Gaze-Controlled Instructions for Manual Assembly Tasks – A Usability Evaluation Study

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ABSTRACT

People interact with technical systems every day, making use of manifold input methods. One possible but not yet very established input method is eye gaze. The present article investigates a gaze-controlled interface in the context of manual assembly tasks, where it provides a language-free and at the same time hands-free input alternative. To this end, we implemented a gaze-controlled instruction prototype and compared its efficiency, usability, and user experience to that of an established paper manual. Both instruction forms were assessed on subjective measures (NASA-TLX, UEQ, and USE) as well as on an objective measure (assembly time). Albeit being prototypical and novel to the participants, the usability of the gaze-based instruction form was at least comparable to that of the paper manual and on some scales even better. Further, the gaze-based interface yielded similar assembly times and was rated preferable in terms of user experience. Taken together, our results suggest that gaze-based instructions can be a valuable alternative to previously used instruction forms in the work context.

CCS CONCEPTS

• **Human-centered computing** → Human computer interaction (HCI); HCI design and evaluation methods; Usability testing; Human computer interaction (HCI); Empirical studies in HCI; Human computer interaction (HCI); Interaction devices.

KEYWORDS

Gaze-controlled interface, manual assembly task, usability, UX

ACM Reference Format:
Solveig Tonn, Antonia van Duijn, Moritz Schaaf, and Wilfried Kunde. 2022. Gaze-Controlled Instructions for Manual Assembly Tasks – A Usability Evaluation Study. In *Mensch und Computer 2022 (MuC '22), September 04–07, 2022, Darmstadt, Germany.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3543758.3547537

1 INTRODUCTION

People are very used to interacting with technical devices: They open programs on their computer with a mouse click, scroll through news feeds on their smartphones with a finger, or ask their smart TV to play their favorite movie by voice commands. The mouse clicking, finger scrolling, and voice commands serve as input methods for interacting with the devices. Another possible but not yet very established input method is eye gaze [1., 2.]. Gaze-controlled interfaces have been used primarily in assistance systems for people with severe physical disabilities [e.g., as communication tool via gaze-controlled keyboard typing or as a wheelchair navigation system; 3., 4.] to improve quality of life [5.]. These implementations revealed promising advantages that could be beneficial for other contexts as well. Therefore, it is not surprising that ongoing research already aims at implementing gaze-controlled interface devices in automated driving [6.] or at making gaze control feasible in daily life [7.]. We assume that the manufacturing industry could likewise profit from such gaze-controlled interfaces, as gaze-controlled instructions provide a hand- and language-free solution for workers trained on new assembly routines. Here, we evaluate the usability and user experience of such a gaze-controlled instruction for manual assembly in comparison to a conventional instruction method.

1.1 Gaze as input modality

Eye movements are among the fastest movements humans can perform [8.]. Moreover, objects are typically looked at before a manual action can even be initiated [9.]. Earlier research observed a general speed advantage of eye movements in object selection compared to other input modalities like joysticks or computer mice [10., 11.] that even held for elderly participants [12.] or those who were naïve at using gaze as an input method [10.]. Further, simple gaze pointing is said to come rather naturally. This assumption is supported by the observation that participants reach asymptotic performance earlier during learning when using gaze rather than a computer mouse as input device [11.].

However, there are also observations suggesting that pointing by gaze may be evaluated as less user-friendly than other input methods, at least in assistive technology [13.]. How well gaze works as an input method also depends on the task difficulty. For complex tasks like keyboard typing, manual input is faster than gaze input, and learning advantages are observed [14.].

Another caveat is that the eyes serve a double function in gaze-controlled interfaces. They not only convey information from the

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MuC '22, September 04–07, 2022, Darmstadt, Germany

ACM ISBN 978-1-4503-9690-5/22/09…$15.00
https://doi.org/10.1145/3543758.3547537

user to the machine, but inherently also gather the information provided from the machine to the user. Consequently, even glances carried in service of visual exploration bear the risk of accidentally triggering a gaze-related command. This can lead to errors and make the users overly aware of their gaze, resulting in an unnatural user experience. Early research described this so-called *Midas touch problem* as the main obstacle in implementing gaze-controlled interface devices [15., 16.].

