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ABSTRACT

Studies in the field of human-robot collaboration have shown that the direct cooperation of humans and robots can lead to increased anxiety feelings of workers. Previous studies realize either a collaboration with lightweight robots or a temporal and spatial separation of humans and robots. We use a robot with a load capacity greater than 200 kg with a temporal and spatial overlap of the working areas. Three different prototypes for Google Glass render the current state of the system in the form of text, icons or a traffic light. The evaluation in a comparative field study shows that when using any of the three prototypes, the perceived state anxiety is low. However, the usability of the system with the icon-based interface is better than the other interfaces.

Author Keywords

human-robot collaboration; head mounted displays; trust; performance;

INTRODUCTION

The working areas of robots and humans are physically and temporally strictly separated from each other for safety reasons. Protective fences or light fences reliably prevent violation of the protected area during the robot's automatic mode. Any intrusion in today's production lines results in an immediate emergency stop of the robot and subsequently, if necessary, of an entire production line. Because of new variants of human-robot collaboration, the aim is to merge the workplaces of humans and robots. Recent studies, introduced in the next section, have shown that this can have a negative impact on the human. The proximity to the robot produces a subjectively higher workload reflected in the form of stress and anxiety. Our work deals with the question of whether the use of head mounted displays (HMD) can possibly reduce this fear and lower the workload through targeted information delivery. In a field study, we evaluated three prototypes against each other to work out whether the subjects could experience a reduced workload during the collaboration when using a Head-Mounted display.

RELATED WORK

Currently breaking the barrier between humans and robots for direct collaboration is a matter of research driven by the manufacturing industry ([14], [10], [8]). The international standard of ISO 10218 part 1 [6] and part 2 [7] suggests that there are four different types of human-robot collaboration: Safety Monitored Stop, Hand Guiding, Speed and Separation Monitoring, Power and Force Limiting. For Speed and Separation Monitoring, the speed of the robot is reduced according to the current distance between humans and robots up to the complete standstill. Naber et al. [12] have shown that performance and risk cognition of a worker depends on the speed of the robot and distance to it. This finding converges with the results of Or et al. [13], which have found that size and speed of a robot have influence on the subjective perception of occupational safety. People feel less safe when robots move fast. This is consistent with findings of Hsee et al. [4] that could show people being in general "afraid of things that come physically closer to them". The study states that it makes no difference what kind of objects are moves toward them. Arai et al. [1] show that this has an influence on the mental stress of workers in a human-robot collaboration. They recommend informing the worker about movements of the robot in his vicinity. Likewise, Ikeura et al. [5] showed that users have more positive emotional reactions if robot movements were announced by signal and were thus predictable.

RESEARCH QUESTIONS

- Can one reduce the perceived anxiety of the subjects by continuous provision of context information?
- Is any prototypical implementation of this more suitable regarding usability and performance?

EXPERIMENTAL METHODOLOGY

Setup

In a field study, we realize the human robot collaboration according to the principle of Speed and Separation Monitoring. We simulate an assembly task of a heavy car engine as known from a real set-up: The robot grasps an engine block and presents it to the worker. The worker has the task to insert four pairs of screws. This should happen in an action supervised by our system. After completion of this task the robot proceeds with its program and in the meantime the worker assembles an oil pan outside the reach of the robot. This task does not require the supervision by our system, which it indicates to the worker as an unsupervised action. In the period between the tasks, the worker can rest. Instead of a real engine block, we used a cardboard box, where the subjects had to simultaneously tighten two nuts on screws four times (see Figure 1). Instead of mounting the oil pan, they had to as-

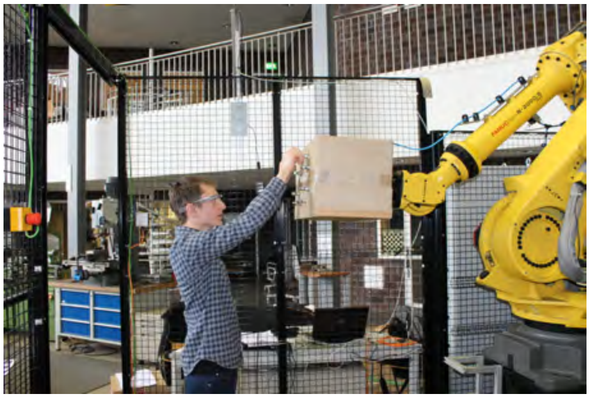


Figure 1: Secured task

semble a Lego model (see Figure 2). This gave us the ease of reproducibility and dismantling possibility of the individual components. For the realization of the human-robot collaboration, we retrieved and evaluated the context information in real time. The system localizes the worker using a laser scanner within the work cell and accesses the position data of the robot through the internal robot interface.

