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Minimal AR: Visual Asset Optimization for the Authoring of Augmented Reality Work Instructions in Manufacturing

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Abstract

This work investigates the possibility of using a novel "minimal AR" authoring approach to optimize the visual assets used in Augmented Reality (AR) interfaces to convey work instructions in manufacturing. In the literature, there are no widely supported guidelines for the optimal choice of visual assets (e.g., CAD models, drawings, videos). Therefore, to avoid the risk of having AR technical documentation based only on the author's preference, our work proposes a novel authoring approach that enforces the minimal amount of information to accomplish a task. Minimal AR was tested through a simulated AR LEGO-based assembly task. The performance (completion time, mental workload, errors) of 40 users was evaluated with 4 combinations of visual assets in 4 tasks with an increasing amount of information needed. The main result is that visual assets with an excess of information do not significantly increase performance. Therefore, the location of a specified object should be "minimally" authored by an auxiliary model (e.g., a circle, an arrow). For identifying an object within a couple, color coding is preferred to using additional visual assets. If more than two objects must be identified, a drawing visual asset is also needed. Only when the orientation of a selected object must be conveyed, animated product models are required. These insights could be helpful for an optimal design of AR work instructions in a wide range of industrial fields.

Keywords

Industrial Augmented Reality, Authoring, Minimal Information, Visual Asset, Work Instruction, Industrial Metaverse.

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Declarations

Conflicts of interest/Competing interests

The authors have no relevant interests to disclose

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Availability of data and material

We uploaded the data (completion time, mean time of dual task, errors) collected for each user during the experiment.

Code availability

We uploaded as supplemental material a video that shows the main features of the AR simulated application developed for the experiment.

Authors' contributions

Enricoandrea Laviola: Methodology, Software, Visualization, Investigation, Writing - Original Draft **Michele Gattullo**: Conceptualization, Methodology, Formal analysis, Investigation, Writing - Original **Vito Modesto Manghisi:** Software, Investigation, Writing - Review & Editing **Michele Fiorentino:** Supervision, Resources, Funding acquisition, Writing - Review & Editing **Antonio Emmanuele Uva:** Supervision, Resources, Funding acquisition, Writing - Review & Editing

Ethics approval

The students volunteered for the experiments.

Consent to participate

Not applicable

Consent for publication

Not applicable

1. Introduction

This research focuses on optimizing the visual assets [1] to provide work instructions in Augmented Reality interfaces. Over the last years, numerous studies confirmed that Augmented Reality is a powerful tool to provide work instructions in technical documentation for manufacturing such as assembly, maintenance, quality control, and so on. In a world that is going towards the metaverse, i.e., a virtual environment in which participants interact through digital objects and avatars [2, 3], the introduction in the manufacturing processes of technologies like Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR) is crucial. Thanks to the increasing maturity of display technologies and the spreading of markerless tracking methods, many companies are convincing to invest in AR [4]. However, AR is still not broadly used in real industrial settings due to the complex requirements that AR applications must deal with [5]. One of the main unsolved issues is the authoring of AR interfaces. In the traditional technical documentation, work instructions are usually shown in the form of text or drawings, rich in information to process for operators at the same time. Therefore, a high mental workload is needed to understand them [6–8]. Conversely, AR allows chunk instructions into atomic pieces of information [9] to choose among various types of visual assets [10] to precisely convey the information needed. However, this choice requires highly qualified designers because it depends on many factors such as environment, people, and process that need to be considered at the same time [11]. A misinterpretation of these aspects could lead to the inclusion of visual assets that require more authoring effort and are not suitable for operator's usage, resulting in a performance reduction. Unfortunately, there is still a lack of expert knowledge of AR in the companies. Furthermore, the rapid growth of AR/VR/MR authoring tools leads to difficult challenges for inexperienced designers [12–14]. These factors may either limit AR adoption in the industry [15] or lead to an AR technical documentation where visual assets are not optimized. In fact, without established guidelines to follow, the choice would be based only on personal preference [16] with the risk of having an inadequate design of the user interface characterized by redundant information that does not necessarily improve operator performance, but on the contrary it can be distracting [17] and represents an extra effort and cost for their modeling. Furthermore, most of AR devices have a limited presentation space [18]. Then, displaying on a see-trough device an AR technical documentation with many visual assets may occlude the real world, and operators could not correctly see their hands and the object they are working on.

In the industrial context, many studies on AR mainly focused on evaluating the concept of AR as such instead of paying attention to the information content [19, 20]. Although various methods have been proposed aimed at generating visual assets [21–23] for industrial AR interfaces [24–30], there is no agreement in the literature about the best way to provide AR instructions [31]. The review of industrial AR interfaces made in [10] pointed out an interesting result. For the simple task of “locating” auxiliary models are the most used visual assets. They provide a limited amount of information and highlight with a simple virtual shape (e.g., a circle, an arrow) the 3D position of a real object. On the contrary, for the more complex “operating” task, product models are the most used. They provide a greater amount of information than the auxiliary model, such as the shape of the virtual object and its orientation respect to the real objects. A possible reason for this difference is that for simple tasks, additional information does not cause an improvement of operator performance, as observed in [32], instead they may produce information overload. This is just an example considering two types of visual assets, but we can generalize by saying that presenting a large amount of information quickly leads to a cluttered presentation, making it difficult for a viewer to gain insight into the data [33]. However, it is not clear from the literature how different designs of visual assets affect operator performance in achieving an industrial task [32, 34]. Then, the following research question is formulated: "How does the information provided through AR visual assets affect user performance in task completion?"

To answer our research question, an information model was first formalized based on Norman's definitions of affordance and signifier [35]. In this model, the task complexity is established by the amount and type of information needed to correctly accomplish the tasks included in a work instruction. This information can be provided through object affordance and/or AR signifiers, i.e., one or more visual assets with their properties. Then this work proposes a novel authoring approach, called "minimal AR," where *the information provided through AR visual assets is the minimum needed to accomplish the task*. Finally, an experiment was carried out to demonstrate that AR signifiers which provide more information than the minimal AR signifier, do not cause an increase of users' performance (completion time, mental workload, errors). We identified four task complexities with an increasing amount of information needed to accomplish the task. For each task complexity, users' performance was analyzed with four AR signifiers that can provide an increasing level of information.

The main contributions of this work are:

- Formalizing a novel information model to understand the information involved in an industrial task and which one should be conveyed through AR visual assets.
- Proposing a novel authoring approach for the choice of visual assets that provide the minimal amount of information in AR interfaces involving work instructions.
- Demonstrating the validity of the approach through a user study involving four task complexities, four AR signifiers, and a constant affordance.

This paper is organized into 7 sections. Section 2 reports the related work on previous authoring approaches for the choice of visual assets in AR work instructions. In Section 3, the proposed information model and the minimal AR approach were described for the visual asset choice, also applying them to industrial case studies. In Section 4, the design of the user study was reported to answer our research question. In Section 5, this paper presents the results of the user study that were finally discussed in Section 6. In Section 7, a conclusion and considerations about future works were provided.

2. Related work

The difficulty of selecting appropriate visual assets for operator guidance in AR is widely asserted in the literature [11, 32, 36, 37]. However, research studies rarely present motivations for the choices of visualization methods and, when present, guidelines regard general technical issues as occlusion, geometric consistency, computational cost [23]. Also, big companies, such as Microsoft [38], Google [39], and Apple [40], provided guidelines on how to create user-friendly AR interfaces with their software libraries. However, as Tainaka et al. [36] revealed, the knowledge provided in these guidelines is intended for general AR systems. Therefore, the literature lacks a discussion on designing visual assets to convey specific information contained in work instructions.

In most cases, the AR authoring systems presented in the literature provide a selection of visual assets based on technical or empirical considerations, with the final choice left to end-users based on their preferences. For example, Tainaka et al. [36] proposed a decomposition of assembly tasks into subtasks with a list of candidate visual assets, among which the end-user can choose. A similar study was conducted by Chu et al. [41], who associated visual asset proposals with assembly steps of Dougong Chinese architecture. However, authors followed an empirical approach that is hardly scalable to other industrial applications for both the definition of the assembly steps and the choice of the visual assets.

In other research studies, end-users do not make the last choice based on their preference, but context-aware AR systems, as those proposed in [42, 43], suggest the best visual asset based on user capabilities. Syberfeldt et al. [19] and Holm et al. [44] developed a framework called ARES (Augmented Reality Expert System) that can display an increasing level of AR information based on the growing learning of operators when accomplishing new tasks. Similarly, Wolfartsberger et al. [45] used assets with a decreasing level of detail in working instructions, based on the increasing level of operator qualification. However, authors did not present any rationale behind the choice of one asset rather than another.