However, these challenges can be overcome by appropriate design choices. The most widely used method to deal with the Midas touch problem is a moderate prolongation of the required fixation time, also called dwell time, to a fixation time that is beyond that of natural fixations during visual exploration [1., 2.]. Compared to other methods like specific gaze gestures, dwells are easier to conduct, easier to remember, less mentally demanding, and less frustrating [1.]. Although the ideal threshold always depends on the presented material and the target's design, placement, and size [17.], research indicated that participants consider dwells between 250-1000 ms as useful, depending on the task [18.]. Additionally, participants considered 400 or 600 ms as most valuable [18., 19.], whereas dwells longer than 800 ms were often interrupted by eye blinks or corrective saccades [2.]. Further, implementing feedback on the interface's status reduces the Midas touch problem by informing participants what is going on and thereby giving them a chance to react to detection errors and prevent unwanted activation [20.]. At the same time, such feedback promotes users' contingency awareness and enhances satisfaction and performance [20.]. Useful feedback items convey information on the eye tracker's current gaze detection and on successful command initiation [21.].

1.2 Manual assembly tasks

Manual assemblies are repetitive work tasks in the manufacturing industry involving the permanent and manual joining of various components into end products or subassemblies [22., 23.]. They are of great importance for the value-creation process, and as the demand for individualized products increases, they will likely remain prevalent despite the increasing spread of robot-assisted manufacturing. However, the assembly processes of modern products are potentially complex, and assembly workers must frequently adjust to changes in the tasks [24., 25.]. Therefore, efficient teaching of employees is essential for contemporary workflows. Currently, expert tutorials are considered the ideal solution for instructing manual assembly [26.]. However, they rely on spoken instructions, requiring experts and workers to communicate in the same language. While instruction methods that can overcome language barriers (e.g., instruction booklets, instruction videos or more recent approaches using augmented reality) are tried-and-tested [27., 28.], they do not yet offer a hands-free interaction experience. Providing a hands-free instruction would avoid manual dual-tasking and thereby ensure a smooth assembly process without needless interruptions.

1.3 Gaze-controlled interfaces in manual assembly task

There have been first attempts to implement gaze-controlled instruction interfaces for manual assembly with head-mounted eye tracking devices. For example, one study used a head-mounted gaze tracker and divided the workspace of assembly workers into interactive parts with buttons activated by gaze and non-interactive parts where instruction pictures were presented [29.]. Participants' ratings on usability suggested that gaze-controlled interface devices facilitate manual assembly as compared to hand-needed instructions, but only if the eye tracker ensured robust and natural use of the interface. However, this study came with one major practical limitation: Although head-mounted gaze trackers can be flexibly used and tolerate movements [30.], they often come with considerably less user comfort than settings without head-mounted devices [29., 31.]. This problem can be overcome by using a desk-mounted eye tracker.

Based on these findings, a gaze-controlled and desk-mounted prototype for instructing manual assembly tasks was developed and compared with an instruction booklet regarding its usability and user experience in a user-testing study.

2 METHOD

2.1 Participants

Twenty-four volunteers (mean age: 25.5 years, *SD* = 4.3, 18 identified as female, 6 identified as male) gave informed consent and received course credit or monetary compensation for participating. The sample size is based on Faulkner [32.], who reported that at least 95% of all usability problems are detected with 20 participants. As per our preregistration, five participants were excluded from the data analysis because at least one of their built models had deficits after completion. One further participant was excluded from the analysis of assembly times due to a logging error. Preregistration, data, and analysis scripts are available at the Open Science Framework, https://osf.io/wy2uz.

2.2 Assembly task and instruction material

Participants assembled two predefined fantasy objects, each consisting of 62 building bricks, with different instruction types (see Figure 1). Every participant tested both, a gaze-controlled instruction on a screen and a conventional paper manual, in a row. The order of the instruction types was counterbalanced, with half of the participants starting with the gaze instruction followed by the paper manual, and the other half working in the opposite order. Further, the assignment of to-be-built object to instruction type was counterbalanced. For both instruction types the same instruction photos were used. They were taken from the top view and each new photo depicted one additional, brightly illuminated brick to ensure easy identification.

