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*Original Citation:*

Evaluating the effectiveness of spatial augmented reality in smart manufacturing: a solution for manual working stations / Uva, Ae.; Gattullo, M; Manghisi, Vm.; Spagnulo, D; Cascella, Gl.; Fiorentino, M.. - In: INTERNATIONAL JOURNAL, ADVANCED MANUFACTURING TECHNOLOGY. - ISSN 0268-3768. - STAMPA. - 94:1-4(2018), pp. 509-521. [10.1007/s00170-017-0846-4]

*Availability:*

This version is available at <http://hdl.handle.net/11589/123984> since: 2022-06-24

*Published version*

DOI:10.1007/s00170-017-0846-4

Publisher:

*Terms of use:*

(Article begins on next page)

Link to publisher version with DOI

<https://doi.org/10.1007/s00170-017-0846-4>

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# Evaluating the effectiveness of Spatial Augmented Reality in Smart Manufacturing: a solution for Manual Working Stations

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Received:

**Abstract** Augmented Reality (AR) is a key technology for the development of Smart Manufacturing. One of the main advantages of AR is that it can help workers to accomplish several tasks, making it possible the shift from mass production to mass customization. However, it is still not clear how these promises can be fulfilled in an industrial scenario. In particular, the question about which display solutions fit better the industrial constraints remains open. Based on literature overview, laboratory experiments and feedbacks from industrial companies, we supported the use of Spatial Augmented Reality (SAR), designing a prototype intended to be used for Manual Working Stations of the future Smart Factories. This work presents the evaluation of the effectiveness of conveying technical instructions with this SAR prototype as compared to paper manual. We run a within-subjects experiment with 16 participants to measure user task performance (completion times and error rates) and to collect subjective evaluation. We projected technical information on a motorbike engine during a 7-tasks maintenance procedure. Our results proved that SAR technology improves operators' performance respect to a paper manual and that users well accept it. We found that SAR is more effective for difficult tasks than for simple ones and that the main advantage of SAR is related more to the reduction of error rates than to completion times. These results confirm the goodness of our design choices; then our prototype can be a valid candidate solution for a Smart Manufacturing application.

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**Keywords** Spatial Augmented Reality · Industry 4.0 · Maintenance · Assembly · Projection · Technical Instructions

## 1 Introduction

Augmented Reality is one of the nine enabling technologies that will power the transformation supported by Industry 4.0 initiative [1]. In this transformation, sensors, machines, workpieces, operators, and IT systems will be connected to the value chain beyond a single enterprise. In particular, there are specific industrial areas where the visualization of information through AR is very effectiveness respect to other technologies: examples are remote assistance [2], [3] and localization of points for inspections [4]. These AR-supported systems are currently in their early stages, but we strongly believe that, in a next future, companies will make much broader use of AR to provide workers with real-time information to improve decision making and work procedures. In fact, the use of AR minimizes cognitive load and issues of divided attention induced in attending to both the real working space and the information space on the manual. Divided attention is the ability to respond simultaneously to multiple tasks or multiple task demands and is regarded as the highest level of attention [5].

In the literature, we found several successful demonstrations of the use of AR in the medical domain, military training, telerobotics, entertainment, maintenance, and manufacturing [6]. However, Augmented Reality solutions are still struggling to reach the factories. This issue is mainly due to display solutions that still do not fit with strict industrial constraints about ergonomics, color coding, training of operators, the reliability of proposed solutions. Common AR applications use Head-Worn Displays (HWDs), which suffer from bad ergonomics, low resolution, an excess of weight, limited/fixed focal depth

1 [7]. Industrial operators have to wear the HWD for long  
2 sessions and, for this main reason, industries do not well  
3 accept AR with these displays.

4 An alternative approach to HWD is to use handheld devices  
5 like smartphones and tablets. Although this kind of AR is  
6 very easy to implement due to the availability of low cost  
7 and powerful devices, in practice it has various limitations.  
8 One of the most important is that operators should employ  
9 one or even two hands for the visualization, thus limiting  
10 their ability to operate.

11 In a previous work [8], we experimented a setup with a large  
12 screen to avoid the use of HWDs and handheld devices. We  
13 found that the use of an AR approach compared with a  
14 traditional approach based on paper manuals produces a  
15 significant improvement in operators' performance for  
16 maintenance tasks.

