

Factors Influencing Visual Attention Switch in Multi-Display User Interfaces: A Survey

Umar Rashid
University of St Andrews
ur9@st-andrews.ac.uk

Miguel A. Nacenta
University of St Andrews
mans@st-andrews.ac.uk

Aaron Quigley
University of St Andrews
aquigley@st-andrews.ac.uk

ABSTRACT

Multi-display User Interfaces (MDUIs) enable people to take advantage of the different characteristics of different display categories. For example, combining mobile and large displays within the same system enables users to interact with user interface elements locally while simultaneously having a large display space to show data. Although there is a large potential gain in performance and comfort, there is at least one main drawback that can override the benefits of MDUIs: the visual and physical separation between displays requires that users perform visual attention switches between displays. In this paper, we present a survey and analysis of existing data and classifications to identify factors that can affect visual attention switch in MDUIs. Our analysis and taxonomy bring attention to the often ignored implications of visual attention switch and collect existing evidence to facilitate research and implementation of effective MDUIs.

Categories and Subject Descriptors

H5.2 [Information interfaces and presentation]: User Interfaces – Graphical user interfaces.

General Terms

Design, Human Factors.

Keywords

Multi-display environment, visual attention switch, distributed user interfaces, multi-display user interfaces, device interoperability, smartphones, large displays.

1. INTRODUCTION

Users are increasingly shifting from using a single personal computer to interacting with a wider range of computing devices (including laptops, tablets, mobile phones, media players and e-book readers). The proliferation of computing devices has created opportunities to make different applications and services readily accessible on multiple devices. For example, it has become commonplace to play videos, check emails and read documents on mobile phones and tablets, in addition to desktop computers. Researchers and developers are also attempting to support interaction *across* multiple devices [3] in order to take advantage of the diverse input and output capabilities of these devices and overcome their limitations. Deployed examples include accessing web pages on a desktop computer and reading them later on a mobile [8] as well as playing Scrabble on an iPhone and an iPad simultaneously [33].

Multi-display User Interfaces (MDUIs) have a large potential to improve interaction because combining heterogeneous displays

allows people to use the right display for the right subtask. For example, they can take advantage of the mobility and direct touch of tablets and PDAs, while simultaneously being able to see their data on a very large display without the limitations of mobile screens [3]. Efforts are already underway to support the design and implementation of user interface (UI) elements distributed across multiple devices [18].

Although MDUIs allow flexibility for the design of novel interfaces with optimal input, output and collaborative capabilities, they also introduce the overhead of visual attention shifts. Because human vision can only focus on a limited area at a glance [35], distributing UI elements across multiple displays will inevitably cause switching of visual attention that might involve cognitive focus, gaze, head or body displacement. The overall effects of the visual attention switching will likely depend on the task (e.g., [26, 39]), as well as on the design of the input and output aspects of the system. Unfortunately, making informed decisions regarding MDUI design is difficult because the existing literature is partial and fragmented, and there is not a clear identification of factors that can influence switching of visual attention in different visual arrangements (VA) of MDUIs. In an attempt to fill this gap, this paper reports on a literature survey of six existing taxonomies that are applicable to MDUIs. We identify a set of factors associated with the visual arrangement of UI elements that can affect attention switching, present a taxonomy of the work containing MDUIs based on those factors, and review existing research that is relevant to each factor.

The paper starts by providing a critical overview of the existing taxonomies that are applicable to MDUIs. In rest of the paper, we sequentially present the factors that form our taxonomy. For each factor, we describe different categories, classify existing systems according to each category of that factor, and discuss its relevance to visual attention switching in MDUIs.

2. TAXONOMIES FOR MDUIs

We define MDUI as an interface where its output and/or input is distributed across two or more displays. The area of multi-display environments (MDEs) has been very active in the last few years; several researchers have proposed taxonomies or categorizations that, although generally with different purposes, provide a valuable starting point for our work.

Ballagas et al. [2] propose a taxonomy for interaction of mobile devices with large situated displays. They borrow three sub-tasks from desktop-GUI taxonomy that are relevant to mobile input space: *position* (specifying a position in application coordinates); *orient* (specifying an orientation in a coordinate system); and *select* (makes a selection from a set of alternatives). In order to accommodate the increased diversity of mobile input, they included four additional dimensions in the taxonomy: *dimensionality* (up to 3 dimensions); *measurement* (relative or absolute); *environmental feedback* (continuous or discrete); and *interaction style* (direct or indirect). The *interaction style*

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The copy of record of the paper can be found in:
<http://dl.acm.org/citation.cfm?doid=2307798.2307799>

dimension of this taxonomy is the most relevant for visual attention switching, and will be discussed further in Section 3.

