Situated Micro-displays for Activity-Aware Systems

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Abstract. Most activity-aware systems designed to support mobile workers in dynamic environments, such as hospitals or industrial plants, typically consider the use of mobile devices and large displays. However, we envision potential benefits of using ubiquitous micro-displays as support of mobile workers activities. Particularly, in this paper we show how the use of situated micro-displays, as a mechanism for embedding information into a physical environment, can contribute to improve the performance and experience of mobile workers in those scenarios. The article also describes the prototype of a micro-display network designed to support people performing spatially distributed activities. It also presents a user study that helps understand how the spatial distribution of situated micro-displays impacts on the mobile workers performance.

Keywords. Situated micro-display, activity-centric system, mobile work.

1 Introduction

Advances in wireless communication, sensor networks and ubiquitous computing have made possible the interaction between people and numerous devices that are interconnected and physically distributed in the environment [1]. These advances have promoted the evolution of single-monitor setups towards multi-display environments [2], where it is possible to have displays embedded in a physical ambient and also in everyday objects. Several studies on workplaces have shown how instrumented environments and everyday artefacts support people cognition and collaboration [3,4]. Researchers have emphasized the need to deliver task-centric information in dynamic workplaces, such as hospitals or industrial plants, as a way to support the activities performed by mobile workers [5,6].

Typically, *situated information systems* [7] provide information of the physical environment to mobile workers, and *activity-aware systems* [8] infer the workers' activity context in order to offer them suitable supporting services. Most of these systems types rely on the use of mobile devices and large displays [9]. However, recent researches [10] advocate for the use of micro-displays to provide situated information in activity-aware systems and offer activity-specific guidance. These micro-displays are mobile and adaptive. They are distributed across the environment and provide simple visual representations of human activities that are linked to physical entities –such as objects and people– and integrated in the environment.

We envision the potential benefits of using micro-displays to provide instructions and activity-centric information to mobile workers in highly dynamic work contexts. Consequently, this paper describes a prototype of an activity-aware system based in micro-displays.

As stated in [10], the use of multiple micro-displays raises a number of questions regarding their spatial placement and distribution. For instance, where and how the displays should be deployed in a physical environment to optimize the information support to mobile workers? In that sense, particular studies are needed to identify the trade-off between the quality of the information provided by the micro-displays and the fragmentation of users' attention. By increasing the number of displays we can show the information in a fine-grained and situated fashion. However, too much and/or not-so-relevant information demands higher cognition and could lead to information overload, jeopardizing its assimilation by the end-users. Therefore, it is critical to understand the impact of the distribution granularity and placement alternatives of micro-displays to positively impact the effectiveness of activity-aware systems. Trying to deal with that issue, this article also reports the results from a user study aimed at understanding the impact of spatial placement and distribution of situated and activity-aware micro-displays, on the users' awareness and attention. Our results show that adding situated micro-displays to support the participants' activities enhances user experience and do not causes information overload. Both, quantitative and qualitatively results clearly show the benefits of introducing situated micro-displays. By increasing the density of micro-displays in an area, the performance of individuals improves and they also get favourable impressions after the activity completion.

Next section describes the prototype of a micro-display network. Section 3 presents the user study and section 4 discusses the obtained results. Section 5 presents several design guidelines obtained from the user study. Section 6 presents the conclusions and future work.

2 Activity-Aware Micro-displays Prototype

A micro-display in an activity-aware system provides activity-specific guidance to mobile workers according to the design guidelines proposed in [10]. A network of these micro-displays enables the presentation of contextual cues at critical places to aid human activities that are spatially dispersed. These contextual cues describe the necessity or possibility for action in a given location and involving a specific object. They also show the result or execution state of preceding actions, and present a possible next action. More specifically, the representations of these contextual cues have different properties according to generic activity patterns that define particular routines at structured workplaces. These properties are the following:

- *Colour*: Used to represent the relationship between a given entity (people or object) and the current activity.
- *Identity*: Represented by a number. We also use a circle to indicate that a given entity is present and active.
- *Textual description*: Provides an explanation about something; e.g. an instruction.

Accordingly, Fig. 1 shows examples of visual representations displayed in the micro-displays to the participants of our study. Fig. 1 (a) shows a representation that provides an overview of the activity that participants had to complete. Fig. 1 (b) shows information about an object related to such an activity.