A hybrid authoring approach based both on user preference and capabilities is proposed by Geng et al. [11], consisting of a semantics structure where an industrial procedure is divided into a series of tasks, which consists of actions. Then, for each action, indicators are used to express virtual information. Scheffer et al. [46] presented an adaptive architectural framework for everyday maintenance merging the expertise with the user preference to increase performance efficiency.

Stork and Schubo [47] proposed another approach for the authoring of AR interfaces with the design of predetermined visual assets. The choice derives from the analysis of the information involved in the task that also depends on task complexity. This assembly task model was used as a theoretical basis in the study of Yang et al. [34] that involved the joining subtask, too. They proposed as AR assistance, highlighting the target part with a black rectangle for the commissioning subtask, while for the joining subtask, a 3D model of the part to be assembled is displayed on the assembly zone. The influence of task difficulty was also considered in the research work carried on by Radkowski et al. [32] whose hypothesis is that the complexity of the visual feature must comply with the difficulty level of the assembly step.

The authoring methods found in the literature can be summarized as follow. The choice of the visual assets can be based on:

- Both technical considerations and end-user preferences [36, 41].
- End-user performance [19, 44, 45].
- Both end-user preferences and performance [11, 46].
- The type of information involved [34, 47].
- Task complexity [32, 34].

Compared to these prior works, our work presents a novel authoring approach, minimal AR, which aims to propose through AR visual assets only the minimal amount of information needed to accomplish the task, considering the combined effects of real objects involved, end-user, and task complexity. A similar approach was presented by Wang et al. [48], who proposed a choice of visual assets to reduce the data quantity transferred between a local technician and remote expert in AR-based collaborative maintenance. However, the authors did not provide any rationale behind this classification, and the proposed framework was not tested through a user study. Therefore, in our work we also tested our approach through a user study where we evaluated user performance in terms of completion time, errors, and mental workload.

3. The "minimal AR" authoring approach

The authoring approach proposed in this work could orient designers in choosing the visual assets to be used in AR technical documentation. The choice is based aimed at providing through visual assets only the information needed to accomplish a task. Thus, it is important to define an information model to understand both which is the information needed and how it can be achieved.

3.1 The information model

Manufacturing work instructions need to be decomposed into single atomic tasks, as described in [9]. For each elemental task, it is possible to determine the set of information needed. The information contained in work instructions can be of different types, and there is not a standard classification. In a previous work [49], six information types were defined, based on the analysis of ten manufacturing manuals:

- IDENTITY: e.g., the identity of a part to position, of an object to grasp.
- LOCATION: e.g., location and destination of an object.
- ORDER: e.g., order to do a motion or a structured sequence in a plan.
- WAY TO: e.g., the way to dis/assemble parts, to use an object.
- NOTIFICATION: e.g., confirmation that parts are dis/assembled or information that a problem is occurring/has been solved.
- ORIENTATION: e.g., the initial or desired orientation of an object.

Each elemental task could have a variable task complexity based on the type and amount of information needed. Then, designers have to choose case by case how to convey this information in the AR interface. It can be provided either by exploiting the affordance of the objects involved in the task or through an AR signifier, i.e., one or more visual assets with their properties (Fig. 1).

Fig. 1 *The information model used in minimal AR: the task complexity is defined by the amount and type of information needed [49]; they can be provided exploiting affordance [35] and AR signifiers, i.e., visual assets with their properties [10]*

As defined by Norman, affordance is "the relationship between the properties of an object and the capabilities of the person that determine just how the object could possibly be used [35]." There is no standard way to measure affordance and it should be determined by analyzing the objects and the capabilities of people involved in the task. A high affordance could be attributable to a good object design that naturally communicates how to use it, such as a panic bar in emergency doors. If the object could be used in various ways, users can rely on their capabilities to accomplish the task, such as: (i) technical skills that can change from people to people based on their attitudes, (ii) overall experience in doing similar tasks, and (iii) previous knowledge in doing that specific task. If object affordance is low, an external source of information is needed. To define this source, our work refers to "signifier," intended by Norman as "any mark or sound, any perceivable indicator that communicates appropriate behavior to a person."

An AR signifier is then a combination of one or more visual assets which can convey a set of information. We used the classification of visual assets that arose from a literature survey on industrial AR interfaces [10]: text, signs, photographs, drawings, video, product model, auxiliary model. Each type of visual asset can provide one or more information according also to its design properties, such as frame of reference (screen/world fixed), color coding, and animations. For example, a world-fixed visual asset implicitly conveys the additional information about the location respect to the same screen fixed visual asset. In the same way, through color-coding it is possible to provide notifications (e.g., warning in yellow) or the identity of two parts to be assembled (e.g., a pin and its relative hole). Animations could be exploited to provide dynamic information such as how to orientate objects during an assembly operation, the way to do some specific tasks, the order in an assembly sequence involving more than two parts.

3.2 The minimal AR signifier

In the authoring of AR technical documentation, designers must choose the AR signifiers to provide the information that operators need to accomplish a work instruction. This choice is critical for operators since they can cope with three different scenarios:

1. Incomplete information: the AR signifier is not well designed because the information provided is not clear or incomplete (Fig. 2.b).
2. Minimal information: the AR signifier is tailored to the information required to accomplish the task (Fig. 2.a, Fig. 2.c).
3. Redundant information: the AR signifier is not optimized because it allows for either redundant information or information not needed to accomplish the task (Fig. 2.d).

Fig. 2 *The minimal AR authoring approach applied to the case study of a hydraulic valve. For the instruction "push the manual descent button" the affordance is enough to accomplish the task, then no AR signifier is needed (a). For the instruction "open regulator #7 until the nominal pressure is read on the pressure gauge" affordance is not enough, and AR signifiers are needed: information provided through signifiers can be incomplete or not clear (b), minimal (c), redundant (d).*

The presentation of the previous scenarios represents the main step forward to Norman's theory due to the room for designing of interfaces offered by AR. In fact, in traditional technical documentation designers could exploit only visual assets suitable for printing, i.e., text and drawings. Furthermore, documentation was not tailored to operator knowledge and experience. Then, for expert operators, documentation could result rich of redundant information while, for novices, it could be not clear or with missing information (e.g., left to experience). On the contrary, it is possible to achieve the optimal condition in AR interfaces through a careful design of visual assets.

In the minimal AR authoring approach, a strategy was proposed for the design of AR signifiers aimed to minimize the difference between the information they provide and that needed to accomplish a task. Hence, we called them "minimal AR signifiers." The hypothesis behind this approach, derived from the literature [10, 32] and the observation in industrial projects with local companies, is the following: compared to the minimal AR signifier, user performance (completion time, mental workload, errors) does not improve with those conveying additional information. This hypothesis was tested through the user study described in Section 4.

3.3 Application to industrial case studies

To better understand the information model and how to define minimal AR signifiers, our authoring approach was applied to two examples of industrial tasks, frequent in technical documentation: pushing a button, opening a regulator. They were taken from a real technical manual of a hydraulic valve for elevators, specifically from the procedure for the pressure regulation of the stem.

The first example of instruction is: "push the manual descent button." This is a simple instruction with just one elemental task that is the pushing of a button. The set of information needed to accomplish this task is: i) *identity* of the button; ii) *location* of the button; iii) *way to* push the button. In this example, the affordance of the valve is enough to provide all this information, and no AR signifier is needed (Fig. 2.a). In fact, the manual descent button is the only button on the valve, then it is easy to identify and locate also for a novice operator. Furthermore, the mushroom-shaped button provides a high affordance, and any further AR signifier on how to push it (e.g., an animated 3D arrow) would be redundant.

The second example of instruction is: "open regulator #7 until the nominal pressure is read on the pressure gauge." This instruction can be divided into two elemental tasks: open the regulator and reading the pressure value. For each elemental task, using the information model proposed, it is possible to determine the specific set of information needed and if they could be provided through affordance or AR signifiers.