17 However, the use of a large screen is not an easily scalable  
18 solution in various industrial scenarios: not everywhere  
19 there is enough space for a large screen. Furthermore, it  
20 suffers from a high angular offset, i.e. the offset between the  
21 real world being observed and the display through which the  
22 user sees it. A high angular offset may lead to alignment  
23 problems: users may not readily understand the relationship  
24 between what is seen directly in the real world and what is  
25 shown on the screen when comparing both, which may  
26 require difficult mental rotation and scaling [9].

27 A display solution that does not suffer from the problems  
28 above (ergonomics, not free hands, angular offset) is  
29 represented by Spatial Augmented Reality (SAR) using  
30 digital projectors. Thus, it could be an optimal solution for  
31 the visualization of both instructions and technical  
32 information directly on the industrial workbench. In a real  
33 working environment, operators stand in front of the  
34 workbench, and currently, instructions on monitors assist  
35 them. Monitors are usually placed on their workbenches or  
36 tool carts. SAR makes use of digital projectors to  
37 superimpose virtual data (such as text, symbols, indicators)  
38 directly on the real environment, as early found by Bimber  
39 and Raskar [10].

40 The main disadvantages of SAR, as pointed out by Kruijff  
41 et al., are: i) surface-based distortions; ii) brightness,  
42 contrast, and visibility of projection; iii) lower color fidelity;  
43 iv) higher latency; v) limited FOV of the projector; vi)  
44 registration [9].

45 Surface-based distortions may cause problems with  
46 legibility of projected text. Thus we already made a study to  
47 evaluate if it was possible to read in an effective way  
48 instructions directly projected on the workbench. It revealed  
49 that projecting text directly on workbench surfaces  
50 guarantees the same legibility performance of a traditional  
51 LCD monitor [11].

We then designed an SAR workbench [12], trying to solve  
all the other potential issues. It consists of an aluminum  
structure that holds a projector and a camera that is intended  
to be mounted on Manual Working Stations (MWS). Common  
operations that are accomplished into an MWS are assembly,  
welding (especially spot welding), packing, testing,  
repairing, inspecting. The camera, using a tracking  
algorithm, computes in real time the position and orientation  
of the object while the projector displays the information  
always in the desired position.

The main contribution of this work is the evaluation of the  
designed SAR workbench, to verify if the proposed  
solutions were effective to aid users in the visualization of  
technical instructions. In fact, it is known for a long time  
that AR can help for the support of technical operators.  
However, this was plenty demonstrated for traditional AR,  
but scarcely for SAR. The distinction is not negligible  
because the visualization capabilities of SAR are poorer  
than those of traditional AR. For example, it is not possible  
to display mid-air virtual objects, but only 2D objects on a  
physical surface. Furthermore, surface-based distortions  
remain an issue, and the user could misunderstand the  
projected instructions.

Therefore, we designed an experiment to evaluate user  
performance, regarding task time and error rate, and user  
acceptance obtainable with the SAR interface, comparing  
them with those obtained with a traditional paper manual.

We organized the paper as follows. In Section 2, we present  
related works on user evaluations of AR and applications of  
SAR in the industry. Then, in Section 3, we describe the  
design of the experiment. In Section 4, we illustrate the  
results achieved in the experiment. Finally, in Section 5, we  
provide a detailed discussion and our conclusions.

## 2 Related Works

In this paper, we organized the related works into two  
sections: in the first section, we present the related works  
regarding user evaluations of AR systems in industrial  
applications; in the second section, we present the related  
works about the use of SAR in the industrial domain.

### 2.1 User evaluation of AR in the industry

The integration of Augmented Reality with assembly and  
maintenance operations is a topic that has been widely  
addressed in the last years. Wang et al. [13] presented an  
extensive review of researches on AR in assembly tasks  
reported between 1990 and 2015. They divided the literature  
related to AR assembly research into three categories: AR  
assembly guidance, AR assembly training, and AR  
assembly simulation, design, and planning. At the end of

1 this review, they remarked the importance of the  
2 familiarization for both users and developers with the new  
3 proposed AR assembly solution.