The robot receives adequate speed limits analyzed on an industrial PC, which obtained and evaluates the mentioned data. The robot reduces its speed as it comes closer to the subject until it eventually stops in front of the subject. On the industrial PC we further take into account the activities the worker has to carry out at the present time as well as the location of the robot. The resulting action is displayed on the HMD. This has several advantages over conventional techniques: (1) The use of acoustic warnings continuously informing the worker is impractical due to the noisy environment. (2) Stationary erected traffic lights or monitors are not suited either, because the worker is not working on a fixed position.
The robot starts each run from a resting position (see Figure 3). From this resting position, the robot moves to catch the cardboard box with its suction cups from a conveyor. The motion continues toward the position where the human-robot collaboration takes place. The robot remains at this position for five seconds, so that the worker can easily enter the shared workplace performing the required assembly task. The worker leaves the shared workplace and the robot continues its program. Meanwhile the worker assembles a Lego model at a standing workstation outside the robot's reach. After the completion of the Lego-assembly the worker takes a break. The Lego-assembly can easily be completed in the given time and was chosen so that it does not cause unnecessary additional stress. In case the subject does not complete the Lego-assembly in time, he was instructed to always prefer the engine assembly task. The task sequence contained five repetitions for each user interface followed by a questionnaire in respect to the tested interface.

Interfaces

We developed three user interfaces for the presentation of work instructions matching the current context of the system, each with three different states respectively. One state stands for the execution of the activity in the robot's reach with the robot in a secured position. The second state indicates that the worker has to carry out an unsupervised activity outside of the robot's reach. The third state instructs the worker to leave the danger zone of the robot. The user receives this context information by means of the HMD, the Google Glass System.

We opted for the Google Glass, because this system uses the See-Through-Approach and as such does not greatly restrict the field of view of its user. This allows for a more comfortable experience while working within the robot vicinity. The display is not central to the eye of the user, but slightly to the right above the eye. Therefore, the user always has unobstructed views of his activities. The Google Glass has a better wearing comfort compared with other currently available off-the-shelve HMDs.

Our software prototypes inform the user about the current task during his work. The implemented user interface uses the Android and Google Design Guidelines and the Google Glass media libraries to facilitate the recognition factor for the user. This applies to the display of text and audio data, too.

Textual User Interface

Our system provides a pure textual interface to the user in form of a short sentence or statement concerning the currently appropriate action. A brief look at the display provides concise information. Figure 4a shows the three possible instructions as described above.

Lights

The user is shown a three-color traffic light (see Figure 4b). The states of the traffic light stand for three currently appropriate actions. Green stands for the execution of a task in the robot's reach with the robot in secured position. Yellow indicates that the worker has to carry out an unsupervised activity outside of the robot's reach. Red directs the worker to leave the danger zone of the robot.

The display of the individual states were arranged horizontally over the width of the screen. In this way, one can compensate probable color vision defects. We further provide text