For the opening task, the set of information needed is: i) *identity* of the regulator; ii) *location* of the regulator; iii) the *way to* open the regulator. This information can be achieved through the affordance only if the operator has already accomplished this task. In fact, the valve is provided with more than one regulator that can be turned clockwise or counterclockwise. Then, novice operators could not know which is the regulator and how to use it (i.e., counterclockwise) for the opening action. In this case, AR signifiers are needed. An example of a minimal AR signifier for this set of information could be a static counterclockwise arrow placed near the physical regulator (Fig. 2.c). A simple circle would not be enough because it does not provide the information about the opening action (Fig. 2.b). Thus, some operators may guess the direction of rotation with consequent errors. On the contrary, the animation of the arrow and any further AR signifier would provide redundant information (Fig. 2.d).

For the reading task, the set of information needed is: i) *identity* of the pressure gauge; ii) *location* of the pressure gauge; iii) *identity* of the nominal pressure value; iv) *notification* that the pressure has reached the nominal value. In this case, the only information to be provided with an AR signifier is the identity of the nominal pressure value because there is only one pressure gauge, and it is easy to locate also for novice operators. The nominal pressure value (35 bar in the example) can be provided through different visual assets. An example of a minimal AR signifier could be a text reporting the nominal pressure value (Fig. 2.c). Using a drawing of the pressure gauge reporting the nominal pressure value could be a cool solution, but it provides a redundant information (the drawing) that occludes the real world (Fig. 2.d). Using just a line that highlights the position to be reached by the needle on the real pressure gauge is the less occluding solution (Fig. 2.b), but it leads to a not clear information since the line could indicate a wrong number on the pressure gauge due to tracking errors.

In the next section, through the description of the user study, it is possible to understand how the minimal AR approach could be used to provide the information about order and orientation, too. In fact, our user study refers to a typical task of manufacturing, such as assembling two parts.

4. User study

4.1 Design of the experiment

The goal of the experiment is to test our hypothesis: compared to the minimal AR signifier, user performance (completion time, mental workload, errors) does not improve with those conveying additional information. For this purpose, a LEGO-based assembly task was designed with users asked to assemble abstract shapes with LEGO Duplo bricks. As demonstrated by previous studies [50–53], LEGO-based tasks can well simulate industrial assembly because the interactions involved are very similar as picking and placement tasks. Moreover, it is possible to easily modify many variables such as quantity, order, and shape with a progressive increase in complexity in accordance with the industrial manufacturing requirements. In addition, LEGO bricks have a small volume, light weight, and are considerable safe, thus they are convenient for laboratory operations, as argued by Yang et al. [34]. A LEGO-based assembly task also allowed us to have a fixed affordance that is not enough to accomplish the task. In fact, all the selected users had previous experience with LEGO; thus, they knew how to hold them, contrary to the assembly of complex equipment that strongly relies on human capabilities. At the same time, users had not any knowledge about the specific task because they were asked to assemble an abstract shape that is different in every tested condition.

For the definition of the tasks, an incremental amount of information was considered. Our work referred to the classification of the information types provided in [49]. The required information in a LEGO-based assembly task is:

- The brick destination *location*.
- The *identity* of the brick to pick, in terms of color and shape.
- The *orientation* of the brick along the axis normal to the assembly plate (this information is provided through the brick affordance along the other axes).
- The sequence *order* of the bricks in the assembly.

Then, four LEGO sets were designed with an increasing complexity. The different amount of information needed was achieved using one to three LEGO bricks shapes and from one to two colors (Fig. 3). In every LEGO set, the total number of bricks was twelve, and they were balanced among the different types.

Fig. 3 *LEGO Duplo brick shapes used in the experiment; colors used for each brick are blue and red*

For each LEGO set, the next step was to apply the "minimal AR" authoring approach to create a specific AR signifier intended as the combination of one or more visual assets which can convey a set of minimal information. In this way, a total of four AR signifiers (Table 1) were designed. The choice among visual assets that provide the same information is not a variable of this study and is left to designers according to their preference or technical considerations. For example, as to auxiliary models, alternative shapes to the one chosen for this experiment (a filled rectangle) could be designed too. To assess the goodness of the design of the AR signifiers, we also measured the performance with an established baseline. It is represented by a traditional way of presenting LEGO brick assembly instructions [54], consisting of the drawing of exploded isometric views with every assembly step and a target drawing of the completed assembly. The information about the sequence is provided using numbered balloons in the drawings (Fig. 4), whereas in the AR interface, it is achieved displaying only the instruction for a brick per time.

Table 1 *AR signifiers designed for the experiment*

Fig. 4 *Reproduction of a traditional signifier employed in LEGO manuals [54], used as baseline in the experiment*

Considering the independent variables of LEGO sets (4) and signifiers (4 AR, 1 traditional used as baseline), we had 4x5=20 conditions. Therefore, for each LEGO set, 5 tests were created, each one composed of a different signifier among those proposed. However, only 14 were tested (Table 2) because we did not consider those conditions where the information provided by the AR signifier is lower than the minimal. For example, for the LEGO set 2, we excluded the condition with the AR signifier 1 because users could not know if a blue or red LEGO brick had to be placed. We designed a within-subject experiment so that each participant tested all the experimental conditions, with the scope to collect user performance regarding completion time, mental workload, and errors.

Table *2 LEGO sets and signifiers tested in the experiment*

As to the mental workload, it was evaluated through a dual-task paradigm. Users were asked to perform a secondary task that, in our work, was a simple visual-monitoring task, requiring them to react as soon as possible to a color change, as previously made by Brunken et al. [55]. As pointed out by Cegarra et al. [56], the idea underlying measurement of an additional task is that the capacity that is not being used to perform the primary task can be used to perform another task; therefore, the performance of the additional task can be used as an index of the demands made by the primary task. We decided not to use workload assessment tools such as the NASA Task Load Index (TLX) or SWAT (Subjective Assessment Technique), which would lead to an increase in the time needed to carry out the entire experiment for each user due to the high number of conditions to test.

4.2 Experimental set-up

The experiments were run in a simulated AR environment. Simulated AR technology, also called indirect AR [57] or Immersive Virtual AR [58], has already been used as a design tool in many different domains, such as architecture, city planning, and industrial design [59–61]. Before the main experiment, a preliminary evaluation was carried out to validate the simulated AR environment in comparison with the true physical task. It involved a focus group of ten people (2 females, 24 to 48 years old, mean=35.7, SD=9.42) with previous experience in the authoring of AR interfaces. The discussion in the focus group revealed that there is little difference in the visualization of the information conveyed by the visual assets in the two modalities and that it does not affect user performance. The focus group detected some differences in the interaction between users and LEGO bricks. In fact, in the simulated AR environment, we used some interaction metaphors, afterwards detailed, inspired by other UI (e.g., Virtual Reality testing applications [62] and videogame GUIs) to simulate the interaction between user hands/eyes and physical LEGO bricks, as regards: i) picking the requested brick; ii) rotating a brick before placing it; iii) assembling a brick on the plate or on other bricks; iv) disassembling a brick (e.g., wrongly placed); v) the point of view from which they observe the assembly. However, users in the focus group agreed that these differences little affect the information conveyed by the AR signifiers, object of this study. Only for the point of view, the focus group pointed out that if users could not change it in the simulated AR environment, there may be some cases in which the information remains hidden. Then, we decided to add a slider in the interface to allow users to rotate the LEGO plate in the virtual scene along the vertical axis.

This preliminary evaluation revealed that there was no need to accomplish the true physical task to test our hypothesis. Thus, the entire test was conducted and followed remotely, asking users to perform it at home. In this way, we could also respect the restrictions due to the SARS-CoV-2 epidemiological emergency. Users run the simulated AR application using their personal computers/laptops equipped with keyboard and mouse. Inspired by game interfaces, we designed a close arrangement of the keys (ASD) that users could press on the keyboard, and we suggested them to have one hand on the keyboard and the other one on the mouse during the experiment.

4.3 The Simulated AR interface

The simulated AR application was developed on Unity 3D Engine, importing the 3D CAD models of LEGO bricks previously modeled with Autodesk Inventor and exported in .obj format. In the Unity 3D environment, the simulated AR application interface was set up, and the scenes for the 14 testing conditions were created. Users could place LEGO bricks on a virtual 26x26 green LEGO Duplo plate to create the assemblies. The virtual LEGO bricks were distinguished from the AR instruction using a transparency shade. In fact, virtual LEGO bricks were rendered without transparency (Fig. 5.1), whereas auxiliary and product models were rendered with a semi-transparent shade (alpha 150 in the range from 0 to 255) (Fig. 5.2), as made in [34, 51, 63]. Virtual models of picking bins, where LEGO bricks are stored, were not represented. As shown in other works [61, 63], the main reason for this choice is to focus the user's attention only on the information to analyze. Therefore, the pictures of the LEGO bricks available for a LEGO set were put on the top-left corner of the interface (Fig. 5.3).

