Usable Multi-Display Environments: Concept and Evaluation

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Abstract. The number of conference or meeting rooms with multiple displays available is on the rise. While this increased availability of displays opens up many new opportunities, the management of information across them is not trivial, especially when multiple users with diverging interests have to be considered. This particularly applies for dynamic ensembles of displays. We propose to cast the Display Mapping problem as an optimization task, where we define an explicit criterion for the global quality of a display mapping and then use computer support to calculate the optimum. We argue that in dynamic multi-user, multi-display environments, an automatic – or at least computer supported – document-display assignment improves the user experience in multi-display environments.

1 Introduction: Managing Multi-Display Environments

Multi-Display Environments[1] support collaborative problem solving and teamwork by providing multiple display surfaces for presenting information. Typical examples for such environments are meeting rooms, conference rooms, and "mission control centers", as shown in Figure 1.

One difficult task here is the *Display Mapping problem* – that is, deciding which information to present on what display in order to optimally satisfy the users' needs for information. While this task is more or less trivial in single-user, single-display situations, it becomes challenging in multi-user, multi-display settings: Users and displays are spatially dispersed so that the visibility of (semi-) public and private displays varies across users. Also, information needs may vary across users, so that finding the "best" assignment of information to displays becomes a typical optimization problem.

One solves an optimization problem by defining an objective function $q(x)$, the "quality" to maximize, and then applying a suitable optimization algorithm to compute $x_{max} = \arg\max_{x \in X} q(x)$.

In this setting the Display Mapping problem gives rise to two subproblems:

[1] See e. g. the UbiComp 2004 workshop on Ubiquitous Display Environments [1].

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Fig. 1. Examples of multiple display environments. (i, left) Stanford's iRoom; (ii, right) Rostock University Smart Appliance Lab; (iii, bottom) the "Management Cockpit" at Iglo-Ola, Unilever Belgium

- What is a suitable definition for $q(x)$? I. e., what is the objective function to be maximized in order to achieve an optimal (or at least: satisfactory) solution for the Display Mapping problem?
- How should the computation of x_{max} be distributed across the members of an ensemble of displays? – This is especially interesting, when dynamic ensembles have to be considered (e.g., portable projectors carried into a meeting room, etc.).

In this paper, we outline a strategy for achieving an automated display mapping using an optimization framework, and we discuss an experimental setup for evaluating the benefit of automated multi-display environments.

The further structure of this paper is as follows: in Section 2, we motivate why an automated display mapping is necessary. In Section 3, we provide an in-depth discussion of the display mapping problem and our proposal of a global quality function q for this problem. The experimental design and first results of our evaluation of an automated display mapping in comparison to a manual assignment is described in Section 4. A discussion of the results and further work is given in Section 5.

2 The Need for Automatic Display Mapping

Why do we need automated display mapping? – Couldn't the users just do the assignment manually, using a suitable interactive interface, resolving conflicts by social protocols (negotiations)? One example for such a manual display assignment is the ModSlideShow system [7], which is designed to manage presentation slides on multiple displays. Displays can be linked and grouped into flexible configurations depending on their physical layout in the environment and on the scenarios of use. For assignment of content to displays, meeting participants drag-and-drop presentations from their note books to any of the available displays. Another example providing a similar interaction mechanism is the PointRight software developed for Stanford's Meyer Teamspace [2].

However, we do not believe that such a solution would be successful in the long run (i. e., as multiple display environments become more and more complex) because of the following issues:

1. **Interest conflicts** between users will need a computer supported negotiation mechanism: Morris et al. [8] have already observed that social protocols do not always suffice for coordinating the use of shared resources, such as display surfaces, in teams – even in relatively simple situations. They suspect that the need for coordination may increase as the number of users, the number of documents, or the number or size of the surfaces increases. Indeed, they advocate the development of specific strategies for automatizing the negotiation process.
2. The need for **dynamic realignment** of Display Mapping is caused by topic changes in the user population – in this situation, the user's focus of attention will be on the changing topic rather than on convincing the display infrastructure to change the topic.
3. In a dynamic multiple display environment, the **user will not be able to know** (and will not want to know) the **displays currently available** to him. With dozens to hundreds of possible display configurations, the user will have to rely on the infrastructure to select the best choice for him.