Figure 2: Unsupervised task

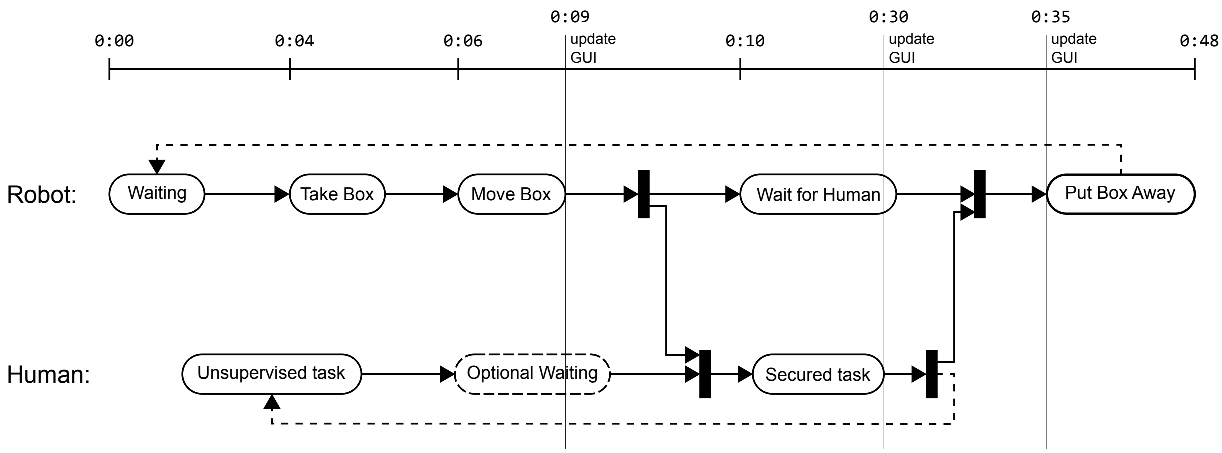


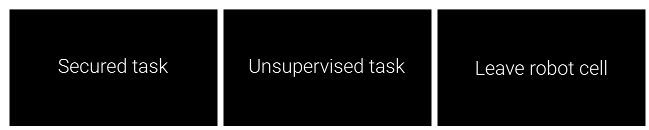
Figure 3: Sequence of the experimental setup

similar to the interface described in "Textual User Interface" in a smaller but still readable font below the traffic light. At any given time, only one traffic light is displayed as illuminated. The unlit positions are displayed as auxiliary circles so that the user can see all traffic light positions at any time.

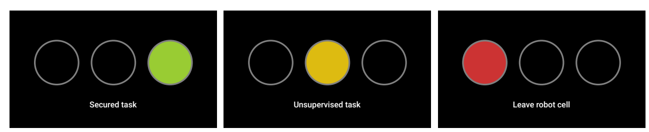
Icons
In this interface symbols are used in addition to the colors and the explaining text of the previous interface (see Figure 4c). The "check" Icon indicates the secured position of the robot and therefore the unrestricted movement of the worker. The "tool" Icon indicates that the worker can perform his unsupervised task outside of the robot's reach. The "attention" Icon indicates that the worker is instructed to leave the field of reach of the robot marked on the floor.

Optimization: Audio feedback interfaces
All interface types are also equipped with an audio feedback capability. It signals the beginning of work tasks performed by the robot. This audio feedback consists of a short concise sound output every 3.75 seconds as long as the worker is within the robot's reach. This audio signal can be a guide for the user when to turn on the next pair of screws. We decided to use an additional acoustic signal because it can be perceived without losing the visual focus from the current work task.

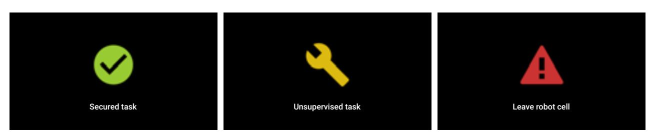
Data collection
In our field study we evaluated the three different user interfaces using a "within subjects" set-up for a direct comparison. By using a Latin Square counterbalancing to the sequence of the individual user interfaces we excluded possible learning effects. For testing we recruited 12 subjects (2 females and 10 male) between 20 and 35 years of age. Prior to the study, each subject had to fill out a Likert scale based self-assessment. We scrutinized the following relevant criteria: experience with Lego, dealing with industrial robots and HMD. We conducted the study on weekdays between 10:00 and 17:00. The ambient noise and light influences were almost constant without measurable influence on the study. An instructions describing the functions and the user interface were handed out and explained to each subject prior to the tests. The subjects used each of the three user interfaces in sequence. The instructor asked the subjects to think aloud and ask questions if necessary. Beside the instructor, the supervisor of the test procedure handled the Deadman control.



(a) Text-based interface



(b) Lights-based interface



(c) Icon-based interface

Figure 4: User Interfaces

The reaction time of the subjects was measured from the moment the instructions were received via the user interface to the moment they started working. We counted an error each time a subject started a task too early without prompting. We used the System Usability Scale (SUS) [2] and two of the four parts of the Unified Theory of Acceptance and Use of Technology (UTAUT) [15] to determine the assessments of usability and effort expectancy. With the STAI questionnaire [9] we determined the State and Trait Anxiety. For the subjective experience of stress, we used the NASA Task Load Index (TLX) [3] and recorded the test runs with an industrial camera.