Fig. 5 *Interface of the simulated AR application: a LEGO brick already placed (1), instruction provided using a world-fixed auxiliary model (2), GUI buttons with pictures of the LEGO bricks available for the assembly set (3), a slider to rotate the camera (4), GUI buttons to move to the following assembly step and to display the popup window with instructions (5),changing color letter for the dual task (6), the GUI area for the screen-fixed visual assets (7)*

Users picked the brick to place by clicking on their corresponding pictures, then a 3D preview of the brick chosen appeared on the GUI in the mouse cursor position. When users understood the instruction, they released the LEGO brick by clicking on the desired location on the green LEGO Duplo plate or onto a previously placed LEGO brick. They could also rotate the block around the vertical axis, clockwise or counterclockwise, by pressing the keys "D" and "A" on the keyboard, respectively. As suggested by the preliminary evaluation, a slider on the GUI allowed users to rotate the camera in the virtual scene along the vertical axis to change the point of view for a more comfortable placing of LEGO bricks (Fig. 5.4). For the tests with traditional signifiers, the interface was the same except for the absence of the visual assets. In this case, the assembly instruction was displayed as a drawing on the screen of the user's smartphone placed beside the main screen where the application was running. All these choices have been designed to overcome the technical obstacles that may arise in the software physical simulation, such as unpredictability of virtual object behavior, collision, and attaching [52].

4.4 Participants

40 unpaid participants (9 females, 12 to 49 years old, mean=24.6, SD=5.08) were recruited mostly from the local university students and staff. It was ensured that all the participants were not colorblind and were familiar with LEGO assembly, rating 4.1 on average (SD=0.93, Median=4, Min=2, Max=5) on a 5-point Likert rating item (1: Not at all familiar – 5: Extremely familiar). Users were equally distributed regarding familiarity with AR applications, rating 2.7 on average (SD=1.48, Median=3, Min=1, Max=5). For each user, the experiment lasted on average 40 minutes. The experimenters used the Microsoft Teams platform to communicate with each user, one by one. Users were asked to share their screens to allow experimenters to follow the whole test. The sessions were also recorded to have a check of the eventual errors during the trials.

4.5 Procedure

The user study consisted of executing the 14 trials with the simulated AR application. At the beginning of each session, the experimenter collected general information about users, informed them about the test procedure, and instructed them on how to use the application. Then, users started a training with the application to become familiar with it, which could last from 1 to 5 minutes. At the beginning of the training, a popup window was displayed, explaining all the possible interactions with the interface. This window could always be open on request during the trials (Fig. 5.5). The training scenario shows an example for each AR signifier that will be shown during the experiment. When users felt trained, the experimenter gave the possibility to start the experiment saying the trial ID to execute from time to time.

A balanced Latin Square design was used for the task complexity and the signifier variable to minimize the order effects (learning, fatigue) and the carry-over effect on the collected data. This resulted in 40 different orders of execution of the 14 trials.

The main assembly task in each trial can be summarized as follows:

- Users click a button to start the trial.
- Users perform the assembly task, selecting and placing the twelve LEGO bricks according to the instructions.
- When users placed a LEGO brick, if the step was accomplished without errors, they could move to the following step by clicking a button in the GUI (Fig. 5.5). Otherwise, the experimenter said a mistake was made, and users had to repeat the step. An "undo" button allowed them to delete the last brick wrongly placed.
- At the end of the twelve steps, users pushed a button to end the trial.

During the main assembly task, users also performed a secondary task for the mental workload measurement. At various times, they received a signal consisting of the color change (from blue to white) of a letter [55], placed at the top center of the interface (Fig. 5.6). They have to respond to this signal as quick as possible by pushing the "S" key on the keyboard. After the users' response, the color of the letter reversed to blue, and the software recorded the reaction time. The timing for the color changing was defined through a predetermined time sequence whose intervals between two changes could range from 8 s to 18 s. Therefore, we had repeated measures of reaction time within each condition.

4.6 Measurements

The following data were gathered during the experiment for each trial: completion time, reaction time in the secondary task, and errors. Times were automatically acquired by the application and stored at the end of each trial in a simple ASCII text file, including the trial name. The completion time was measured since users pushed the button to begin the trial to when they pushed the button to end the trial. As to the reaction time in the secondary task, the mean time of the repeated measures was considered for every trial. Errors were manually detected by experimenters, who also distinguished the error type: order, location, orientation, color, shape, and their combinations. For every user, the total number of errors was collected in each trial for the analyses.

5. Results

All data recorded from each participant (completion time, mean reaction time, and error) were classified as matched continuous variables because data were obtained for each user under all 14 experimental conditions. To verify our hypothesis, we made separate analyses for the complexity levels (i.e., LEGO sets). Only for LEGO sets from 1 to 3, there was a comparison between the minimal and other AR signifiers.

The Shapiro-Wilk normality test, AS R94 algorithm, revealed that all the original data did not follow a normal distribution. However, performing a Box-Cox transformation (λ=-0.5) on completion time and reaction time, normal samples were obtained. On these data, Repeated Measures ANOVA was performed to compare more than 3 samples. It was observed if the assumption of sphericity is violated through Mauchly's Test of Sphericity, and, in that case, the Greenhouse-Geisser correction was used for the ANOVA. ANOVA post hoc tests were made using the Bonferroni correction. The Box-Cox transformation was not successful for total errors, and then nonparametric tests were performed. Friedman 2-way ANOVA was used to compare more than 3 samples. The Wilcoxon ranks-sum test, with the Bonferroni correction, was used as post-hoc test of the Friedman 2-way ANOVA.

5.1 Completion time

For all the LEGO sets, it was observed that the mean completion time of the task differed statistically significantly among all the conditions (Table 3).

Post hoc tests revealed no statistically significant reduction of time with all the AR signifiers respect to the one conveying minimal information. On the contrary, there is a significant increase of time with signifier 2 (22%) and 4 (14%) in LEGO set 1 (Fig. 6). This result allowed us to confirm our hypothesis for all the LEGO sets as regards completion time.

Post hoc tests also revealed that the traditional signifier caused a significant increase in time respect to all the AR signifiers ($p<0.001$ for all the pairs). This confirmed the goodness of all the AR signifiers proposed.

Table 3 *Results of statistical analyses for completion time*

Fig. 6 *Task completion time (error bar: standard error, *: significant difference) for the three LEGO sets for which there is a comparison between the minimal and other AR signifiers*

5.2 Mental workload

For all the LEGO sets, we observed that the mean reaction time of dual-task differed statistically significantly among all the conditions (Table 4).

Post hoc tests revealed no statistically significant reduction of time with all the AR signifiers respect to the one conveying minimal information. This result allowed to confirm our hypothesis for all the LEGO sets, as regards also user mental workload.

Post hoc tests also revealed that the traditional signifier caused a significant increase in reaction time respect to all the AR signifiers (p<0.001 for all the pairs). This confirmed the goodness of all the AR signifiers proposed.

Table 4 *Results of statistical analyses for mental workload*

Fig. 7 *Reaction time for the three LEGO sets for which there is a comparison between the minimal and other AR signifiers*

5.3 Errors

For all the LEGO sets, a statistically significant difference was observed in total errors (Table 5). Post hoc tests also revealed no statistically significant reduction of total errors with all the AR signifiers respect to the one conveying minimal information, except than for LEGO set 3. In this condition, a statistically significant reduction was observed (Fig. 7) with signifier 4 (1 error) respect to signifier 3 (15 errors), even if this last one provides all the needed information. Our hypothesis is then confirmed for all the LEGO sets, except for LEGO set 3, as regards total errors.

Post hoc tests also revealed that the traditional signifier caused a significant increase in total errors respect to all the AR signifiers (p<0.001 for all the pairs), except for signifier 2 for LEGO set 1 (α=0.005, p=0.028).

Table 5 *Results of statistical analyses for total errors*

Fig. 8 *Total errors (*: significant difference) for the three LEGO sets for which there is a comparison between the minimal and other AR signifiers*

6. Discussion

6.1 Findings from the user study

The user study results support our hypothesis that there is no advantage in using AR signifiers that convey more information than the minimal signifier. This behavior was observed for all the measured variables of completion time, mental workload, and errors, as well as for different types of tasks involving an increasing amount of information needed. The minimal AR authoring approach was tested with a LEGO-based assembly task, but the results can be generalized to other manufacturing tasks, as pointed out in Section 6.2. Then, from this study, it is possible to propose the use of minimal AR approach as a guideline for the authoring of future AR technical documentation for manufacturing, choosing the most suitable visual assets to avoid information overload and excessive authoring efforts.