4 Fiorentino et al. [8] performed a user evaluation test using  
5 video-based AR with a large screen display near the  
6 operator workbench, and a combination of multiple fixed  
7 and mobile cameras. Participants performed similar  
8 operations in two modalities: paper manuals and AR  
9 instructions. In the AR mode, visual labels, 3D virtual  
10 models, and 3D animations supported tool selection, bolts  
11 removal, part (dis)assembly. Statistical analyses showed  
12 that AR instructions displayed on the large screen  
13 significantly reduced participants' overall performance time  
14 and error rate. Furthermore, user acceptance of the AR  
15 system was higher than the paper manual.

16 Tang et al. [14] compared assembling operations of toy  
17 blocks with four different instructional modes: 1) printed  
18 manual, 2) 2D static images on a laptop with 15" display,  
19 3) static images on a see-through HMD and 4) a spatially  
20 aligned 3D models on the see-through stereo HMD using  
21 magnetic tracker (full AR). They measured: time of  
22 completion, the number of errors and mental workload. As  
23 far as regards the time of completion, their test verified a  
24 relevant improvement passing from the paper manuals to the  
25 computer supported ones. However, only with full AR,  
26 there was a significant reduction even of error rates and  
27 mental workload respect to printed manual. On the contrary,  
28 there was not a significant time advantage of full AR  
29 comparing with other computer-assisted approaches.

30 Tegeltija et al. [15] implemented AR in the disassembly of  
31 a heating circulation pump. The experiment was carried out  
32 on three different types of the pump, and with the  
33 disassembly procedures done in four variant modes. These  
34 modes were the combination of using AR and hard copy  
35 documentation and performing the disassembly sequence  
36 with the worker who has and has not previously performed  
37 pump disassembly. Observing the results of the experiment,  
38 the authors concluded that the implementation of AR in the  
39 area of disassembly systems could lead to a series of time  
40 reductions in the disassembly process. They did not make  
41 analyses about the accuracy of the procedures.

42 Elia et al. [16] proposed a multi-criteria model to support  
43 quantitatively production managers and researchers in  
44 evaluating the performance of different AR devices based  
45 on both technological and organizational performance  
46 required by the specific manufacturing process. They  
47 developed an expert based tool to support, in a more  
48 efficient way, the design of AR applications in specific  
49 manufacturing issues. They validated the model with a test  
50 case of a complex maintenance task carried out in a harsh  
51 workplace. Even if their test case aimed only to demonstrate  
52 the actual applicability of the proposed multi-criteria model,

their results are interesting for our work. In fact, they found  
that projectors are the best AR alternative in a set also  
containing HWDs, haptic and handheld devices. Projectors  
were also the most 'agile' devices, whereas their reliability  
was lower respect to handheld and haptic devices.

## 2.2 Applications of SAR in the industry

In the recent years, we are assisting to an increase in the  
number of works where SAR is used to perform assembly  
and maintenance tasks.

The traditional use of SAR in the industry is for the spot  
localization in spot-welding operations. Doshi et al. [17]  
improved the precision and accuracy of manual spot-weld  
placements with the aid of projected visual cues. The  
prototype system was deployed at a General Motors (GM)  
plant. They observed a reduction of 52 % of the standard  
deviation of manual spot-weld placement when using  
augmented reality visual cues. This reduction demonstrates  
the benefit of having an AR projection system on the  
production line as opposed to not having one. The visual  
cues helped to identify spot-weld locations quicker and has  
the potential to be used as a training tool for new operators  
or new vehicle types. The SAR projection system can be  
positioned at any manual production station for spot  
welding, welding, adhesive application, and inspection.

Schwerdtfeger et al. [18] explored the use of laser projectors  
as an alternative to Head-Worn Displays for Industrial  
Augmented Reality applications. They used two scenarios  
to gather practical experiences with AR laser projectors:  
quality assurance and maintenance. They concluded that  
laser-based augmentations have much potential and they  
said to be in the process of installing, evaluating and further  
developing the system in the context of real industrial  
applications.

Otto et al. [19] presented a scalable, interactive augmented  
floor surface in combination with a tangible tabletop  
hardware and a material zone planning software. The floor  
projection hardware was used for true to scale assembly  
station layout visualizations. The system was installed,  
introduced and piloted during on-site production planning  
workshops for a mid-size premium car. A preliminary  
evaluation found that by tendency, true to scale visualization  
using the interactive augmented floor surface supports the  
workshop participants to better estimate sizes, speeds and  
spatial relationships than on traditional desktop displays.