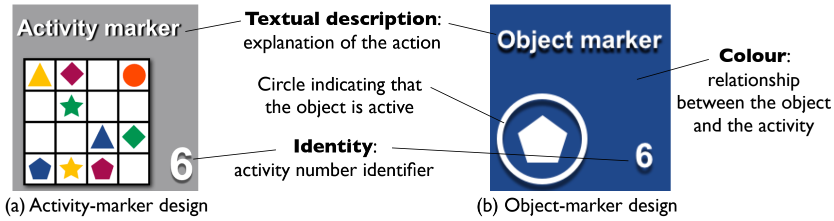
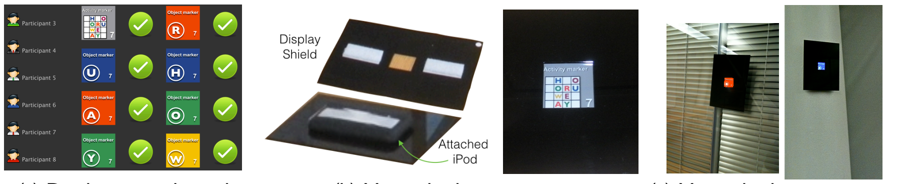


Fig. 1. Design of the visual representations of activities

In our prototype activity-aware system, we have used shielded mobile devices of varying size as the placeholders (i.e., micro display) of these visual representations. In Fig. 2b, and Fig. 2c, two different form factors of micro-displays are shown, where the former is used to present object-specific information pertaining to a task at hand, and the latter is used to provide an overview of the activity in context. Each of these displays runs a tiny client application (*Ajax-Comet*) that shows this activity-related information, and all of the displays are connected to a central display server in a *RESTful* way following multitenancy principles. The activity information shown in the micro-displays is stored in the central display server, which pushes the appropriate information to a specific micro-display in a contextual fashion. Although we did not implement actual context recognition in our prototype, this pushing mechanism enabled us to dynamically display and update the information in the micro-displays appropriately. For instance, when a participant arrives to the main entrance of the room where the activity is taking place, a micro-display located at the entrance automatically provides him an overview of the whole activity.

The micro-displays network was implemented connecting several computing devices through Wi-Fi, using an Apple's Airport Express base station; particularly a MacBook laptop was used to run the server and allowed us to manage the control panel of the system (Fig. 2a); nine iPods touch that represent the regular micro-displays that provide object-related information and one Apple's iPad that emulates the main micro-display that shows the activity overview. We covered part of these devices screen with black acrylic plastic in order to create the effect of having displays with small size screens (see Fig. 2b and 2c). The iPad's micro-display had a screen size of 7 x 7 cm (i.e. the acrylic plastic window), whereas the iPods had a window of 3 x 3 cm.



(a) Display control panel (b) Micro-display prototype (c) Micro-display in operation

Fig. 2. Micro-display network prototype

3 User Study

This section introduces the user study performed to explore the spatial distribution aspect of situated micro-displays and its impact in users' satisfaction, attention and performance. Particularly we want to understand whether and under what circumstances the use of situated micro-displays is useful to support human activities.

The user study involved mobile workers that had to complete a given activity using the information displayed in the micro-displays. We varied the distribution and density of micro-displays presented to the participants, generating thus different work conditions. The placement of situated micro-displays followed the guidelines given in [10], and the study involved three experimental scenarios. The first scenario considers that mobile workers only have one micro-display (activity-marker) located in an *activity-centric* fashion (i.e. the device is located at the main area where the activity is taking place) and it shows information about the activity as a whole. The second and third scenarios represent the *space-centric* and the *entity-centric* distribution respectively. The *space-centric* distribution considers micro-displays placed in a space shared by multiple entities (people or objects) and the *entity-centric* distribution involves a micro-display embedded in every entity.

For these last two scenarios, additionally to the activity-marker, we also had 3 and 9 extra micro-displays used as object-markers respectively. These object-markers show information about the objects involved in the main activity. In the second scenario, we placed 3 micro-displays at different locations of the physical space where the several objects involved in the activity had been placed. For the latter scenario, due to the study' activities entail interactions with 9 different objects, we placed the micro-displays very close to these objects location. We decided to use this number of micro-displays due to hardware restrictions –wireless connectivity– and also to make the study conveniently manageable and not tiring for the participants. Summarizing, the three experimentation scenarios involved 1, 4 and 10 micro-displays respectively.

