with 4 participants), only the number of participants and the type of use are available.

For both tasks, the computer monitors showed heavy use, being used by all participants and accounting for 70 % of architectural task time. As mentioned before, this heavy use was partly due to task constraints. Eleven of 12 participants used each of the 3 computer monitors (and the other person used 2). Monitors were used mainly for active use. One participant adjusted AWE by removing the whiteboard from the middle of the lower vertical row and moving the two lower monitors together.

Among paper display areas, the center and right tables received heaviest use. Across both tasks, 10 of 12 participants used both of these tables; and for the architectural task, 5 of 8 participants used them for more than 23 % of their total task time. These tables were used primarily for active use, with some storage use as well. Most participants (11 of 12) spread out documents across the center table, while fewer (4 of 12) did this for the right table. The main activities accomplished on the center and right tables were sketching, looking at reference pictures and completed sketches, reading tax documents, entering data into tax forms, and information storage. Across both tasks, the left table was used relatively infrequently, by 6 of 12 participants, and mainly for storage use.

Across both tasks, the three vertical paper displays (whiteboard, corkboard, and paper display) were used by 8 of 12 participants, but only for a small percentage of participants' time. This was because these displays were used mostly for information storage. When information is put in a workspace area for storage and only accessed occasionally, the small amount of time interacting with this storage area does not necessarily mean that this information is unimportant to the task. The vertical paper displays were used mainly for displaying one or more drawings or pictures, writing notes or task reminders on the whiteboard, and arranging tax documents on the corkboard. Notably, the vertical displays were not used for reading small text or sketching, as they did not afford these activities. (Due to late design changes, 4 of the 12 participants had only two vertical display locations, the whiteboard and the corkboard; the other 8 also had a third location where they could post paper notes. Vertical display use seemed to increase when the third location was added.)

Table 2 Use of individual AWE work areas in terms of percentage of users and percentage of time for two usability tasks

AWE area	Architectural task			Tax task	
	% using	Main use	% of time	% using	Main use
Computer monitors	100	Active	70.5	100	Active
Vertical paper	62	Storage	0.5	75	Storage
Left table paper	62	Storage active	0.3	25	Storage
Center table paper	100	Active	20.7	100	Active
Right table paper	87	Active storage	4.1	75	Storage

5.3 Usability test summary

Despite task constraints encouraging computer-based work (especially in the architectural task), all participants used paper regularly in both tasks. Many participants made extensive use of AWE's horizontal tables for spreading out paper spatially. These usability tests also documented how people switched between paper, computer, or combined use at different stages of their task, which supports one of the key findings of our task analysis. Overall, these usability test findings regarding use of mixed media provide quantitative support for the qualitative findings of our task analysis and other ethnographic studies of knowledge workers [3, 4, 26]. Our usability findings also begin to validate that AWE achieved one of its primary design goals—to facilitate flexible use of paper and digital media.

With regard to the goal of better integrating non-digital displays into knowledge work, the main way in which AWE went beyond the traditional workstation was in the vertical non-digital display spaces. Two-thirds of our participants used these displays, but they used them mainly for short-term information storage ("hot storage") and rarely for active use. One of our design goals for future iterations of AWE is to improve the functionality of these vertical non-digital display spaces.

Our usability research concentrated on an observational study of how people used paper versus generic digital displays. We used flat panel monitors connected into a single display space (i.e., information that can be easily transferred between applications running in different displays by copying and pasting). However, separate tablet PC's could also be used. Our design had the limitation that paper could be displayed primarily on the horizontal spaces (but also on one of the vertical spaces), and digital information could be displayed on the vertical spaces. Tablets could add flexibility in allowing digital information to be displayed horizontally. However, having separate tablet PC's could reduce flexibility in transferring information between applications running on separate tablets. Our participants copied and pasted information between digital displays regularly—this could be harder to do with tablets. Therefore, while it would be interesting to test tablets, we tested a display option which is still widely used and which may have some advantages over tablets.

6 Discussion and conclusions

Our full-scale, working prototype of an animated work environment has been guided by a human-centered design approach involving surveys and ethnographic study. Specifically, we report results from participants engaged in the complex tasks such as completing tax forms and engaged in a design activity requiring digital and analog materials and tools. These tests have shown the potential of AWE to support complex human activity involving mixed media and tools.

The usability study reported in this paper tested use of a static AWE configuration by single users. More general studies featuring real-time reconfiguration of AWE by multiple users have not yet been conducted. This is a current limitation of the project, and future usability research needs to be conducted to test collaborative use of AWE and reconfigurability.

We also note the current trends and exciting possibilities offered by the availability of small, smart devices, with ever-increasing internet accessibility. These ever-emerging "third places" are enabling people to work away from both the office and from home. Our research, as reported in this paper, does not explicitly consider "third places." However, we view our innovations as being on the boundaries of the "third places": neither at work, or at home, but both. With AWE (as we envision it) both at home and at work, it is between (interactions with) AWE that people will visit the "third places." Note that our vision explicitly imagines people "transporting" the current configuration of their (large, fixed point) (AWE) workspace environments while they are mobile. Therefore, while our focus is on specific environments, our goal is to make those environments flexible to support the type of dynamic and mobile lifestyles exemplified by the "third places."