Terrenghi et al. [42] present a taxonomy of multi-person interactions in multi-display ecosystems that identifies three main factors which constitute what they call the “geometries of interaction”. These include *size of ecosystem* (inch-scale to chain-scale), *nature of social interaction* (one-one to many-many), and *interaction methods for binding multiple displays*. The size of ecosystem dimension relates to our angular coverage factor.

Swaminathan and Sato [38] describe three configurations of multiple displays: *distant-contiguous* (multiple displays placed at a large distance that occupy the same visual angle as a standard desktop monitor); *desktop-contiguous* (multiple displays that tend to widen the visual angle when placed at a distance equivalent to a standard desktop monitor); and *non-contiguous* (multiple displays at different distances from a user that do not occupy a contiguous physical display space). We borrow this classification to formulate categories according to our display contiguity factor.

Nacenta et al. [22] classify interaction techniques for cross-display object movement according to the *referential domain* (the way the user and the system refer to a particular display), the *display configuration* (the way displays are arranged in the logical workspace), and the *control paradigm* (the nature of the visual feedback). Of these, only *display configuration* is directly relevant for attention switching and relates to our display contiguity factor.

Dix and Sas [10] outline a design space of private mobile devices and public situated displays based on six factors including *physical size* (poppyseed-scale to perch-scale), *input device use* (e.g. selection, pointing, text input), *social context* (witting/unwitting participants/bystanders), *participant-audience conflicts* (e.g. conflicts of content), *spatial context* (fully public, to semi-private) and *multiple device interaction* (when and where interactions with multiple devices happen). The multiple device interaction is relevant for our purpose because it affects how content relates across different displays, which corresponds to our content coordination factor.

Luyten and Coninx [18] propose a model of Distributed Interaction Space (DIS) with an implicit taxonomy. A Distributed Interaction Space (DIS) consists of UI elements distributed across input/output resources of multiple computing devices [18]. The behavior and performance of people interacting with a DIS is affected by the UI components, as well as by the characteristics of the devices that render these components (e.g., mobility and tangibility). A DIS is classified according to three categories: *location-oriented* (location of UI elements in the user's space); *task-oriented* (tasks one or more users execute to achieve a shared goal); and *device-oriented* (interaction resources, which represent the separate input/output capabilities of each device). Our focus is on “device-oriented” DIS because it deals with the input and output capabilities of the devices containing MDUIs.

3. VA-BASED TAXONOMY OF MDUIs

Building upon the taxonomies described in Section 2, we propose a taxonomy to help understand the relationship between MDUIs configuration and visual attention switching. The factors in our taxonomy represent the characteristics associated with the visual arrangement (VA) of MDUIs that can affect attention switching patterns. There are five factors:

- display contiguity (visual field contiguity, depth contiguity),
- angular coverage (panorama, field-wide, fovea-wide),

- content coordination (cloned, extended, coordinated),
- input directness (direct, indirect, hybrid), and
- input-display correspondence (global, redirection, local).

For each factor, the following subsections provide a detailed explanation, classify some of the existing work containing MDUIs accordingly, and analyze related research relevant to visual attention switching.

3.1 Display Contiguity

Swaminathan and Sato’s classification of multi-display configurations [38] is useful to understand the spatial relationship between displays; however, it does not take into account the increasing diversity of display form factors such as handheld displays. For our purposes, we define two categories of display contiguity: visual field contiguity and depth contiguity.

Visual field contiguity. Displays appear contiguous in the visual field, but may be separated by bezels or placed at different distances from the observer.

Depth contiguity. Displays are placed at the same distance from the observer but they may not be placed adjacent to each other.

This classification generates four different permutations of display contiguity as shown in Figure 1. We classify some of the existing work containing MDUI under each of those permutations.

3.1.1 Visual Field & Depth Contiguous

Displays in this category are placed at the same distance from the observer and they also appear contiguous in the visual field, as shown in Figure 1(a). Multi-monitor setups are often arranged in this configuration. Another example is ConneCTable displays [40] that form a larger display area when put together, or display walls composed of multiple flat displays.