Physical Setup. The space were the study took place was a conference room of 20.4 m^2 approximately. Fig. 3 shows, on a blueprint of the area, the physical setup used in the third scenario.

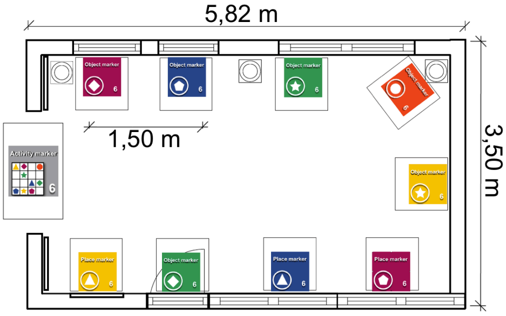


Fig. 3. Floor Plan showing the physical setup

In this case the distance between micro-displays was about 1.5 m. It is important to notice that across the different study settings, the spatial distribution of the micro-displays in the room was maintained, independently of the number of devices. Particularly, the maximum distance (in metres) between the farthest pair of micro-displays was the same for all scenarios. Thus, we intend to assure that the different scenarios settings do not determine or affect the results of this study. The activity took place mainly on a tall table placed at the main entrance of the room. There we placed the main micro-display with the activity overview (to represent the activity-centric placement of situated micro-displays). We also placed across the room the different objects involved in the study activities. Other objects and activities were intentionally introduced in the room to simulate a scenario where the same physical space can be shared between several activities and entities. The walls of the room were partially covered with Velcro material to be able to place and remove the micro-displays when needed, according to the study scenario.

Tasks. The activities that participants had to complete involved a number of simulated simple tasks. Little information processing was required to understand the information displayed and to carry out a single task. We decided to use simulated tasks instead of real-world work activities due to our research is a proof-of-concept focused on the use of micro-displays to build *situated information system* to support mobile workers, independently of the specific domain where it is applied. According to [7], these kinds of systems are based in the situational theory of action, which states that a goal-oriented activity can be done through the minimally reflective and fluid actions performed by skilled workers engaged in routine tasks. However, we have added some complexity to the activity as a whole due to the fact that the information about many operational tasks was displayed at the same time. Specifically, the activities were several puzzles that the participants had to solve using the information shown in the micro-displays. In order to do that, they had to pick up the correct objects –among the objects distributed around the room– and place them in the correct positions on a grid. The tasks selected for this study have the following properties:

1. *Physical:* The tasks involve physical movement and involve tangible interaction with objects.
2. *Spatially distributed:* Participants have to move from one place to another to complete the tasks.
3. *Goal oriented:* Tasks have a common final goal.
4. *Non-sequential:* The interdependency among tasks is minimal.

Accordingly, we selected this particular puzzle activity from the nine categories for manual tasks referenced in [11], however we normalized it to assess the quality of non-sequentially and spatial distribution of situated micro-displays. The *independent variable* of the study is the number of micro-displays. For this reason, each participant was always exposed to the same activity, but we varied the distribution granularity of the micro-displays between the different study scenarios. By doing so, we maintained the complexity level of the tasks that the participants have to perform, so that the activity itself does not influence the study results. In order to avoid learning effects that can lead to the improvement in the users' performance, for each study scenario we altered the pattern of the activity and the objects involved on it, as a way to make that the activity looked like a completely different one. Accordingly, each study scenario had a different activity pattern, as well as a specific number of micro-displays.

Participants. The participants in this study were 14 students from Lancaster University. We did not involve participants with a particular profile or groups with special characteristics, because the study was not intended for a specific domain. Prior to perform the study, we asked participants to provide demographic data. There were 9 male and 5 female, aged 21 to 27 (average of 24.3). The study took approximately one and a half hour per participant.