The gaze-controlled instructions were programmed with E-Prime 2.0, and for eye tracking, a Smarteye Pro dx eye tracking system with three 3D cameras sampling at 60 Hz was used. As this eye tracker is desk-mounted, it ensures a natural assembly process without any restrictions that come with a head-mounted device. The cameras were beneath a 53 × 30 cm screen on which the gaze-controlled instructions were presented with a viewing distance of approximately 50 cm. The instruction photo (15 × 15 cm) was positioned in the center of the screen. On the left and right side were black-framed white areas (13 × 7.5 cm) with arrows that enabled participants to go forward and backward in the instructions. More specifically, if the eye tracker detected the participant's

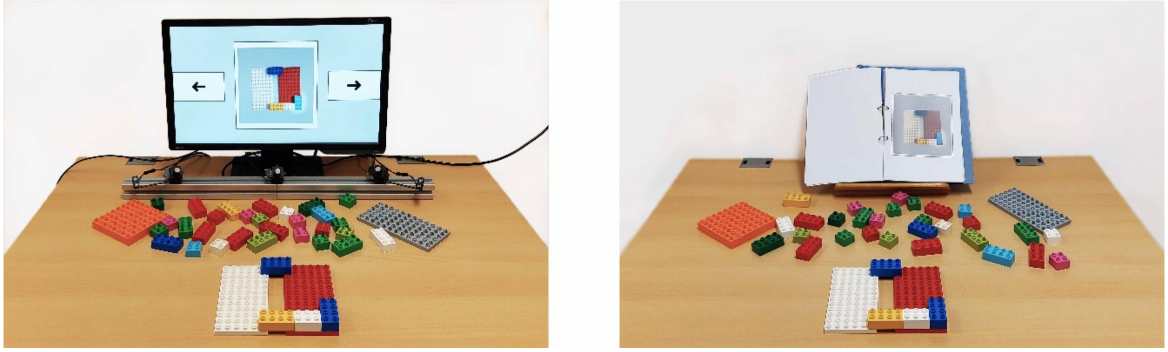

Figure 1: The two used instruction types: gaze-based instructions on screen and paper manual instructions.

gaze on one of the three elements, the frame of this element turned green to inform participants of the successful detection. When the participant's gaze was detected for longer than the set dwell time of 500 ms on one of the two arrow areas, the instructions switched to the previous or next instruction step. To avoid unintentional skipping of multiple pages and to provide feedback for successful command activation, a white area was displayed on the screen for 50 ms after each successful activation. These times were chosen based on the literature discussed in the introduction [e.g., 18., 19.] and piloting of the prototype.

The paper manual consisted of A4 sheets sorted into a ring binder. Each sheet depicted one instruction photo (15 × 15 cm) printed in the center of the sheet. The ring binder was placed on a bookrest. Participants were allowed to freely adjust the position of the bookrest but were asked to not remove the paper manual from it to simulate a working process on an assembly line where adjusting the location of the instruction manual would also be restricted to a certain amount.

2.3 Measures

Usability and User Experience were assessed with post-test questionnaires (subjective measures) and assembly time (objective measure) as part of a formative evaluation process. Questionnaires were filled right after the completion of each model, i.e., before participants switched to the next instruction type or completed the experiment.

First, participants filled in the German version of the *National Aeronautics and Space Administration-Task Load Index* [NASA-TLX; 33.]. This well-tested questionnaire is currently the most used self-assessment tool for subjective workload [34.]. It measures the six subscales Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration, each with one item on a scale of zero to twenty. Higher values are considered negative on all scales, except performance, where higher values reflect higher perceived performance and would therefore be considered positive. We used the raw NASA-TLX [35.], a modification of the questionnaire in which the subscales are not weighted, making it easier to use without reducing the reliability [36.].

Afterwards, participants completed the *User Experience Questionnaire* [UEQ; 37.]. The UEQ was initially developed in German. It includes 26 items in the format of a semantic differential, each consisting of two opposite adjectives rated on a scale of one to seven. The UEQ measures not only an overall valence dimension, the Attractiveness scale, but also scales of the pragmatic quality aspects Perspicuity, Efficiency, Dependability, and the hedonic quality aspects Stimulation and Novelty [38.]. While the pragmatic quality aspects are synonymous with usability aspects, the hedonic quality aspects include dimensions that focus on the user's subjective experience [39., 40.].

Finally, participants completed the *Usefulness, Satisfaction, and Ease of use questionnaire* [USE; 41.], measuring the usability on the four dimensions Usefulness, Satisfaction, Ease of Learning, and Ease of Use on scales ranging from one to seven. High values are positive. Additionally, this questionnaire collects positive and negative aspects in an open format. As no validated German version is publicly available, we used our own, unvalidated translation.