We call a solution process that does not require human intervention an *unsupervised* process. Although there is substantial research in multi-display environments, to our knowledge, the development of an interaction-free, automatic display assignment has not yet been addressed on a general level (i.e., independent of a specific ensemble).

In [3] we have presented a distributed optimization algorithm supporting the unsupervised display assignment. This algorithm has the further advantage that it requires only *local knowledge* at each participating device. Next, we discuss the basic properties of a quality measure – q(x) – that can be used for solving the display mapping problem.

3 Defining Optimal Display Assignment

3.1 The Basic Idea

Consider the simple Display Mapping problem outlined in Figure 2, left. There are two users u_1, u_2 sitting at a table and three display surfaces s_1, s_2, s_3 (for instance, backprojection displays or simply screens with an associated projector). User u_1 is interested in documents d_1 and d_2, user u_2 is interested in d_1 and d_3. Also, u_1 has very high interest in d_1 (maybe it is the presentation currently delivered by u_2). In this situation, considering the positions of users and display surfaces, the resulting display visibility, and the user's information needs, an optimal mapping of documents to the available display surfaces is given by the mapping outlined in Figure 2 at right: $u1$ gets optimal visibility of his most important document on $s3$ and acceptable visibility of $d2$ by looking sideways on $s1$. Similarly $u2$, gets acceptable visibility of $d1$ and $d3$.

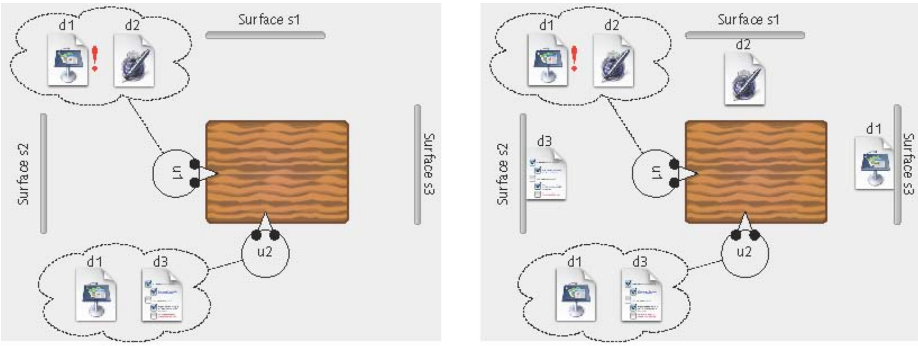

Fig. 2. Mapping documents to displays. Initial situation (left) and optimal mapping

Let D, U, S be the sets of documents, users, and surfaces, respectively. Let $impt(d, u) \in [0 .. 1]$ denote the importance of the document $d \in D$ to a user $u \in U$ and $vis(s, u) \in [0 .. 1]$ the visibility of surface $s \in S$ by user $u \in U$. Let furthermore $sm \in D \rightarrow 2^S$ be a mapping of documents to display surfaces, such that $sm(d) \in 2^S$ denotes the set of surfaces to which document $d \in D$ is assigned. Then the quality achieved by the mapping sm can be defined as

$$q(sm) = \sum_{\substack{u \in U \\ d \in D}} impt(d,u) * \max_{s \in sm(d)} vis(s,u) \tag{1}$$

This definition is based on the manifest intuition that, in a good mapping, documents with high importance (for specific users) should be assigned to display surfaces with high visibility (for this user). In addition, if a document is assigned to multiple display surfaces, only the best one for a given user is considered when computing the quality for this user (this is the "max vis" term).

Finding the optimal mapping $sm_{max} = \arg\max_{sm \in D \rightarrow 2^S} q(sm)$ requires to explore the possible document-to-surface maps in a suitable manner in order to find surface map giving the best quality.

A basic issue with the notion of multiple displays environments is whether they are modeled as a single continuous surface or as multiple loosely connected surfaces. The former model has been investigated in projects such as [9, 2], where a continuous surface is formed by mapping the edge of each display to the nearest edge of the nearest display. In our discussion, we use the latter model, where the displays can be freely distributed across a room, e.g. [10–12].