Method. Participants took part in the experiment individually. They began the study being told about the study purpose and with a brief training session. We used A/V equipment to record the experiments and the people interviews for later analysis. The study followed a *within-subjects design*, where each participant experienced the three study scenarios. In addition, we used a *Balanced Latin Square* for counterbalancing to mitigate potential learning effects. We ensured that two participants completed each row in the Latin Square. The scenarios entailed the completion of 3 different activity patterns composed by 9 tasks each, which corresponds to the number of objects the users had to interact with to complete the activity. Following the completion of each study scenario, we asked each participant to answer several subjective questions taken from the *IBM Computer Usability Satisfaction Questionnaires* [12] and the *NASA Task Load Index* [13]. We also asked them additional questions for further evaluation of divided attention and information overload issues. In addition, after the whole experimentation process, each participant answered the questions of a final *semi-structured interview* aimed at gathering additional feedback about the best distribution arrangement of micro-displays.

4 Study Result

In this section, we discuss the result of the study from four perspectives: Task performance, multitasking effect, context switch and participant' behaviour.

4.1 Completion Time and Errors

In [14] the author presents the use of the reaction time to measure the division of attention and also the accuracy and speed of an action as a measure of the spare cognitive capacity. Accordingly, we use completion time and errors to measure the appearance of divided attention and information overload respectively.

We computed the activity's *completion time* as the time elapsed from the moment the participants first looked at the main micro-display and the moment just after they placed the last piece of the puzzle in the right position. Results show that a higher number of micro-displays can help decrease the activities' completion time. We obtained an average difference of 8.67 seconds (7.9%) between the fastest and the slowest performance (considering the three scenarios). The difference in the maximum and minimum completion times was 11 and 28 seconds respectively.

Errors were classified into two types: *completion* and *location errors*. *Completion errors* are those occurred during the completion of the puzzle, e.g. placing a wrong object in the grid, having some missing, etc. The number of these errors was very small and we did not observe a direct correlation between the number of micro-displays and this kind of error. However, the completion errors for the scenario with the highest number of micro-displays were 50% smaller than those with the lowest number of micro-displays. *Location errors* were counted when the participant picked the wrong objects from the different room locations. Location errors are a good metric of performance and efficiency, especially when the tasks are physically dispersed.

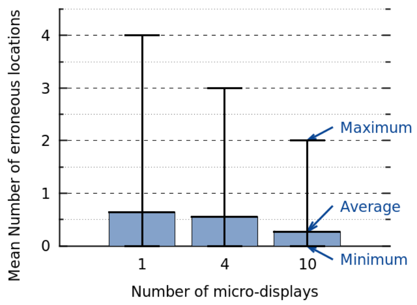


Fig. 4. Location errors

A high number of location errors imply that the individuals have to walk longer distances to complete the activity, and as a result, the effort and time required is higher. Fig 4 shows that the mean and maximum values of the location errors have a negative correlation with the number of micro-displays. The experiments in the first study scenario had a significantly higher average error rate (57.1%) than in the third one.

4.2 Simultaneous Tasks and Iteration Steps

The participants' performance shows a direct relationship between their overall satisfaction when completing the activity and the number of simultaneous physical tasks they engaged with. Participants' satisfaction also has a negative correlation with the number of iteration steps that they had to perform for completing the activity. For this reason, we have included this metric to try understanding the information overload on the mobile workers.

We computed the number of *simultaneous tasks* performed by participants, counting the maximum number of objects that they picked in the routes followed for completing the activity. We defined the *iteration steps* as the number of stages that participants needed for completing the activity, e.g., the number of rounds around the room.

Fig. 5 (a) shows the number of simultaneous tasks (minimum, maximum and average) performed by the participants. These results indicate a direct correlation between the average values of this variable and the micro-displays density. When we have nine object-related micro-displays, the number of simultaneous tasks is (in average) 43.3%, which is higher than when we only have the main micro-display (scenario 1).

Fig. 5 (b) shows the results of the iteration steps for the three study scenarios. The results show a negative correlation between the number of micro-displays and the number of iteration steps required for the activities completion. There is a difference of 33.3% between the average values obtained in first and the last study scenario respectively. The same tendency in followed by the maximum and minimum values.