The overall processing time of each participant for each object was measured from the point in time where participants received the instruction until they stated that their object is completed.

3 RESULTS

Prior to data analysis, inverted items were converted and for scales with multiple items, the scale mean for each participant and instruction type was computed. For all measures, we compared the two instruction forms with paired, two-sided t-tests (see Figure 2).

In the NASA-TLX, participants reported significantly lower Effort with the gaze instruction than with the paper instruction (5.32 vs. 8.00), $t(18) = -2.79$, $p = .012$, $d = -0.64$. Gaze and paper instructions received similar values concerning their Mental Demand, $t(18) = 1.56$, $p = .136$, $d = 0.36$, Physical Demand, $t(18) = -1.19$, $p = .249$, $d = -0.27$, Temporal Demand, $t < 1$, Performance, $t(18) = 1.19$, $p = .249$, $d = 0.27$, and Frustration, $t < 1$.

In the UEQ, the Attractiveness of the gaze instruction was rated higher than that of the paper instruction (5.32 vs. 4.54), $t(18) = 2.59$, $p = .019$, $d = 0.59$. Likewise, the gaze instruction was rated higher than the paper instruction regarding its Stimulation (5.46 vs. 4.54), $t(18) = 3.26$, $p = .004$, $d = 0.75$, and Novelty (5.57 vs. 3.53), $t(18) = 4.62$, $p < .001$, $d = 1.06$. Instructions did not differ in terms of Perspicuity, $t < 1$, Efficiency, $t(18) = 1.67$, $p = .113$, $d = 0.38$, and Dependability, $t(18) = -1.37$, $p = .188$, $d = -0.31$.

In the USE, the Ease of Learning of the gaze instruction was rated higher than that of the paper instruction (6.61 vs. 6.32), $t(18)$

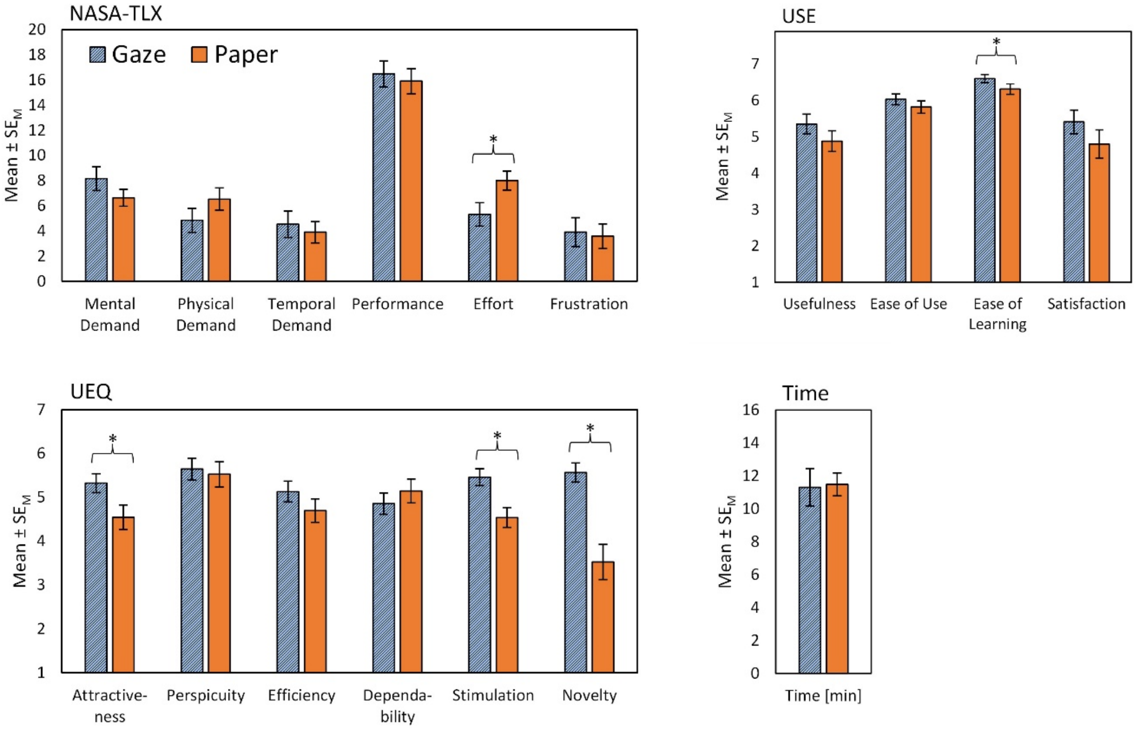

Figure 2: Questionnaire and time results for gaze and paper instruction. * indicate significant differences with $p < .001$.