The minimal AR authoring approach can be summarized in the following steps:

1) Isolate the instructions to provide in the AR technical documentation
2) Divide the instruction into elemental tasks
3) Analyze the elemental task to find the set of information needed to accomplish it
4) Analyze the operating context (real object, user) to evaluate its affordance
5) Define which information could be provided through the affordance
6) Define which information must be provided through AR signifiers
7) Consider all the AR signifiers that can provide the needed information
8) Choose the AR signifier that minimizes the difference between the information provided and that needed (minimal AR signifier)

6.2 Design implications

It is possible to draw some design implications from the results of this study, trying to discuss how the minimal AR approach could be applied to some manufacturing tasks found in the industrial AR literature.

If the only information contained in a work instruction is the location of an object, it was found that using an auxiliary model without a particular color is enough. Examples of manufacturing tasks involving this kind of information are disassembly operations [64], inspection tasks [65], remotely supported maintenance [66], and point welding [67]. Henderson and Feiner [6] provided a good example of using auxiliary models (a combination of arrows and a highlighting effect) to provide location.

The results of our experiment for location are in accordance with Radkowski et al. [32], who did not find a significant difference in errors between an AR interface with product models and one with auxiliary models for locating tasks. When considering an industrial AR application, it is easy to think of a CAD model overlaid on the corresponding real equipment, as seen in many prototypes [68, 69]. This behavior is confirmed by Gattullo et al., who found that potential AR technical writers would prefer product models to all the other visual assets for every information type if they had not to consider design issues [49]. As a result, in many cases, product models, overlaid to real objects, are used simply to browse them in the environment, as in [70]. Our work revealed that a product model is needed only when the information about the orientation of an object must be conveyed, as in [71]. For simpler information, also considering the design issues, the choice of a product model become disadvantageous. In fact, they are highly sensitive to registration accuracy and require thorough management of depth cues (e.g., occlusion, shading, shadows) to ensure visual coherence respect to real objects. Another issue is the higher modeling effort compared to auxiliary models. Product models cannot always be available due to old equipment or permissions. Their creation requires competence in 3D modeling, and the modeling effort is related to the complexity of geometry and animation. On the contrary, auxiliary models can be chosen from a list of existing models or easily modeled if necessary.

When the complexity of work instructions increases, auxiliary models may need to be coupled to other signifiers that help operators identify the real object they refer to. Examples of these work instructions can be found in assembly operations involving many objects [72] and in maintenance where a particular tool must be used [6]. In these cases, identifying objects through a drawing is suggested, but also a photograph would work well. This signifier is then coupled with an auxiliary model that informs about object location. Our study revealed that no other signifiers are needed if the task to accomplish with that object is not ambiguous. For example, if the task is to insert a pin into a hole, an animation of the product model of the pin, showing how to insert it, is useless for the operator.

There are some cases where the possible choices of products that can be assembled are limited. Our experiment confirmed that color coding can be exploited in these cases: a specific meaning can be associated with the color of visual assets. In our experiment, we verified this behavior with two colors assigned to the auxiliary model, reproducing that of the LEGO brick to insert. In manufacturing applications, different colors could be associated with different objects involved in the task. For example, in Uva et al. [64], users had to assemble the intake and exhaust camshafts of a motorbike engine. They used colored auxiliary models to highlight their different locations without providing information about the shape of the camshafts with visual assets as drawings or photographs. If the number of objects placed in a specific point of an assembly gets higher, color coding may become ineffective because the operator must remember a higher number of associations between color and objects.

An unexpected result was observed in assembly set 3 with the combination of drawing and auxiliary model representing the minimal AR signifier. In fact, besides the product model does not provide further information, it reduces errors. As shown in Fig. 7, 88% of the errors with the minimal AR signifier regard the wrong shape. From the observation of the recordings of the experiments, it has been realized that some users did not focus well on the information about the shape provided by the drawing on the top-right corner of the interface. A screen-fixed drawing was used to reduce occlusions of the real scene [73]. However, users relied mainly on the auxiliary model that is world-fixed, so it is displayed directly in the working area. This result is useful to consider an arrangement of visual assets that does not need a divided attention. For example, in future AR interfaces, a situated visualization for all the visual assets can be exploited with the drawing placed on a label anchored to the auxiliary model.

6.3 Limitations

Interesting findings were obtained from this work, but they need to be further examined considering these limitations. A simulated AR application was used instead of a true AR one for the experiments because there was no need to accomplish the true physical task and respect SARS-CoV-2 restrictions. However, it was considered that the variable we wanted to analyze, i.e., the visual assets, is slightly influenced using simulated AR. Clearly, there are some differences in how visual assets blend with real objects compared to their virtual copies. However, our application was designed to minimize the effect of this discrepancy, and users involved in the preliminary evaluation agreed with this. Another difference with true AR is related to the manipulation of virtual LEGO bricks instead of real ones. However, tactile feedback is not a variable of interest for our study and is common to all the tested conditions; thus, it can be overlooked.

Another limitation of this work is in the choice of the tasks and visual assets. Our user study was limited to four tasks and four AR signifiers to have a not too long experiment. We chose simple tasks that are very common in AR technical documentation, where work instructions are chunked into small pieces of information. Moreover, our minimal AR authoring approach is more powerful with simple instructions than with more complex ones. In fact, increasing the complexity of the task, much information is needed, so there is less risk of information overload. As to the visual assets proposed, the main reason for their choice is the quantity of information they can convey, consistently with our hypothesis. However, with the same amount of information, other alternative visual assets could also be proposed. For example, a photograph could be used instead of a drawing to provide location and identity information. Text was not used because in the literature there are specific studies on text optimization [74–76]. Also, as to auxiliary models, different shapes from a filled rectangle could be designed. It was judged that the results of our experiment would not be affected by the choice among visual assets that provide the same information. Therefore, in the future usage of the minimal AR model, this final choice can be made according to author preference.

7. Conclusion and future work

In this paper, a novel authoring approach, minimal AR, was proposed to define the visual assets to be used in AR interfaces for manufacturing, where work instructions must be provided to operators. The concept behind this approach is the optimization of the quantity of information conveyed through AR signifiers. According to minimal AR, they must contain the minimum amount of information needed to understand and accomplish a task correctly. This authoring approach was tested through a user study involving 40 users on 4 LEGO-based assembly tasks with an increasing level of information needed. The experiment had a simple location task; then it was incrementally added the identity, considering color and shape, and orientation of LEGO bricks. We tested 5 signifiers (4 AR signifiers and a traditional one, used as a baseline) for all the target tasks that provided an increasing amount of information. The experiment results allow us to say that the proposed minimal AR approach can be used as a guideline for the design of future AR technical documentation to avoid information overload and excessive authoring efforts. In fact, the information of location, identity, and orientation is present in a great part of manufacturing work instructions. Compared to traditional forms of technical documentation where much information is provided through single static work instructions, in AR it is possible to chunk them into simple pieces of information [9, 77]. Then, even complex instructions can be ascribed to the information analyzed in this work.

In future work, it was planned to test the validity of minimal AR authoring approach with real manufacturing case studies. They also involve more complex tasks, as the way to assemble two parts or use a special tool, highly influenced by object affordance. Therefore, it will also be considered the combined effect of affordance and signifier on user performance. These experiments will be made in a true AR industrial scenario to exploit the affordance of physical objects.