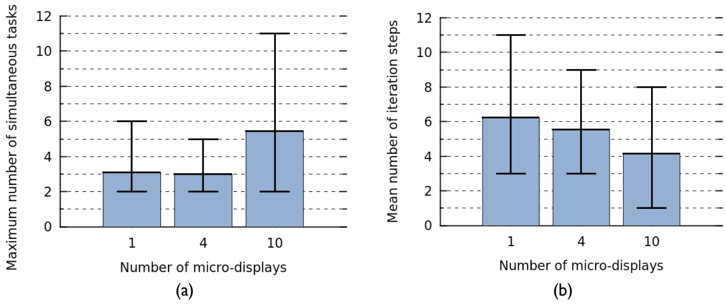


Fig. 5. (a) Simultaneous tasks and (b) iteration steps

4.3 Context Switches

A *context switch* happens when the users' view switches from the main activity micro-display to any other point. Accordingly, we computed the number of eye movements of the participants. The results indicate that mobile workers in the study scenario with the smallest number of micro-displays required a higher number of switches to accomplish the tasks (Fig. 6). The average context switches in the first scenario were 32.5% higher than in the third scenario. The maximum and minimum values of context switches adhere to this tendency.

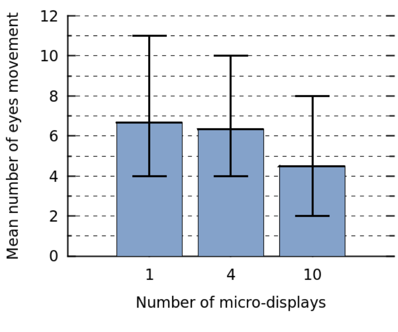
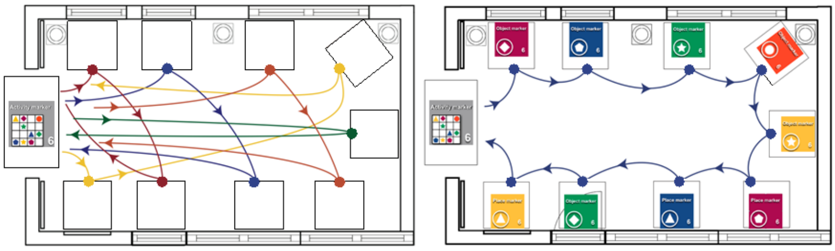


Fig. 6. Context switches

It seems reasonable to think that entity-centric micro-displays introduce maximum fragmentation of attention in comparison to activity-centric placement because the information is dispersed across a higher number of micro-displays, which could demand more context switches. However, these results confirm that a higher density of micro-displays actually reduces the context switching, because the information is presented in a more situated fashion. Therefore, we cannot claim that having a higher number of micro-displays increases the fragmentation of attention.

4.4 Participants' Behaviour

Another interesting observation about the participants' behaviour while completing the activities is related to the physical path that they followed. We observed that there was an important difference in the number and shape of the routes that participants followed for collecting the objects around the room. Fig. 7 depicts two examples of the participants' movement pattern around the room.



(a) Only de main micro-display (b) Ten micro-displays

Fig. 7. Examples of the participants' physical movement pattern

Fig. 7 (a) shows a sample result for the scenario with only the main micro-display and Fig. 7 (b) shows the result when the participants also had 9 additional object-related micro-displays. Analysing these paths we can confirm the participants' impressions that a higher physical effort was needed when the number of micro-displays was small. We can also claim that increasing the number of micro-displays results in a more efficient use of the physical space.

5 Implications: Design Insights

Next we summarize some design insights drawn from the results of our study. These insights allow designers to make informed decisions when developing activity-aware systems.

Increasing the density of micro-displays improves the activity performance and information support. The results indicate that the entity-centric distribution of the micro-displays helps boost user experience and has a positive impact in the activity performance and the quality of the information support. Both, quantitative and qualitative data showed that activity performance increases with the number of micro-displays. Measurements of completion time, location errors, iteration steps and number of simultaneous activities confirmed that the best performance is achieved when we have as many micro-displays as objects has the activity. In addition, the participants' feedback reveals that most participants preferred to have a high density of micro-displays, because the information provided by them becomes clear and easy to find. This would indicate that the quality of the supporting information increases with the micro-displays granularity.