Sand et al. [20] presented a prototype that has many  
similarities with our concept, such as the frame holding the  
projector and the camera. "smARt.assembly" is a  
projection-based augmented reality (AR) assembly  
assistance system for industrial applications. This system  
projects digital guidance information such as picking

1 information and assembly data into the physical workspace  
2 of a user. Compared to their previous prototype with smart  
3 glasses, the projection-based system seemed to be much  
4 more robust on changing light conditions. Furthermore,  
5 users working with the projection-based instructions were  
6 able to assemble products faster and with a lower error rate,  
7 compared to the system based on smart glasses.

8 In summary, the use cases of SAR found in the literature are  
9 the following:

- 10 • Spot-welding
- 11 • Quality assurance
- 12 • Maintenance
- 13 • Designing
- 14 • Assembly

15 Our prototype is intended to be installed on Manual  
16 Working Stations, where all these kinds of operations can  
17 be accomplished. Our work integrates the literature with a  
18 user study on the effectiveness of SAR in support of the  
19 operators while projecting technical instructions.

## 20 2.3 Research questions

21 The goal of our research is to create a technical  
22 documentation based on SAR. It should contain the same  
23 information contained in a paper manual, for example, text  
24 instructions and pictures, directly projected on the  
25 workbench. The added value of SAR is the possibility to  
26 locate with graphic signs on the real product, the parts  
27 involved in the task. Then, it is important to evaluate if this  
28 added value produces improvements in operator  
29 performance and if operators well accept this visualization  
30 modality.

31 From the presented works, we can say that the point of user  
32 evaluation of AR in the industrial domain is well addressed  
33 in the literature. Most of the works show that with AR it is  
34 possible to reduce times and error rates in task execution.  
35 The second section of the related works shows that the use  
36 of SAR in industrial scenarios is continuously growing,  
37 mainly due to brighter, lighter, and cheaper projectors.  
38 However, there are no works about user evaluation of an  
39 SAR system for technical instructions, versus a traditional  
40 mode of presenting instructions, based on printed manuals.  
41 It is not possible to transfer the results of user evaluations  
42 on traditional AR to SAR since most of the works in section  
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2.1 make use of 3D CAD models that are not displayable in  
an SAR interface.

Then, also considering the increasing relevance of SAR  
technology in the industrial contest, we felt crucial to make  
such evaluation. Therefore, in this work, we formulated  
these research questions:

- 1) Are SAR conveyed technical instructions more  
effective than paper ones?
- 2) Is SAR well accepted by users as technical  
guidance compared with a paper manual?

## 3 Material and methods

To compare the two instruction modes (hereafter, we call  
them Paper and SAR), we conducted a mixed design  
experiment evaluating user completion time and error rate,  
and their ratings. In both the approaches, a within-subjects  
experiment was carried out to test our hypotheses.