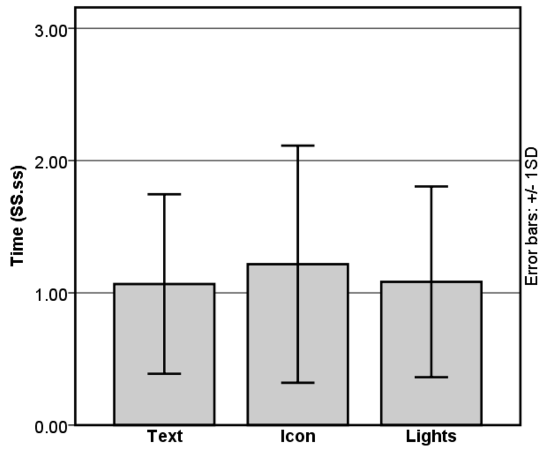


Figure 5: Reaction times: Secured task

RESULTS AND ANALYSIS

All subjects performed the tasks and filled out the questionnaires.

Observations

Generally, all subjects have become accustomed of the use of the various prototypes and they were able to use them correctly without problems. The focus was mostly on the secured activities. During the study the subjects concentrated not only on the instructions on the HMD but often took the current position or motion of the robot as a visual guide. Consequently, a total of 17 times the subjects started the unsupervised activity too early. Subjects rated the audio support predominantly positive - however subjects described the audio signals transmitted through the bone-conduction speakers as hard to hear due to the noise of the robot's tool.

Errors and times

In total 21 errors were committed while during 17 of them, subjects started too early with the unsupervised task and 3 times the subjects started too early with the secured task within the reach of the robot. Once a subject started too late with the secured task using the text-based user interface because the robot had already left the waiting position. Reaction times for the secured task were between 0.2 and 3.6 seconds. Figure 5 shows the average reaction times sorted by prototype (text: 1.07s, SD = 0.68s; Icons: 1.22, SD = 0.90; Lights: 1.08, SD = 0.72).

The reaction times of the unsupervised task were between 0 and 4.8 seconds. The video evaluation of experimental procedures showed that subjects sometimes were distracted by the moving robot and continued watching while neglecting their current task. Figure 6 shows the average reaction times sorted by prototype (text: 1.37s, SD = 0.79s; Icons: 1.35, SD = 1.28; Lights: 1.13, SD = 1.12). Statistical analysis showed no significant differences between the prototypes.