Situated micro-displays require focused attention. During the interviews, the participants mentioned that they looked at the micro-displays one at a time. Therefore, although we initially expected that situated micro-displays with an entity-centric placement would require divided attention, we found that instead they required focused attention. Previous researchers have found that the performance of a mobile worker correlates positively with the amount of information that he receives; however, if the information provided is too much, his performance rapidly decline [15]. For this reason, we hypothesized that increasing the number of situated micro-display would improve activity performance, but up to certain point due to the fragmentation of the users' attention. Nevertheless, our findings revealed that micro-displays require focused attention and a higher density of them help reduce the context switching, because the information is presented in a more situated fashion. The fastest completion times obtained during the experiments confirm this finding. We cannot unequivocally assert the claim due to the limited number of participants and micro-displays involved in the experiments. Therefore, it would be necessary to perform more longitudinal studies in order to confirm statistically these observations.

Spatial distribution does not affect the information capacity. According to the quantitative results and the participants' feedback, it seems that the spatial distribution of the information does not cause information overload. In contrast, the results confirmed that the quality of the provided information and the users' satisfaction increases with the density of micro-displays. Therefore, we can claim that an entity-centric placement of situated micro-displays, when the entities and task involved in the activity are spatially dispersed, does not affect the mobile workers' capacity to successfully process the information. In fact, we used some metrics and indicators of information overload, such as recall and emergent and implicit poles [16], by asking participants some specific questions after finishing the activity. These results did not show signs of information overload in any of the study scenarios.

Situated micro-displays can be used for structured activity route. As already expected and confirmed by the study, there are applications that could benefit of using situated micro-displays distributed in an entity-centric fashion; for instance, those involving a structured activity route. That is, we can deploy the micro-displays in the work area in a way that the user is led to follow a specific path to complete the activity. If the micro-displays are placed one after another in a structured fashion, there is a high possibility that people follow a controlled activity route. An additional benefit is that if the deployment of the micro-displays is carefully planned, we could use more efficiently the physical space.

6 Design Guidelines

The presented results allow us to provide several design guidelines, which can support the design of mobile and ubiquitous solutions to display activity-centric information into situated micro-displays. It is important to follow a user centric approach when deploying a situated micro-display network that supports mobile workers performing spatially distributed tasks. Thus, the designer improves the chances that the system implementation fits with the current practices at the specific workplace.

Entity-centric distribution. Entity-centric placement of situated micro-displays seems to be the best alternative to guide spatially distributed tasks. Therefore, micro-displays should be fully integrated in the work environment and linked to the physical entities that are relevant for the workplace activities.

Micro-display density. The scenario with highest density of micro-displays provided the most effective, enjoyable and effortless support for mobile workers. This finding was also perceived by the participants. Therefore, we recommend embedding as much micro-displays as possible in tools and entities used by mobile workers.

Trade-off between structured deployment of micro-displays and users' autonomy. We can use situated micro-displays to determine the physical movement patterns of the mobile worker at the workplace. Taking away part of the activity's control from the worker, it is possible to make a more effective use of the physical space and reduce the effort required for the activity completion. However, we cannot ensure that it would improve workers' efficiency. Therefore, the deployment of micro-displays should reach a delicate balance between regulating the work practices and preserving the autonomy and decision-making capacity of skilful workers.

Context-based customisation. It is important to consider the work context in the deployment of micro-displays. This work context should consider the current work activities and the environment in which they will be performed. Therefore, some factors such as screen size, visual design and the kind and amount of information to be provided by the micro-displays should be adapted accordingly.

7 Conclusions and Future Work

The use of situated micro-displays is an evident design alternative to present real-time in-situ information to support complex, dynamic and spatially distributed human activities. In this paper we provided a proof-of-concept towards this goal, by developing a prototype of a micro-display network and performing a user study that explores the users' experiences according to spatial distribution of situated micro-displays. We described the prototype solution, and also analysed the effect that the distribution granularity of micro-displays has on the users' performance. The results provide clear evidence of the advantages of having a high situated micro-displays density in the workplace. Some of these advantages are the improvement in activity completion time, the reduction of the errors, the improvement of the efficiency in the use of the physical space and a higher user satisfaction.

The results also indicate that the use of micro-displays to support spatially distributed fluid tasks, which are part of a complex and dynamic activity, can boost user experience and have a positive impact in the people performance. The results of the user study also helped us to gain further insights about the design implications of performing activities in environments with a high micro-displays density.

These results allowed us to provide some design guidelines that help designers of mobile and ubiquitous solutions to deal with the modelling of activity-centric information that will be deployed through situated micro-displays. The next steps consider performing a transversal study to determine the generalizability of the current findings. We also plan to perform a field study in real workplaces.

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