3.2 Accounting for Different Types of Displays

Since some time, steerable projectors such as the Everywhere Display [4] are being investigated for a flexible information display by several research groups (see [5] for a short overview). And our lab infrastructure too provides such a device. The introduction of steerable projectors introduces another degree of freedom in the display mapping process, as a steerable projector may be able to choose between different projection screens. We therefore need to distinguish between *Display*s (devices which can present a document) and *Surface*s (regions in space on which a display renders a document). For some devices, the mapping from display to surface is fixed (i.e., a notebook display will always render on the notebook's screen surface; a fixed beamer will always render on the screen it is looking at), while for other devices it is variable (i.e., a steerable beamer that can pick different screens to project on).

Let Y denote the set of displays and S the set of available (display) surfaces. Furthermore, let $rend(y, s) \in [0 .. 1]$ be the rendering quality achievable by display $y \in Y$ on surface $s \in S$ (for devices with fixed display surface, $rend$ will be 1 for this surface and 0 everywhere else). We now have to replace sm by *two* mappings: $dm \in D \rightarrow 2^Y$, mapping documents to sets of display devices, and $ym \in Y \rightarrow S$, mapping displays to surfaces. And our definition of q is changed to

$$q(dm, ym) = \sum_{\substack{u \in U \\ d \in D}} impt(d,u) * \max_{y \in dm(d)} \left(vis(ym(y),u) * rend(y, ym(y))\right) \qquad (2)$$

so that we now have to look for $(dm_{max}, ym_{max}) = \arg\max_{\substack{dm \in D \rightarrow 2^Y \\ ym \in Y \rightarrow S}} q(dm, ym)$.

As a first approximation to computing vis and $rend$, we have chosen Lambert's law of reflection, which gives the visibility (or rendering quality) as cosine of the angle between the rendering surfaces' surface normal n_s and the vector connecting the surface and the projector (resp. the user). A similar approach has been taken by the EasyLiving Geometry model [6]. We would like to emphasize two points with respect to our definition of q:

- q has been defined completely independent from a concrete ensemble of users, displays, documents, and surfaces. It describes the globally optimal behavior for any possible ensemble. Once machinery is available for computing the optimum for q, any ensemble will be able to behave optimally – as far as q is a correct definition of an ensembles global optimum from the user's point of view.
- Our definition of q for the display mapping problem is still rather simplistic – for instance, it lacks a notion of "history", that would keep a document from confusingly hopping from display to display as the user slightly shifts position. So, q does not yet faithfully describe an ensemble's global optimum from the user's point of view. An improved definition of q is the objective of ongoing user studies (first experiments are described in Section 4 below). But even though q is not final yet, it shows that an ensemble's globally optimal behavior *ca*n (and should!) be defined explicitly in a way that is independent of a specific ensemble realization.

The details on the distributed algorithm we have developed for approximating q can be found in [3]. (Basically, we use a distributed version of the Greedy Randomized Adaptive Search Procedure, GRASP.)

4 Evaluation of Automatic Display Assignment

4.1 Objectives and Overall Experimental Design

Objective of our evaluations is to answer the following questions with respect to automatic display mapping in general and the definition of q specifically:

- Is it possible to predict and automatically generate a good document display mapping that would satisfy a reasonable subset of users? Are the configurations produced by the algorithm actually useful and sensible to users in multi-display environments? What benefits does automatic content distribution offer over manual distribution?
- Is it possible to do automatic content distribution in a way that users find usable, intuitive, understandable, and satisfying? How does this compare to existing techniques for assigning content to displays?
- Is it possible to develop a universal approach, or do different application domains, situations, and contexts require different assignment strategies (or even a pure manual mechanism)?

In this paper, we focus on the objective to quantify the benefit of an automatic display assignment in comparison to a manual assignment in a multi-user, multi-display environment.

The evaluations are based on two experiments:

- Calibration experiment: Objective of the calibration experiment has been to verify that a multiple display environments is able to improve performance in comparison to a single display environment. (We conducted this experiment – for which we considered the outcome as obvious – as safety measure against a seriously flawed experimental setup.)
- Evaluation experiment: Objective of this experiment is to measure the impact of manual vs. automatic display assignment on the performance of a team in solving a semi-cooperative assignment. In semi-cooperative tasks, the need of cooperation and joint use of information is not evident from the start – we think that this kind of aspect pertains to many team processes, specifically in multidisciplinary teams.