Questionnaires

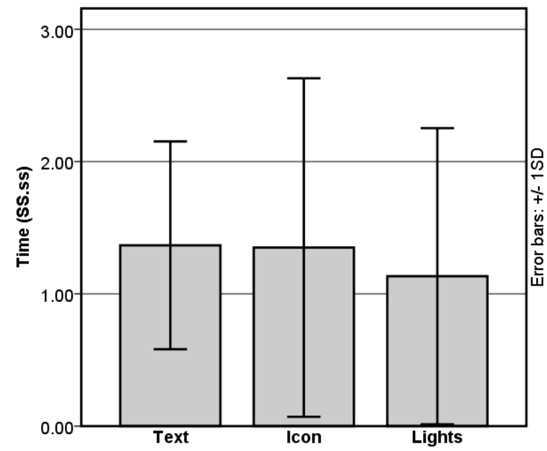


Figure 6: Reaction times: Unsupervised task

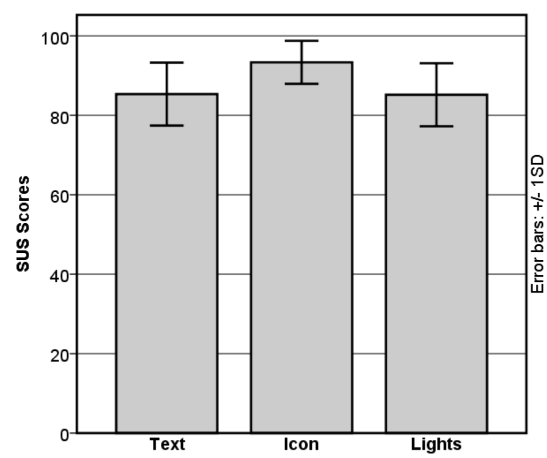


Figure 7: SUS

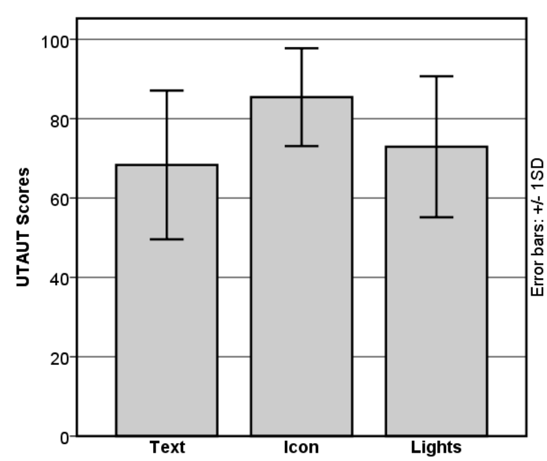


Figure 8: UTAUT: Attitude

The average SUS scores (see Figure 7) are good for the Text and Icon interfaces. However, the icon-based user interface was evaluated significantly better in average (Text: 85.33, SD = 7.92; Icon: 93.33, SD = 5.42; Lights: 85.17, SD = 7.93). A one-way analysis of variance with repeated measures (F2;22 = 12.192, p = 0.000) shows statistical significance. Sidak-corrected pairwise analysis confirms significant differences comparing Text and Icon (p = 0.004) as well as the contrasting juxtaposition of Lights and Icon (p = 0.003).

The average normalized (between 0 and 100) UTAUT values (see Figure 8) regarding the attitude towards the technology shows a similar picture to the SUS scores (Text: 68.33, SD = 18.75; Icon: 85.42, SD = 12.33; Lights: 72.92, SD = 17.77). The higher standard deviations in the text- and traffic light-based user interfaces indicate a higher dependence on personal preferences. A one-way analysis of variance with repeated measures (F2;22 = 8.401, p = 0.002) shows statistical significance. Sidak-corrected pairwise analysis confirms significant differences both for comparing Text and Icon (p = 0.014) as well as the juxtaposition of Lights and Icon (p = 0.024).

The average normalized (between 0 and 100) UTAUT values with regard to the expectation of effort shown in Figure 9 is very good for all prototypes (Text: 92.92, SD = 12.15; Icon: 96.25, SD = 6.78; Lights: 93.75, SD = 10.25). Statistical analysis showed no significant differences between the prototypes.

The average normalized values (between 0 and 15) NASA TLX scores (see Figure 10) for all three prototypes can be considered good (Text: 3.79, SD = 1.60; Icon: 3.44, SD = 2.04; Lights: 3.60, SD = 1.64). Statistical analysis showed no significant differences between the prototypes.

The values determined with regard to the perceived state anxiety were between 21 and 53. Figure 11 shows the average values sorted by prototype (Text: 35.00, SD = 8.32; Icon: 33.08, SD = 7.30; Lights: 33.75, SD = 7.17). In Figure 11 the anxiety as a personality trait was added (trait anxiety: 37.00, SD: 5.26). It appears to behave similar to the anxiety states: the values range from 30 to 47. Generally, one should note that the anxiety state was low no matter which prototype was used. In a direct comparison between state anxiety and anxiety as a personality trait, we found no abnormalities. A one-way analysis of variance with repeated measures (F2;22 = 3.797, p = 0.019) shows statistical significance. Sidak-corrected pairwise analysis confirms significant differences for comparing the icon-based interface and the anxiety as a personal trait (p = 0.027).

Interview

All subjects have ranked the icon-based user interface in the first place. Several times, subjects declared that the combination of shape and color change was easy to identify. In addition, they positively noted that the icons were self-explanatory. Seven subjects chose the lights-based user interface in second place, 5 subjects favor the text-based user interface over the lights-based user interface because recognizing the status change signaled by traffic lights required more