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Fig1

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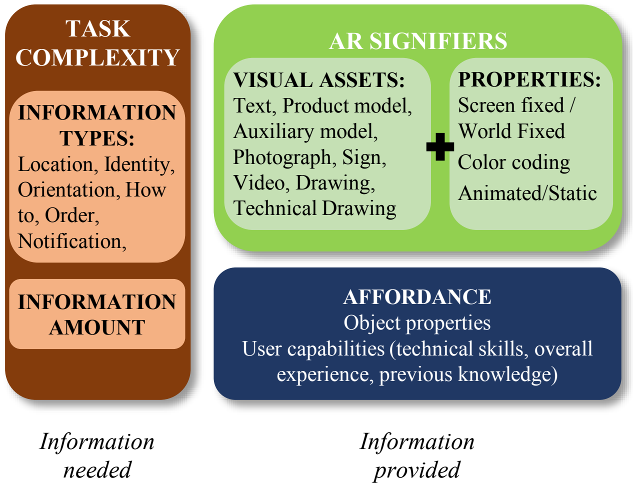


Fig3 Click here to access/download;Figure;Fig3.tif

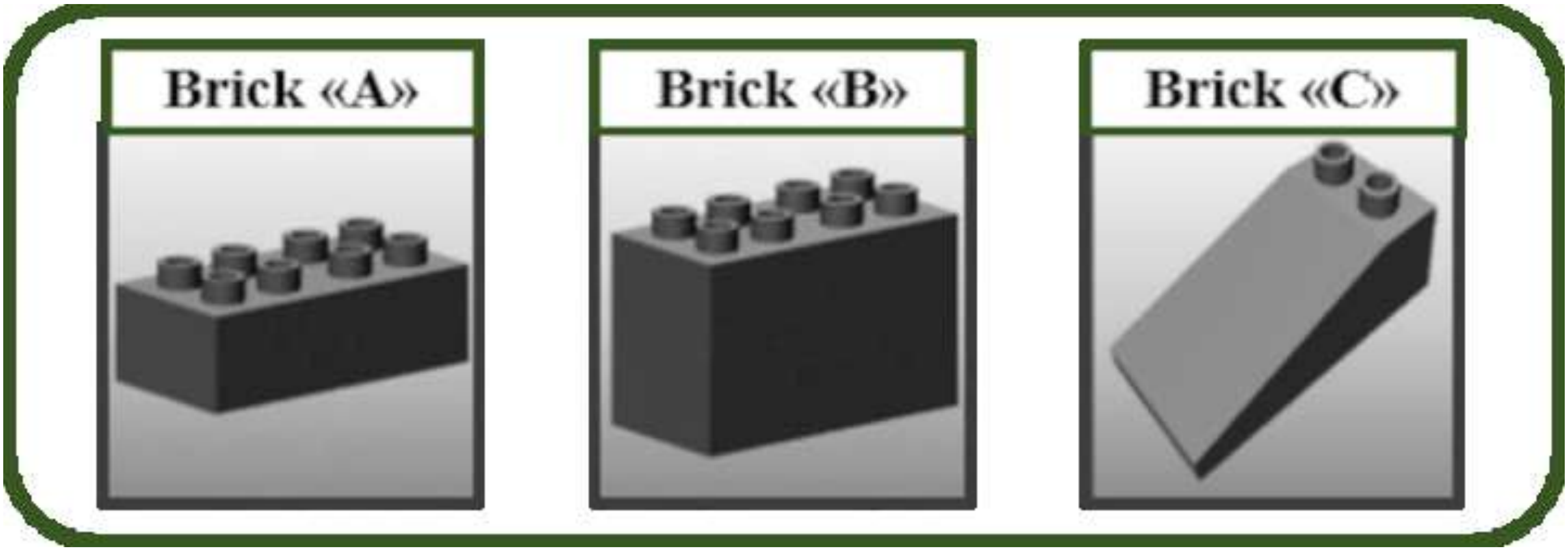


figure3.tif

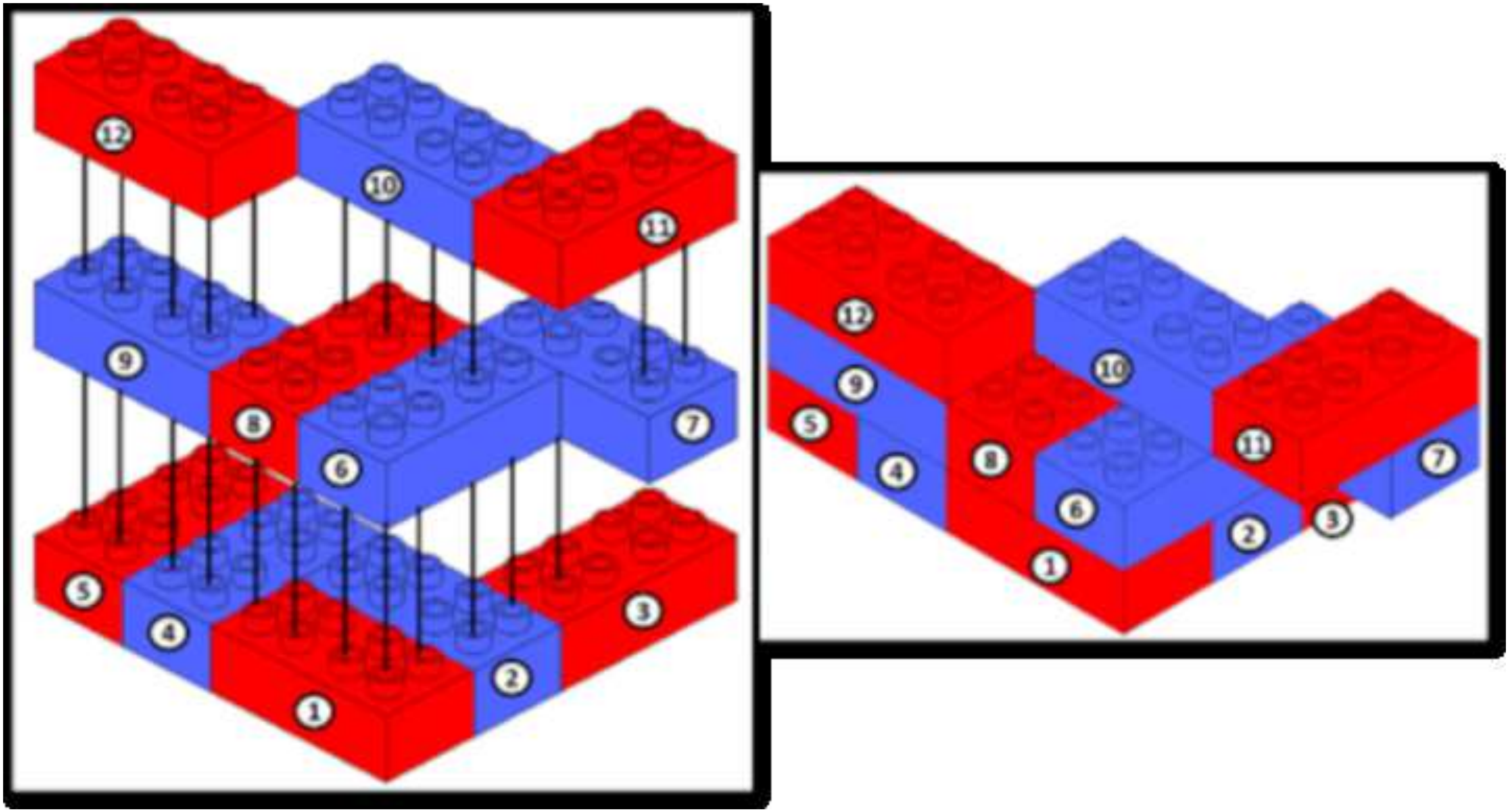


Fig4.tif

Fig2

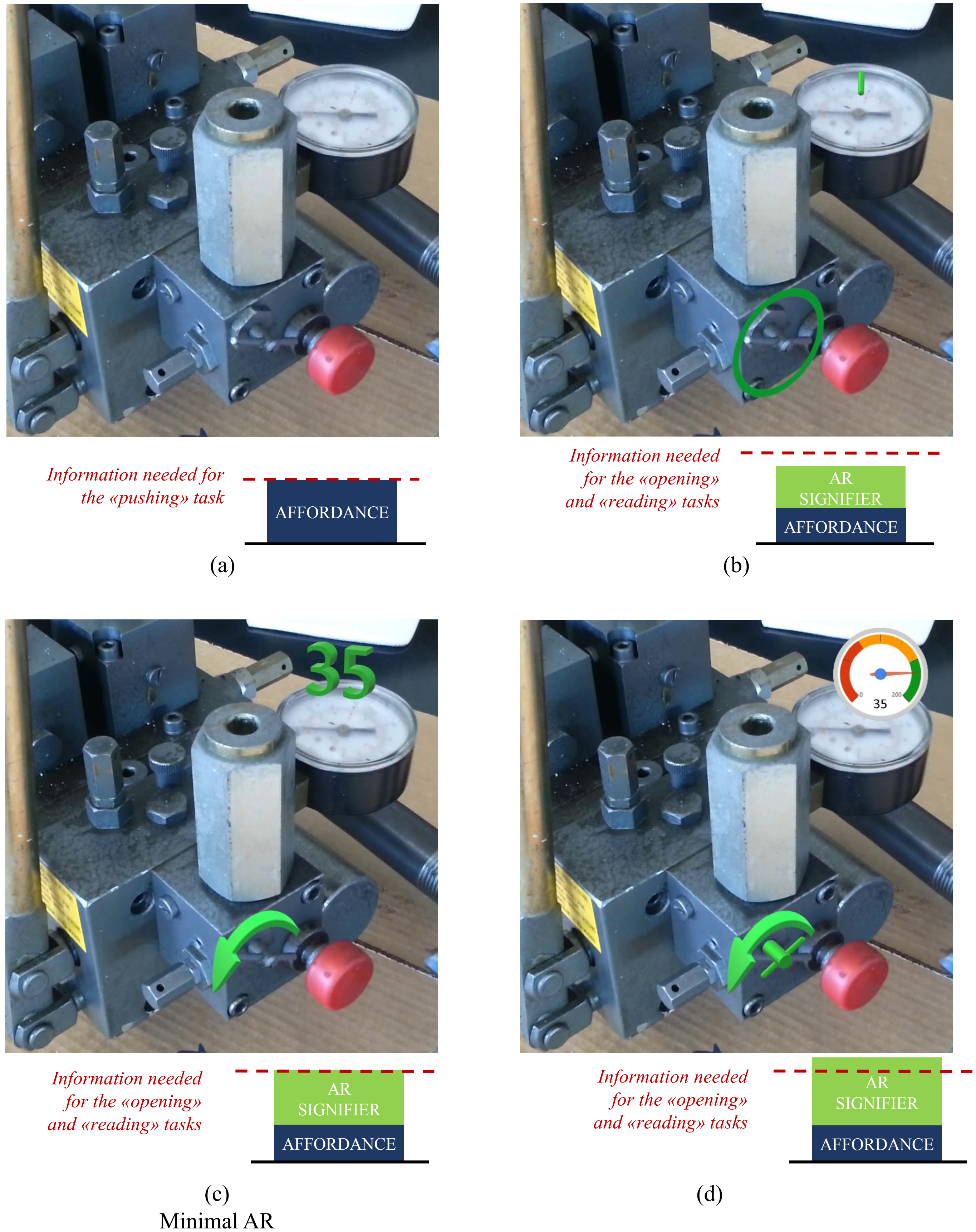

Information needed for the «pushing» task
AFFORDANCE
(a)
Information needed for the «opening» and «reading» tasks
AR SIGNIFIER
AFFORDANCE
(b)
35
Information needed for the «opening» and «reading» tasks
AR SIGNIFIER
AFFORDANCE
(c)
Minimal AR
35
Information needed for the «opening» and «reading» tasks
AR SIGNIFIER
AFFORDANCE
(d)