Both experiments were carried out in our Smart Appliance Lab (cf. Figure 1, right). This environment provides six projection based public displays, arranged in two pairs at three sides of the room that were used for the experiments (see Figure 3, left)[2].

[2] Other infrastructure available in the Smart Appliance Lab – such as steerable beamers, additional motor screens, UbiSense-based location tracking, remote-controlled lighting and HVAC, etc. – will be used in future experiments.

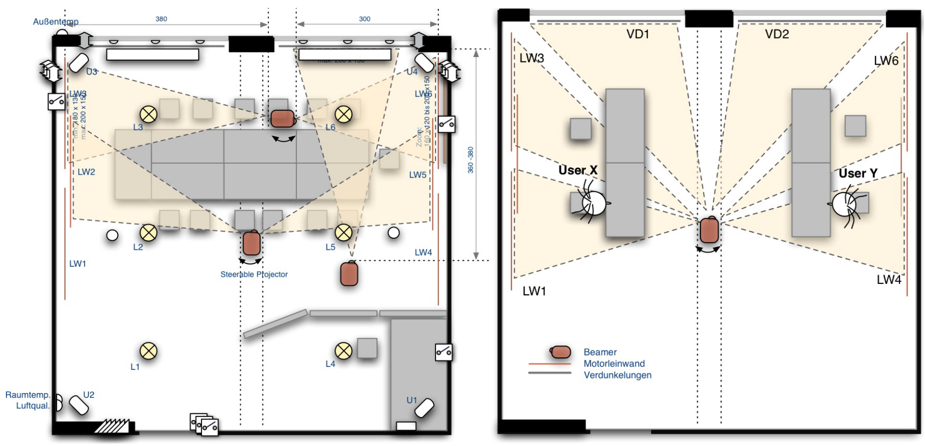

Fig. 3. Smart Appliance Lab, equipment examples (left), configuration option (right)

4.2 Calibration Experiment

Goal and Hypothesis. Objective of this experiment was to establish that multiple display environments improve the performance over single display environments. Specifically, we wanted to make sure that this performance improvement is valid for the type of tasks intended for the following evaluation experiment.

Procedure. The subjects were given the task of finding the differences between two similar pictures[3]. Subjects in group A were given a single display (which could present only one picture at a time), subjects in group B were given two displays, so they could compare both pictures side by side. We measured the time it took the participants to complete each task.

Results. Although only a few participants per group took part in the evaluation, the result was clear. The group with the option to use two displays was able to solve the task in distinctly shorter time. Also the post-experiment questionnaire showed, that all participants would prefer a multi-display environment over a single-display environment for this kind of task. This result is not very surprising and confirms our hypothesis.

4.3 Evaluation Experiment

Goal and Hypothesis. Objective of this experiment was to compare the effect of manual and automatic display assignment on task performance. Our hypotheses is that automatic assignment enables teams to solve their tasks in a shorter time, with less conflicts between team members, and with greater satisfaction.

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[3] Source: Gregory, Richard L.: Eye and Brain – the Psychology of Seeing, Oxford University Press, 1998.

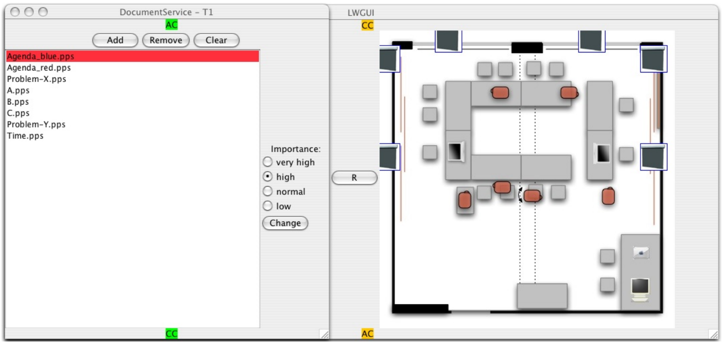

Fig. 4. GUI for document importance and document-display assignment

Procedure. For the experiments, every participant was given a simple user interface for document assignment. Manually assignment of a document to a display-surface is done through a simple "drag & drop" (Figure 4, right). For automatic assignment, the user just associates an importance value with the documents (Figure 4, left). The optimal document-display assignment is then computed using our goal function q.