Acknowledgments The authors acknowledge support from the U.S. National Science Foundation under Grant Number IIS-0534423.

References

1. Malone TW (1983) How do people organize their desks? Implications for the design of office information systems. ACM Trans Office Inf Syst 1(1):99–112
2. Mitchell WJ (2000) e-topia. MIT Press, Cambridge, MA
3. Bondarenko O, Janssen R (2005) Documents at hand: learning from paper to improve digital technologies. In Proceedings CHI. ACM Press, pp 121–130
4. Sellen A, Harper R (2002) The myth of the paperless office. MIT Press, Cambridge
5. Wigdor D, Shen C, Forlines C, Balakrishnan R (2006) Effects of display position and control space orientation on user preference and performance. In: Proceedings CHI. ACM Press, pp 309–318
6. Ziola R (2006) My MDE: configuring virtual workspace in multi-display environments. Work in progress. In: Proceedings CHI. ACM Press, pp 1481–1486
7. Luff P, Heath C, Kazuoka H, Yamakazi K, Yamashita J (2006) Handling documents and discriminating objects in hybrid spaces. In: Proceedings CHI. ACM Press, pp 561–570
8. Washington Medical Center, Microsoft Research (2004) Posting date. http://www.microsoft.com/business/executivecircle/content/casestudydetail.aspx?csid=14967
9. Baecker R (ed) (1993) Readings in groupware and computer-supported cooperative work. Morgan Kaufmann, San Mateo
10. Antonelli P (ed) (2001) Workspheres. NewYork MoMa
11. Johanson B, Fox A, Winograd T (2002) The interactive workspaces project: experiences with ubiquitous computing rooms. In: IEEE pervasive computing, vol 1, issue 2, April/June
12. Streitz NA, Rexroth A, Holmer T (1997) Does "roomware" matter? Investigating the role of personal and public information devices and their combination in meeting room collaboration. In: Proceedings E-CSCW
13. Streitz NA, Tandler P, Müller-Tomfelde C, Konomi S (2001) Roomware: toward the next generation of human-computer interaction based on an integrated design of real and virtual worlds. In: Carroll J (ed) Human-computer interaction in the new millennium. Addison-Wesley, Boston
14. Kapadia A, Walker ID, Green KE, Manganelli JC, Houayek H, James A, Kanuri VKT, Mokhtar T, Siles I, Yanik P (2010) Architectural robotics: an interdisciplinary course rethinking the machines we live in. In: Proceedings IEEE international conference on robotics and automation. Anchorage, AK, pp 48–53
15. Ooosterhuis K (2003) Hyperbodies: towards an e-motive architecture. Birkhauser Press, Basel
16. Jetter H-C, Geyer F, Schwarz F, Reiterer H (2012) Blended interaction—toward a framework for the design of interactive spaces. Workshop designing collaborative interactive spaces (DCIS 2012) at AVI 2012. HCI Group, University of Konstanz, May 2012. http://hci.uni-konstanz.de/downloads/dcis2012_Jetter.pdf
17. Green KE, Walker ID, Gugerty LJ, Witte JC (2006) Three robot-rooms/the AWE project. Work in progress. In: Proceedings CHI. ACM Press, pp 809–814
18. Johnson J, Kwoka M, Houayek H, Walker ID, Green KE (2007) Design, construction, and testing of a novel robotic workstation. In Proceedings fourth international conference on computational intelligence, robotics, and autonomous systems (CIRAS). Palmerston North, New Zealand, pp 155–160
19. Kwoka M, Johnson J, Houayek H, Dunlap I, Walker ID, Green KE (2008) The AWE wall: a smart reconfigurable robot surface.

In: Proceedings of the 4th international conference on intelligent environments. Seattle, WA, pp 1–8

20. Raskar R, Welch G, Cutts M, Lake A, Stesin L, Fuchs H (1998) The office of the future: a unified approach to image-based modeling and spatially immersive displays. In: Proceedings SIGGRAPH, pp 1–10
21. AWE Self-Reconfiguring Robot Wall (2009) Posting date. http://www.youtube.com/watch?v=CaMuS3wZ-bM
22. Chiaverini S, Oriolo G, Walker ID (2008) Kinematically redundant manipulators. Chapter 11. In: Handbook of Robotics. Springer, pp 245–268
23. Nenchev DN (1989) Redundancy resolution through local optimization: a review. J Robot Syst 6(6):769–798
24. Siciliano B (1990) Kinematic control of redundant robot manipulators: a tutorial. J Intell Robot Syst 3:201–212
25. Yoshikawa T (1984) Analysis and control of robot manipulators with redundancy. In: Brady M, Paul R (eds) Robotics research: the first international symposium. MIT Press, Cambridge, MA, pp 735–748
26. Kidd A (1994) The marks are on the knowledge worker. In: Adelson B, Dumais S, Olson J (eds) Proceedings SIGCHI conference on human factors in computing systems (CHI'94). ACM, New York, NY, USA, pp 186–191