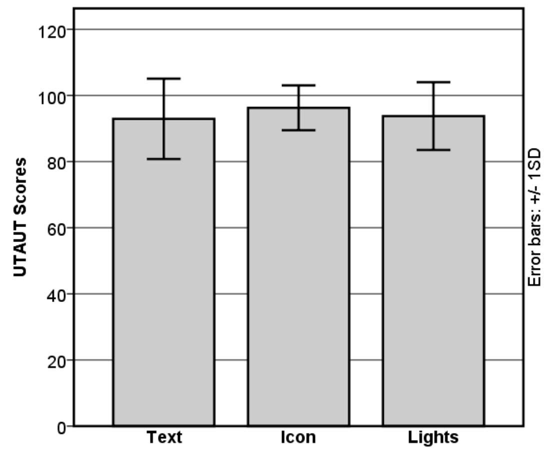


Figure 9: UTAUT: Effort expectancy

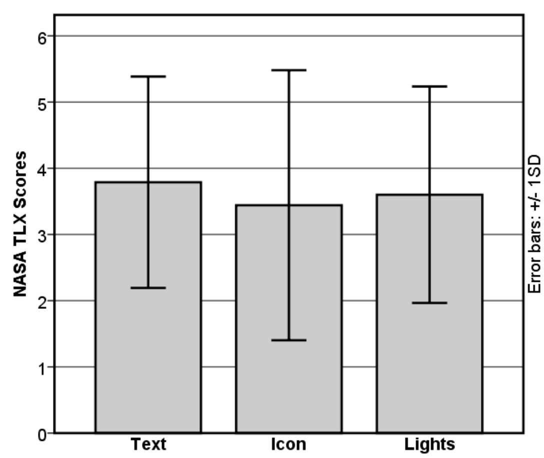


Figure 10: NASA TLX

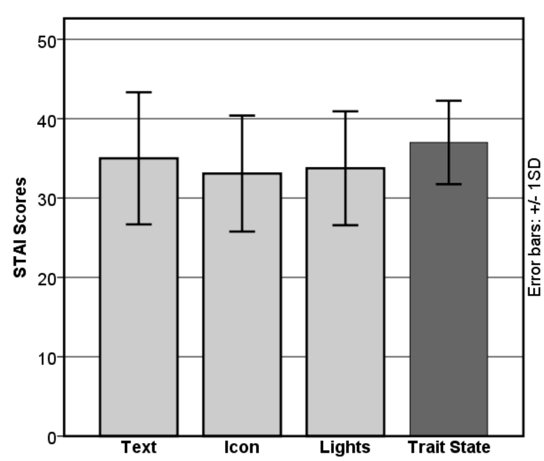


Figure 11: STAI

focus and was frequently overlooked. During the interview five subjects suggested displaying some kind of stop watch, indicating when state changes in the fixed sequence of tasks occur. According to the subjects, this could reduce mental stress even further.

Discussion

All subjects were able to use the prototypes without problems. The results of the field study provide an ambiguous picture. While statistical analysis showed significant differences between the prototypes for SUS score and the UTAUT effort expectancy, there were no significant differences between the prototypes regarding response times and errors, UTAUT attitude, the NASA TLX score and the STAI score. The determined state anxiety at all three prototypes were - regardless of the usability - always in a good range. The results of the NASA TLX suggest that the selected scenario is subjectively experienced as not stressful. Overall, the results and the statistical analysis suggest the icon-based system is favored over the other prototypes. This also coincides with the results of the interviews. All subjects have ranked the icon-based interface in the first place. Most of the design decisions we based on the design guidelines for the Google Glass. However, some essential design decisions were made without knowledge of related work, e.g. to turn the traffic light-based prototypes by 90 degrees. It better exploits the image area of the HMD. A common vertical representation would be more intuitive, probably positively influencing the user experience. Many subjects have expressed that the sound via the bone-conduction speakers of the Google glass was hard to hear in vicinity of the robot. Since the volume was at the maximum level, we do not recommend the use of the Google Glass speaker system for this purpose.

CONCLUSION AND FUTURE WORK

In this paper, we presented an evaluation of three prototypical implementations of user interfaces on a Google Glass, supposed to reduce anxiety in human-robot collaboration at the workplace. In a field study, we compared icon-, text-, and light-based prototypes. We could show that the state anxiety of the worker does not increase regardless of the used interface prototype. Nevertheless, the icon-based user interface was ranked better than the other two interfaces in terms of usability. Future work may include extensions of the user interface such as displaying a countdown or taking further advantage of additional context information, e.g. visually informing the operator of the next steps in the robot program.

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