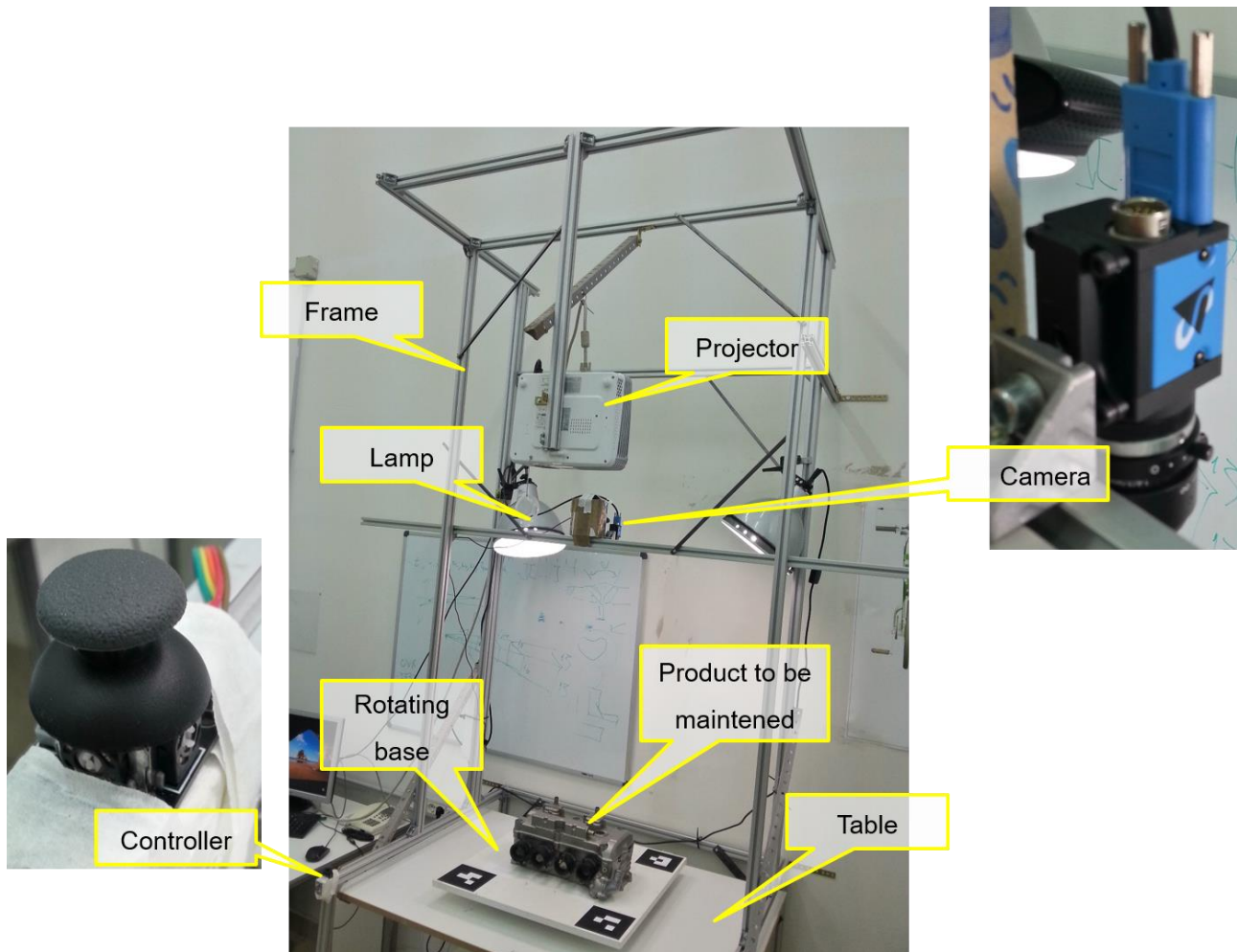
As regards the first research question, we formulated the  
hypotheses *(H1) SAR system will significantly reduce the  
amount of time to complete a set of maintenance tasks,  
compared to paper instructions*, and *(H2) SAR projection  
system will significantly reduce errors of a set of  
maintenance tasks, compared to paper instructions*. As  
regards the second research question we formulated the  
hypothesis *(H3) SAR projection system will significantly  
improve user acceptance*.

### 3.1 The system

We used the SAR workbench (Fig. 1) presented in [12] with  
the following technical specifications:

- A light frame to be clasped on a normal workbench of  
a Manual Working Station: working volume 1200  
mm (L) x 1000 mm (D) x 600 mm (H).
- A DLP projector Benq W1080ST+ mounted on the  
frame.
- An industrial camera Imaging Source DFK 23U445.
- A turntable where the product to be  
assembled/maintained is fixed.
- The optical tracking is based on fiducial markers that  
are glued on the turntable.
- An additional lighting system is provided, to have a  
uniform lighting on the markers.
- A joystick accomplishes the content navigation.

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**Fig. 1** The prototype of the SAR workbench used in the experiment

Further details of the SAR workbench, as well as the software architecture, can be found in [12].

In a previous study, we successfully reorganized, according to a tree-like structure, the instructions for a maintenance procedure in a digital manual [18]. In this tree, each level gives a complete description of the procedure, but as the user moves from the root node towards the leaves, the description of each step is decomposed in more sub-steps with a growing level of detail.

This structure allows technicians a fast and effective browsing of instructions — by skipping well-known details and by accessing specific information only if necessary.

The Graphical User Interface of the SAR system projects the tree structure on the left side of the workbench surface, as the bullets of a multilevel bulleted list. The bullet corresponding to the visualized step has a different color (acting as a bookmark); meanwhile, the graphic signs (such as arrows and circles) and a textbox with instructions are projected on the object and the workbench surface respectively.