3.1.2 Visual Field Discontiguous, Depth Contiguous

Here displays appear discontiguous in the visual field but they are placed at the same distance from the observer, as shown in Figure 1(b). For example, in Synctap [28], tablets are typically separate from each other but in the same plane.

3.1.3 Visual Field Contiguous, Depth Discontiguous

Displays here are placed at different distances from the observer but they appear contiguous in the visual field, as shown in Figure 1(c). For example, in E-conic [25] and Ubiquitous Graphics [32], displays are placed at different depths but they can appear to be in the same visual field (or overlapping) depending on the user's perspective.

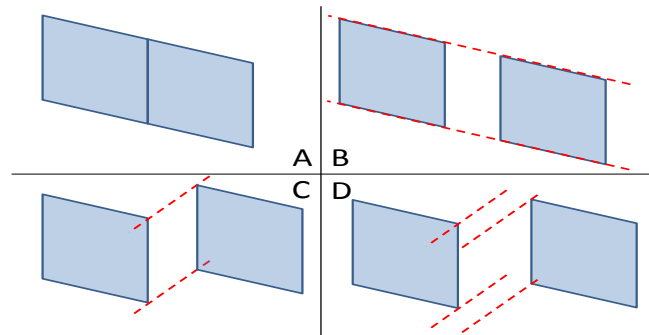


Figure 1. Display contiguity factor: A) visual field & depth contiguous, B) visual field discontiguous & depth contiguous (C) visual field contiguous & depth discontiguous (D) visual field & depth discontiguous.

3.1.4 Visual Field & Depth Discontiguous

Displays here are placed at different distances from the observer and they do not appear contiguous in the visual field, as shown in Figure 1(d). For example, in Courtyard [41], a shared overview is shown on a large screen and per-user details are presented on individual screens. In SharedNotes [14], each handheld PDA shows the personal contents while the public contents are shown on the large wall display.

3.1.5 Summary of Existing Systems

Table 1 shows the contiguity of displays in some of the work containing MDUIs. Note however that some MDUIs can be in multiple categories if the position of the user or displays is adaptable. For example, in regular use, Geney™ [9] supports “depth contiguity & visual field discontiguity” when the handheld displays are held close but it can switch to “depth & visual field discontiguity” if those displays are held at a large distance.

Table 1. Display Contiguity in MDUIs

	Visual Field Contiguous	Visual Field Discontiguous
Depth Contiguous	Connectable [40], Multi-monitor desktop, Multi-tablet composition [19]	Geney™ [9], SyncTap [28], Dynamo wall displays [15]
Depth Discontiguous	E-conic [25], Magic Lense [31], Touch Projector [6], Ubiquitous Graphics [32]	Courtyard [41], Dynamo wall displays & tabletop [15], Interactive TV remote [30], i-LAND [37], iPad Scrabble [33], iRoom [16], LenseMouse [47], Projector laptop and phone, SharedNotes [14], UbiTable [34]

3.1.6 Relevance to Visual Switching

The contiguity of displays can persuade viewers to adopt different levels of attention switching with MDUIs that can affect performance in various tasks. Tan and Czerwinski [39] found no effects of visual separation due to bezels and physical distance between screens alone, for text comparison and proofreading tasks. However, bezel and depth together caused a detrimental though negligible effect on performance in the aforementioned tasks [39]. Yang et al. [47] found that it was the relative depth, and not bezels, between Lens-Mouse (a mouse with screen on top) and the computer screen that caused degradation of task performance. Bi et al. [5] found the bezels on tiled-monitor large displays to be detrimental to performance in straight-tunnel steering task but not in visual search and target selection tasks. Nacenta et al. [23] showed that the “displayless space” (i.e. physical gap between displays) slows down the movement of visual objects across displays. Cauchard et al. [7] found that in a mobile multi-display environment, although performance in a visual search task was unaffected by the displays being in the same or in different visual fields, more gaze switches occurred when both displays were in the same visual field. In contrast, a study by Rashid et al. [26] suggested significant degradation of performance due to replicating contents across a mobile handheld display and a vertical large display for visual search tasks.