Fig5

Click here to access/download;Figure;Fig5.tif

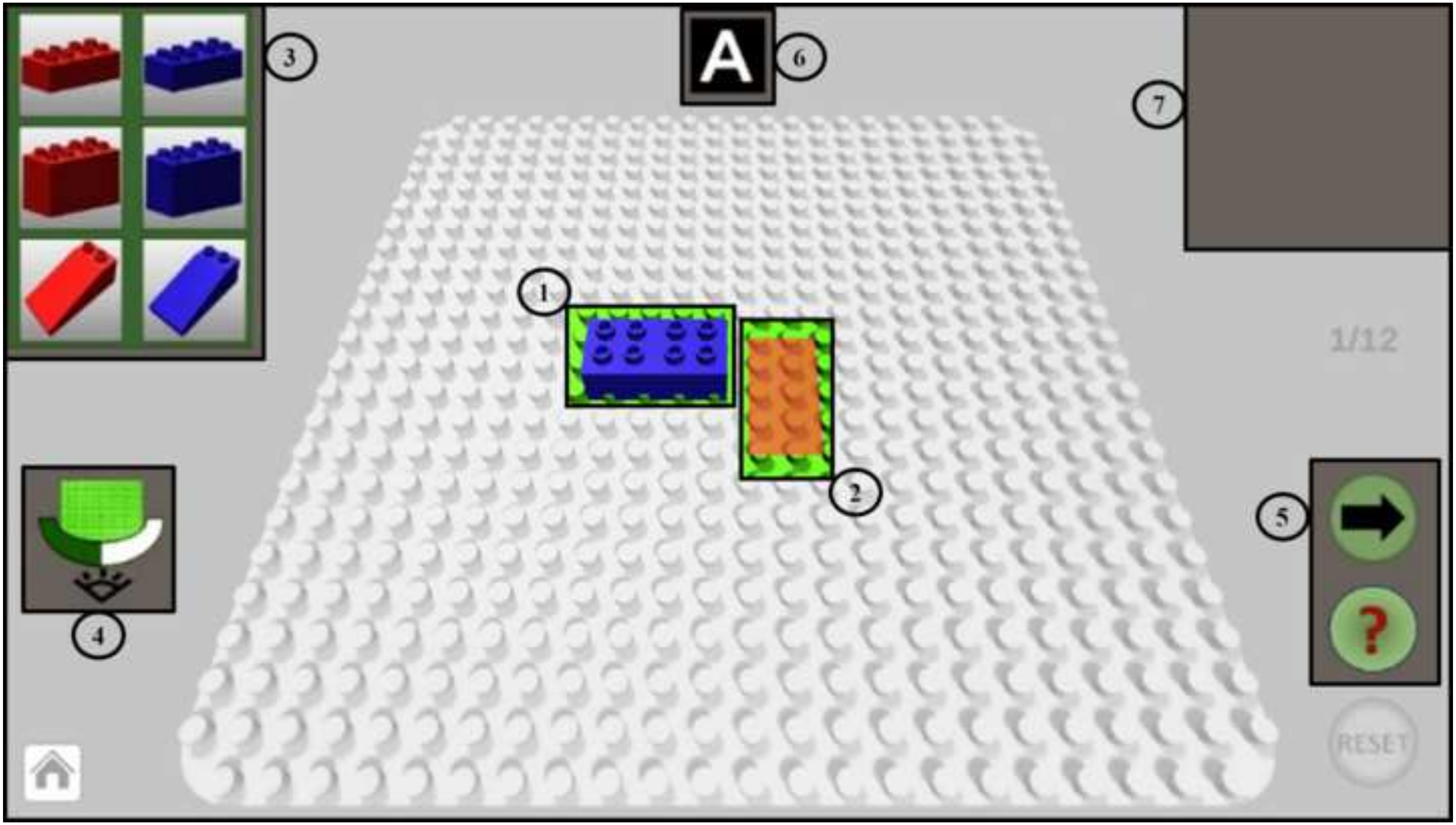


Fig5 new.png

Fig6

Click here to access/download;Figure;Fig6.pptx

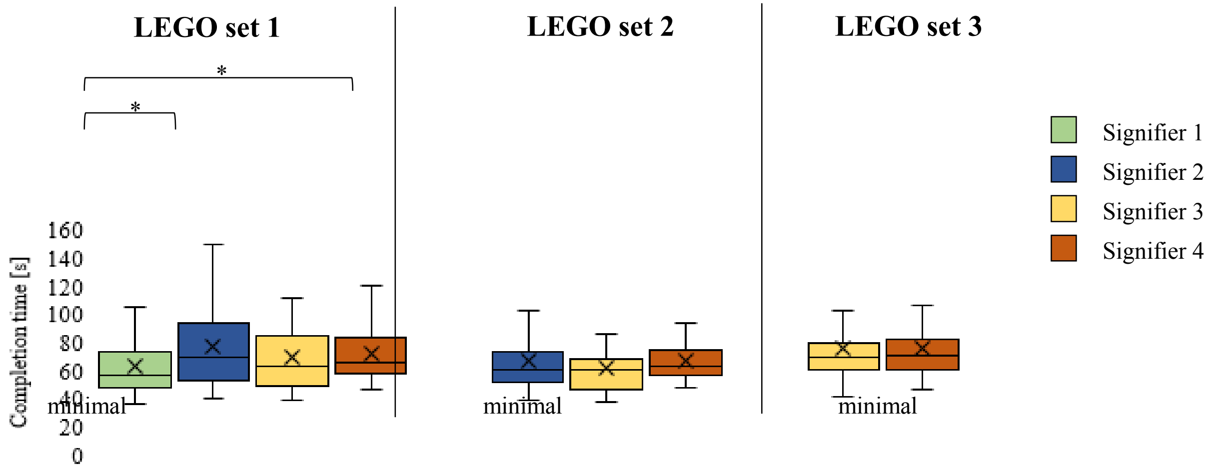


Fig7

Click here to access/download;Figure;Fig7.pptx

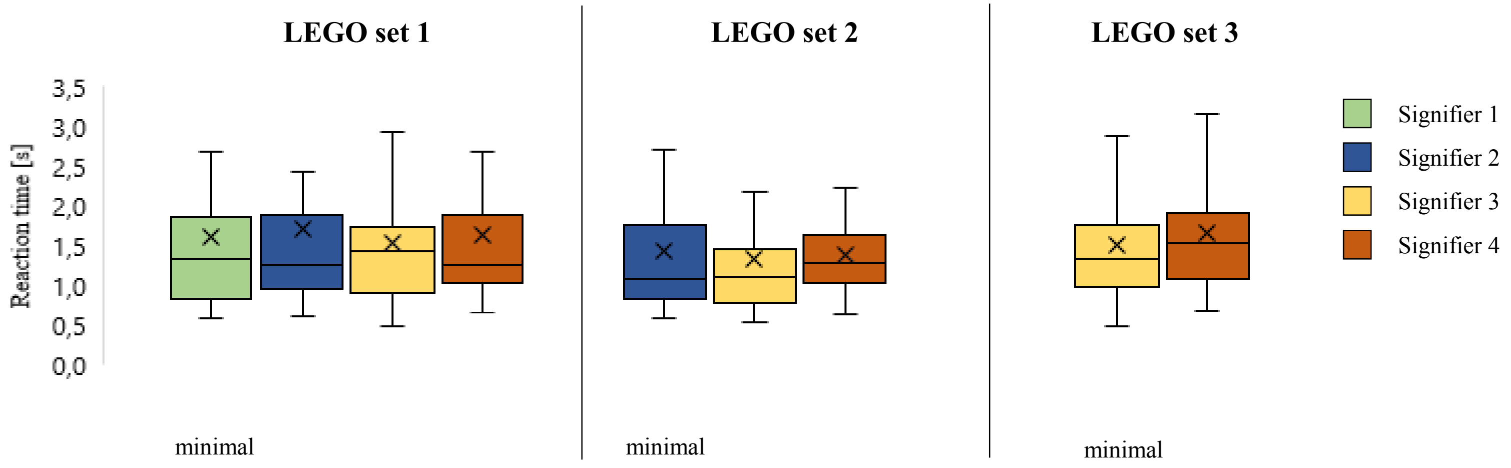
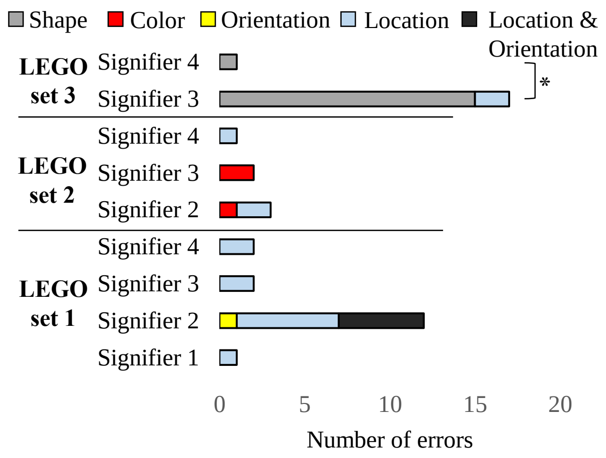


Fig8

Click here to access/download;Figure;Fig8.pptx



Title
Fig1
Fig2
Fig3
Fig4
Fig5
Fig6
Fig7
Table 1
Table 2
Table 3
Table 4
Table 5

Caption
Fig. 1 The information model used in minimal AR: the task complexity is defined by the amount and type of information needed [49]; they can be provided exploiting affordance [35] and AR signifiers, i.e., visual assets with their properties [10]
Fig 2 The minimal AR authoring approach applied to the case study of a hydraulic valve. For the instruction "push the manual descent button" the affordance is enough to accomplish the task, then no AR signifier is needed (a). For the instruction "open regulator #7 until the nominal pressure is read on the pressure gauge" affordance is not enough, and AR signifiers are needed; information provided through signifiers can …
Fig 3 LEGO Duplo brick shapes used in the experiment; colors used for each brick are blue and red
Fig 4 Reproduction of a traditional signifier employed in LEGO manuals [54], used as baseline in the experiment
Fig 5 Interface of the simulated AR application: a LEGO brick already placed (1), instruction provided using a world-fixed auxiliary model (2), GUI buttons with pictures of the LEGO bricks available for the assembly set (3), a slider to rotate the camera (4), GUI buttons to move to the following assembly step and to display …
Fig 6 Task completion time (error bar: standard error; *: significant difference) for the three LEGO sets for which there is a comparison between the minimal and other AR signifiers
Fig 7 Reaction time for the three LEGO sets for which there is a comparison between the minimal and other AR signifiers

between the minimal and other AR signifiers

Table 1 AR signifiers designed for the experiment
Table 2 LEGO sets and signifiers tested in the experiment
Table 3 Results of statistical analyses for completion time
Table 4 Results of statistical analyses for mental workload
Table 5 Results of statistical analyses for total errors

Format