= 2.36, $p = .030$, $d = 0.54$. Instructions did not differ in terms of their Usefulness, $t(18) = 1.74$, $p = .100$, $d = 0.40$, Ease of Use, $t(18) = 1.15$, $p = .266$, $d = 0.26$, and Satisfaction, $t(18) = 1.49$, $p = .154$, $d = 0.34$.

Crucially, both instruction forms had similar assembly times, $t < 1$.

4 DISCUSSION

The current study tested if gaze-controlled interfaces for instructing manual assembly can provide a user-friendly alternative to conventional instruction methods. We found that with gaze-controlled instructions, participants experienced less effort (NASA-TLX), suggesting that they perceived this task as easier to complete [33.]. Further, for this instruction form, the Ease of Learning (USE) was higher, supporting previous claims of an advantage of gaze pointing even without practice [11.]. Finally, gaze-controlled instructions were more pleasing (User Experience scales and Attractiveness dimension of the UEQ). This is especially encouraging as user experience has been described as decisive factor influencing whether a user group adopts a system for later use [42.] and further, it helps to reduce physical and mental stress on assemblers [23., 43.]. Crucially, assembly times did not differ, which indicates that the increase in user experience does not come at the cost of decreased assembly efficiency.

While our gaze-based prototype yielded promising results in the planned measures, the optional list of positive and negative aspects identified some points to improve upon in future gaze-based systems. One especially apparent and repeatedly reported issue is eye fatigue with the gaze-controlled instructions. Such eye fatigue has been found in earlier studies on gaze-based keyboard typing [44.] and was still apparent in our study although we already implemented design features that should work against eye fatigue [e.g., feedback, separation of interactive and non-interactive parts, a reasonable size of all areas; 17., 29., 45.]. It can be assumed that the command initiation by the adjusted dwell time of 500 ms is not the optimal solution for every participant, and that the ideal dwell time differs between users [1., 44.], with values ranging from 230 ms to 674 ms [46.]. Based on these findings, industrial applications of gaze-controlled interfaces should incorporate individually adjustable dwell times. Further, a more flexible page turning mode allowing to turn more than one page at a time or flexible skipping could likewise reduce the problem of eye fatigue. Against this background, the option to choose between manual input and gaze input should be explored in future studies, as it might attenuate the problems associated with each input modality alone.

The main strength of the current experiment is that the standardized and controlled setting enables us to pinpoint the perceived differences in usability and user experience directly to the used instruction type. As such, our decision for a paper manual as control condition reflects a natural baseline, as it is a commonly used instruction type in applied settings. However, this choice also entails that the instruction types differ in both interaction technique (gaze vs. manual) as well as presentation medium (screen vs. paper). To ensure that it is the interaction technique which primarily drives our results, a replication with an additional condition combining manual actions (e.g., button presses) with instructions on a screen could be implemented in future studies.

Still, despite all advantages, standardized experiments cannot fully replace broad investigations in an industrial setting. Therefore, future research should implement gaze-based instructions in more applied settings. As a beneficial side effect, this would naturally provide a representative assembler sample instead of our student sample that is biased towards young females. Further, this would allow to assess the long-term evolvement of the observed effects. For example, the speed of the gaze-instructions might increase with experience, while decreasing novelty might render the gaze instructions more similar in terms of user experience. In fact, we are currently working on implementing gaze-based instructions in a self-learning assistive system [47.] for manual assemblers in an industrial setting.

As a concluding remark, we would like to highlight that increased knowledge about the usability of gaze-based machine interfaces is not only applicable to instructions at industrial assembly lines. For example, a surgeon might request enlargement of certain information (e.g., blood pressure) during a critical operation, where avoiding eye fatigue is critical. Similarly, gaze could provide a hygienic alternative to touch displays and buttons for highly frequented vending machines (e.g., at train stations), where the acceptance of large parts of the population is a prerequisite for success.

ACKNOWLEDGMENTS

This work was funded by the Bundesministerium für Bildung und Forschung (BMBF) Grant no 01|S19043D.

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