The aforementioned examples from the existing literature suggest that performance effects of display contiguity differ with respect to the task at hand. Bezels per se have not shown to cause large degradations in performance in tiled-monitor displays [5, 39, 47] except in the straight-tunnel steering task [5]. The performance overhead in a straight-tunnel steering task, as well as an increased time for multi-monitor display targeting [23] may be due to the discontinuity in visual representation rather than attention switching. In any case, small bezels will result in small

performance overheads, and therefore we exclude bezels from consideration in the classification of systems according to visual field contiguity. On the other hand, depth is reported to have caused an overhead in some tasks across multiple displays [26, 47]. Further research is needed to determine how display contiguities in visual field and depth contribute to attention switching and performance differences in various tasks across MDUIs.

3.2 Angular Coverage

Another important factor that might influence the need for visual attention shifts is the angular size covered by the MDUI. This factor is inspired by the *size of ecosystem* and *physical size* described in Terrenghi et al. [42] and Dix and Sas’s [10] work respectively, and is adapted to consider the relationship between the point of view of the user with respect to the size of the MDUI.

This factor is of a more continuous nature than the rest. Nevertheless, we define three marker points in this continuum: panorama, field-wide and fovea-wide.

3.2.1 Panorama

These are systems that surround the user, and therefore require the movement of body or head to view the whole display space. This does not mean that a single display must cover the whole area, rather that the displays that comprise the system are situated in such a way that they cover a large part of the spherical area around the head of the observer. For example, any room that has displays facing each other will be panoramic to a user located between them. Most room-based MDUIs will therefore fall close to this end of the continuum (e.g., [25, 37, 46]).

3.2.2 Field-wide

The human visual field covers around 200° horizontally and 135° vertically. Field-wide systems have displays that cover an angle that fits within this range and can therefore be centered in the fovea by changing the direction of gaze. Systems that are closer to field-wide than fovea wide include wall-based and MDUIs with large displays (e.g., [15, 17, 34]).

3.2.3 Fovea-wide

At the other end of the continuum, we place systems where the whole display space fits within a human fovea (about 2°). There are very few MDUIs that exist at this extreme end of the continuum, but some examples are closer to fovea-wide than field-wide category (e.g., [9, 21]).

3.2.4 Summary of Existing Systems

Some MDUIs are categorized by angular coverage in Figure 2. As stated earlier, these are subject to user and display repositioning.

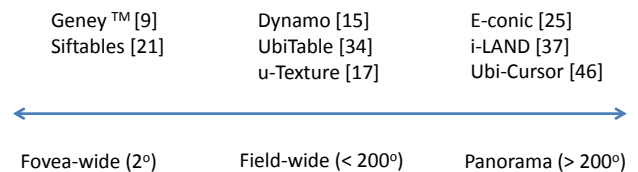


Figure 2. Angular coverage in systems containing MDUIs

3.2.5 Relevance to Visual Switching

Terrenghi et al. [42] associate the size of an ecosystem to eye-, head-, and body movement, which is directly relevant to the focus of our taxonomy. It is expected that MDUIs that have wider angular coverage will require more, and more onerous, attention switching. This area has not been widely studied in the context of

MDUIs, although we can speculate that some degradation in performance (e.g., [46]) is due to this effect. This issue needs to be explored further.

3.3 Content Coordination

Content coordination refers to how the contents in different displays are semantically connected. This notion is motivated by visualization research in coordinated and multiple views [44] (views that contain different visualizations of the same data). Below, we specify three categories of content coordination.

3.3.1 Cloned

In this category, all displays mirror each other's content, although each display might be of a different size and resolution. This type of coordination is supported by most operating systems, and it is common in projector-connected laptops, projector phones and on some commercial systems such as Apple's Airplay technology. Virtual Network Computing (VNC) [29] enables cloning of the interface across standard personal computers.

3.3.2 Extended

In this category, multiple displays act together as a large extended display that spans those displays. Different displays show different parts of the same visual whole. This type of coordination is common with multiple monitors connected to the same desktop computer. Lyons et al. [19] built a multi-display composition system that enables several tablet computers to join together over a wireless network to form a larger logical display.

3.3.3 Coordinated

In this category, each display shows different content, but the contents are related in some way other than complete replication (i.e., other than cloned). There are many ways to coordinate the content across displays; for example, one display can show an augmented or a partial view of certain area of the other (e.g., [6, 9, 14, 26, 31, 32, 41]), or one display can serve as remote control of the other (e.g., [3, 30, 33]).