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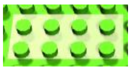
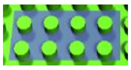
Table 1

Signifier ID	Visual assets	Properties	Appearance	Information provided
1	auxiliary model	World-fixed; no color coding used; static;		Location
2	auxiliary model	World-fixed; color is the same of the brick to place; static;		Location Identity (color)
3	auxiliary model	World-fixed; color is the same of the brick to place; static;		Location Identity (color and shape)
	drawing	Screen-fixed; Color and shape are the same of the brick to place; static;		
4	product model	World-fixed; Color and shape are the same of the brick to place; animated;		Location Identity (color and shape) Orientation

LEGO SET	1	2	3	4
Information needed	Location	Location Identity(color)	Location Identity (color) Identity (shape)	Location Identity (color) Identity (shape) Orientation
LEGO bricks used (Quantity)	A red (12)	A red (6) A blue (6)	A red (3) A blue (3) B red (3) B blue (3)	A red (2) A blue (2) B red (2) B blue (2) C red (2) C blue (2)
Minimal AR signifier	Signifier 1	Signifier 2	Signifier 3	Signifier 4
Other signifiers tested	Traditional Signifier 2 Signifier 3 Signifier 4	Traditional Signifier 3 Signifier 4	Traditional Signifier 4	Traditional

LEGO set	Repeated Measures ANOVA	Post hoc: Minimal Signifier vs.			
		Signifier 2	Signifier 3	Signifier 4	Traditional Signifier
1	$F(3.29, 128.317)=91.109$; $p<0.001$	p=0.003*	p=0.498	p<0.001*	p<0.001*
2	$F(2.578, 100.541)=166.121$; $p<0.001$	-	p=0.506	p=0.639	p<0.001*
3	$F(2, 78)=277.962$, $p<0.001$	-	-	p>0.999	p<0.001*

LEGO set	Repeated Measures ANOVA	Post hoc: Minimal Signifier vs.			
		Signifier 2	Signifier 3	Signifier 4	Traditional Signifier
1	F(4, 156)=23.078; p<0.001	p>0.999	p>0.999	p>0.999	p<0.001*
2	F(3, 117)=35.104; p<0.001	-	p>0.999	p=0.867	p<0.001*
3	F(1.7, 66.293)=34.009; p<0.001	-	-	p=0.132	p<0.001*

LEGO set	Friedman 2-way ANOVA	Post hoc: Minimal Signifier vs.				Post hoc Sign. level
		Signifier 2	Signifier 3	Signifier 4	Traditional Signifier	
1	$\chi2(4)=40.784$; $p<0.001$	p=0.005	p=0.564	p=0.564	p<0.001*	α=0.005
2	$\chi2(3)=36.076$; $p<0.001$	-	p=0.564	p=0.317	p=0.001*	α=0.008
3	$\chi2(2)=36.646$; $p<0.001$	-	-	p=0.002*	p<0.001*	α=0.017

Data

Click here to access/download

Supplementary Material

Supplementary material.xlsx

Video of the AR simulated application