In the experiment, two-person teams had to solve a semi-cooperative task as fast as possible. The seating arrangement used for a team is shown in Figure 3, right. Note that there are two pairs of displays exclusively visible to User X and Y of a team, and one display pair visible to both X and Y. The teams were assigned to two equal-sized groups, A and M, using automatic or manual assignment, respectively. The team members X and Y were given different agendas, containing different tasks for the two users. For X the task was to compare two documents A and B, for Y the task was to compare A and C. The task was a simple letter comparison, counting the number of differences in two letter sequences. In addition, X and Y had to report time information and a random key from another document Time. The seemingly unrelated tasks for X and Y were linked into a cooperative task through the shared documents A and Time – see Figure 5 for the documents.

As the agendas and task descriptions were mutually unknown, the sharing had to be discovered through a conflict in the manual assignment group. (In order to enforce resource conflicts in this simple setting, each document could only be displayed on one display at a time.)

For each team, we recorded the time required for completing the task as well as the subjective feeling of conflict and user satisfaction (using a questionnaire).

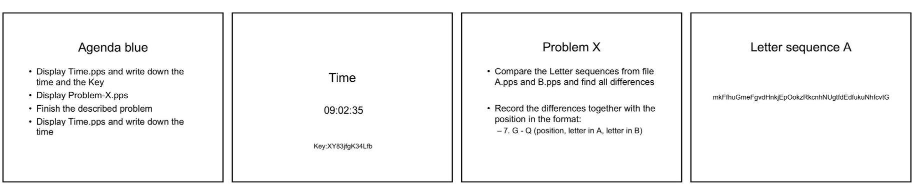

Fig. 5. Problem documents, from left: Agenda, Time, Problem-X, A

Results. Although the first tests involved only a small number of teams (experiments are ongoing), the results seem to indicate a consistent trend: in all cases, the teams from group A finished the tasks in a shorter time than the "manual" teams (group M). The satisfaction seems to be higher, and conflict is experienced less in the A teams. The M teams initially had no idea that they needed to share documents. So they unwittingly "stole" the shared documents from each others "private" displays. It required a couple of minutes, until the M participants realized that they needed to cooperate and to assign some of the documents to a display visible to both users. This process of realization and negotiation was the reason for confusion and delay. In the A group no such conflicts did arise as the system automatically displayed shared documents on a shared screen. This resulted in an overall greater satisfaction for the A group.

5 Conclusion and Future Work

In this paper, we have discussed the problem of assisting teams in effectively using multi-display environments for working together. We have claimed that the optimal behavior of such an environment can be formulated rigorously as an optimization task so that an automated solution to the display assignment problem should be possible. Providing an automated assistance in using multi-display environments is based on the hypothesis that there are situations, where an automatism streamlines and simplifies the social negotiation processes required for agreeing on the use of limited resources in a team of users.

Our – ongoing – experimental work indicates that there is indeed a noticeable effect of display assignment methods on team performance, at least for semi-cooperative tasks. An automatic display assignment here seems to (i) improve the team effectiveness (measured in time to complete a task), (ii) to reduce the level of conflict in the team (i.e., the number of arguments about resource use), and (iii) to improve the individual user experience and satisfaction.

Unfortunately, our experiments are still in a very early stage so that our results are anecdotal evidence and not yet statistically valid. Remedying this deficiency is objective of the next experimental phase. Also, other aspects such as understandability of the computed assignment and its compatibility with user expectations have to be measured. The same holds for an assessment of the usability of automatic display assignment in other team situations.

To summarize, although there are many open questions, we have shown that it seems possible that automatic display assignment provides a measurable benefit in multi-display environments, at least in some situations. Future investigations will have to show whether this benefit offers the universality and significance required to incorporate it generally into such environments.

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