3.3.4 Summary of Existing Systems

Table 2 shows the coordination of content in some of the work containing MDUIs. In some cases, it is the application or the usage that determines the type of content coordination, and some systems can support applications that are categorized differently.

Table 2. Content Coordination in MDUIs

Content Coordination	Examples
Cloned	Projector Phone, Projector desktop
Extended	E-conic [25], Multi-monitor desktop, Multi-tablet composition [19], Connectable [40]
Coordinated	Courtyard [41], Ubiquitous Graphics [32], SharedNotes [14], Dynamo [15], Geney™ [9], Interactive TV remote [30], i-LAND [37], iPad Scrabble [33], iRoom [16], LenseMouse [47], Magic Lense [31], SharedNotes [14], Touch Projector [6], UbiTable [34]

3.3.5 Relevance to Visual Switching

Although it seems likely that content coordination between UI elements in different displays will affect attention switching behavior, there are, to our knowledge, no studies that explicitly investigate this phenomenon. Some previous work partially addresses this issue. For example, design guidelines for multiple coordinated views suggest that views should highlight different aspects of the same information; otherwise context switching between the different views can undermine user interaction [44]. This suggests avoiding *cloned* arrangements for tasks involving a

single user. Rashid et al. [26] found that simple *coordinated* visuals on a mobile-large display MDUI can cause attention switches linked to performance overhead for text, image and map search tasks. Forlines et al. [11] showed that for an individual user, an image shown in different rotations (i.e. *coordinated* arrangement) on four vertical displays screens degraded performance in a visual search task compared to the same image shown on a single vertical display. Bi et al. [5] showed that splitting an object across screens (i.e., *extended* arrangement) leads to increased completion time in straight-tunnel steering task and causes more errors in a visual search task. Grudin [13] observes that the visible gap between individual monitors discouraged users from making the content span multiple displays, and that they instead used additional monitors to separate content belonging to different tasks (i.e. *extended* arrangement). Further research is needed to investigate the influence of different categories of content coordination on attention switching and task performance.

3.4 Input Directness

The previous factors mostly deal with the size and spatial distribution of visual elements across displays; however, how input is provided in MDUIs can also play a role since visual attention is often involved in the input loop. The following categories correspond to traditional HCI categorizations of input.

3.4.1 Direct

Input is *direct* when the motor actions of the user take place roughly in the same location as the output (e.g., in touch UIs).

3.4.2 Indirect

Input is *indirect* when there is a spatial separation between the input device (where the user's motor actions occur) and where the visual feedback is provided (e.g., using a mouse to control an on-screen cursor).

3.4.3 Hybrid

We classify the input of an MDUI as *hybrid* when direct input is present but alternative feedback is provided in a different display, which allows the user to switch to indirect input if desired. Hybrid input is common in systems where output is *cloned* and the main input device is *direct*. Examples include projector phones as well as systems with any kind of World-In-Miniature (WIM) input mechanisms [36] where the input to miniaturized view is reflected as output in both the miniaturized and the full-scale views.

The directness of input in relation to the location of output has been discussed earlier for single-display systems (e.g., [24]).

3.4.4 Summary of Existing Systems

Table 3 shows a classification of some existing MDUIs according to the directness of input.

Table 3. Input Directness in MDUIs

Input Directness	Examples
Direct	Connectable [40], Geney™ [9], i-LAND [37], iPad Scrabble [33], iRoom [16], Multi-tablet composition [19], Pick-and-Drop [27], SyncTap [28]
Indirect	Courtyard [41], Dynamo wall displays [15], E-conic [25], Multi-monitor desktop, UbiCursor [46]
Hybrid	LenseMouse [47], Projector Phone, Ubiquitous Graphics [32], SharedNotes [14], Touch Projector [6], UbiTable [34], WIM [36]

3.4.5 Relevance to Visual Switching

McLaughlin et al. [20] highlighted that the input device itself imposes attentional demands and a user's task performance is affected by the match between the input device and the action performed on the interface. Indirect input is good for tasks such as repetitive motion and precise movement, while direct input is good for pointing tasks and ballistic movements [20].

We have not encountered any research activity that explicitly compares attention switching and performance effects related to input directness in MDUIs. However, some efforts in related domains report on results that can be applicable to MDUIs. Nacenta et al. [24] explored the relative performance of differing input directness in tabletop interactions. Forlines et al. [12] found better performance of direct input for bimanual tasks, and equivalent performance of direct and indirect input for unimanual tasks on a tabletop display. Further research is needed to explore the role of input directness in attention switching and performance in different tasks across MDUIs. In particular, it is important to know whether hybrid input configurations result in equivalent or degraded performance due to the possibility to switch input types between and within tasks, which will likely require visual attention switches.

3.5 Input-Display Correspondence (IDC)

This factor is closely coupled to the input directness factor and partially determines it. We distinguish three types of input-display correspondence.

3.5.1 Global

In this kind of systems, input control is common for all the displays and is bound to none of them in particular. For example, the standard multi-monitor setup uses a single mouse and keyboard to control all sources of output. Similarly in E-conic [25], any user with an air mouse can operate in any of the displays. By definition, MDUIs relying on global input-display correspondence have also indirect input.

3.5.2 Redirectional

This category describes systems where the input mechanism is provided on a single display and input is redirected to other displays to manipulate content on their surfaces. An example is the Point & Shoot technique [1], where the camera phone provides an input mechanism to interact with the large display. Typical projector phone interfaces also fall under this category where the input is provided on the display device. Robertson et al.'s PDA controlled interactive real estate information system [30] also falls within this category. Other examples include the use of mobile phones as optical mice [1], magic lenses [31] or as conduit for exchanging content between displays [6]. Berger et al. [4] built a solution that allows users to push their e-mail messages from a mobile phone to an external large display. Redirectional input-display correspondence will typically result in hybrid input.

3.5.3 Local

Local input-display correspondence refers to systems where each display is provided with its own input mechanism. For example, each PDA in GeneyTM [9] has an independent input. The same holds true for the displays that support Pick-and-drop technique [27]. The SyncTap [28] system establishes a network connection between two devices when the user synchronously presses and releases the button on each device. The SharedNotes system allows data sharing between PDAs and shared public screens in a similar fashion [14]. Usually, local input-display correspondence takes advantage of direct input.

3.5.4 Summary of Existing Systems

Table 4 classifies MDUIs into input-display correspondence categories.

Table. Input-Display Correspondence in MDUIs

Input-Display Correspondence	Examples
Global	Multi-monitor desktop, Dual Screen phone, E-conic [25]
Redirectional	Interactive TV remote [30], LenseMouse [47], Magic Lense [31], Projector laptop, Projector phone, Ubiquitous Graphics [32], Touch Projector [6]
Local	Courtyard [41], Geney TM [9], i-LAND [37], iPad Scrabble [33], iRoom [16], Pick-and-Drop [27], SharedNotes [14], SyncTap [28], UbiTable [34]

3.5.5 Relevance to Visual Switching

The effects on visual attention switching of input-display correspondence are partly determined by its close relationship with input directness; however, there are some additional considerations. Since MDUIs with separate displays and redirectional input-display correspondence tend to use mobile devices for input, it is likely that the spatial mapping between the input space (in the mobile device) and the output space (in a separate device) is not straightforward. Several studies have shown that this kind of mapping is detrimental to performance. For example, Wigdor et al. [45] found that orientation of the control space with respect to the display space affected performance while interacting with a large display in different seating positions, and Wallace et al. [43] reported on performance loss due to input redirection in a multi-display environment when users were seated not facing the display. Further research is needed to determine whether these disadvantages outweigh the benefits of using local input and whether the degradation in performance is affected by visual attention switching behavior.

4. CONCLUSIONS

Based on a review of existing literature on multi-display systems, this paper identifies the factors that can influence visual attention switching across MDUIs. It presents a taxonomy of MDUIs to help understand the relationship between MDUI configurations and visual attention switching. The taxonomy is based on five factors: display contiguity, angular coverage, content coordination, input directness, and input-display correspondence. Some of the existing work containing MDUIs is classified based on these factors. We discuss the relevance of each factor to visual attention switching and identify the avenues for future research in the context of MDUIs. This survey and taxonomy can be helpful for practitioners who want to anticipate possible pitfalls for their designs and acquire a basic understanding of what is known, and researchers who need to communicate about research in this area and address unresolved issues of MDUIs.

The work presented here is intended as an initial step towards a deeper understanding of MDUI design; much research remains to fully map how the basic decisions on the design of MDUIs will affect performance and errors. More importantly, as these systems become more common, it will become more feasible (and more important) to assess how higher-level variables such as comfort, user preference, and fitness for the task, are affected by the different design alternatives.

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