### 3.2 Participants

A total of 16 voluntary participants (all males) were recruited among engineering students at Politecnico di Bari, using convenience sampling. The average age was 24.6 (min 22, max 32, SD = 2.17). We interviewed the subjects about their personal experience in maintenance operations: 14 participants had previous experience; 2 had no experience, half of the participants had previous experience with maintenance manual instructions, 14 participants were novices to AR and computer based maintenance guidance systems.

The participants in this study were all engineering students and therefore, highly interested and favorable to modern technologies. Furthermore, only half of them had previous experience with maintenance instructions. Considering this background of our participants, we designed an experiment with very basic tasks so that the experience and the motivation of the participants would not affect the results.

### 3.3 Procedure

Participants were assigned to both treatments, paper and SAR one, using a Latin square design. Then, we had eight participants performing first the paper mode and then the SAR mode and the other eight vice versa. They were told to complete each task as quickly and as accurately as possible. Each participant was allowed to familiarize with the system for 10 minutes before the test. This training phase helped the participants to get accustomed with the user interface — the controls to navigate the tree of instructions and the visual and textual information given by the system. At the end of the training phase, an experimenter checked that the participant was able to use the system easily.

We video recorded each user test. Completion time was measured by carrying out an offline analysis on these videos. We measured both the completion time of each task and the overall procedure. A human assistant supervised each test and checked for errors in real-time, using a notepad to register types and causes of mistakes. The assistant observed the user from a distance, without hindering her/his movements. After completing the test, users were asked to respond to a questionnaire to get subjective evaluations about the treatments.

We chose as a case study, part of the maintenance procedure of a Honda CBR 600 motorbike engine. We arranged a task sequence based on the maintenance procedure for the camshafts inspection. The operations used in the test include common and crucial maintenance tasks: part localization, components identification, sequences identification.

The sequence of the tasks is the following:

Task 1. Cylinder head cover removal: pull out six bolts in no particular order and remove the cover;

Task 2. Cam chain guide removal: pull out two bolts in no particular order and remove the guide;

Task 3. Removal of the exhaust and intake camshafts and their holders: pull out eighteen bolts in a specific order and remove the camshafts in a given order;

Task 4. Assembly of the exhaust and intake camshafts in a specific order and a proper position;

Task 5. Assembly of the exhaust and intake camshafts holders: assemble the camshafts and insert eighteen bolts in a specific order;

Task 6. Cam chain guide assembly: insert the guide and two bolts in no particular order;

Task 7. Cylinder head cover assembly: insert the cover and first two bolts, then the other four.

We designed an experiment that could be the least affected by users' skills and dexterity in workshop operations. For this reason, we simplified the un/screw operations by

replacing the original bolts with plain unthreaded ones that only needed to be pulled out/inserted from/into their slots. We added an instruction about the correct position of the lobes of two cams for the proper installation of the camshafts (Task 4). For this reason, we separated this task from that of the assembly of the holders. We prepared two similar sequential procedures for paper and SAR instructions, available in Appendix. The instructions about the identification of a component (e.g. a bolt), in the SAR mode, are given red "coloring" the interested area, as can be seen in Fig. 2.

We considered tasks with different levels of difficulty. We used the definition of task difficulty made by Kantowitz

[19]: "task difficulty increases with the capacity investment needed to obtain a specified level of performance." In our test, the level of performance desired is that of a skilled operator doing the task. Task difficulty is an intrinsic property of a task, and it must not be confused with task complexity, which is related to instruction mode. The complexity, according to Kantowitz [19], refers to "the (hypothetical) mental system architecture used to perform a task." As additional internal stages or processes are required, task complexity increases.

In our experiment, we evaluated, in a range from 1 to 3, difficulty and complexity indices associated with our seven tasks with a think-aloud procedure in a team of maintenance experts.

For example, we can observe difficulty and complexity for Task 1 and 3:

	Difficulty	Complexity	
		Paper	SAR
<b>Task 1</b>	*	*	*
<b>Task 3</b>	***	***	*

Task 3 requires the removal of eighteen bolts in a given order. It is more difficult than Task 1, which requires the removal of six bolts in no particular order. As regards complexity, Task 3 is more complex to accomplish with the paper manual than with the SAR because the number of mental processes required to execute the task increases. In the paper, the user has to read the text instruction, to make a mental match of the camshaft holder and its printed image, and to remember the progressive number. With SAR, the user has only to read the instruction (less text) and to localize the red circle projected on the engine. On the contrary, Task 1, presents the same low complexity in paper and SAR instruction mode.

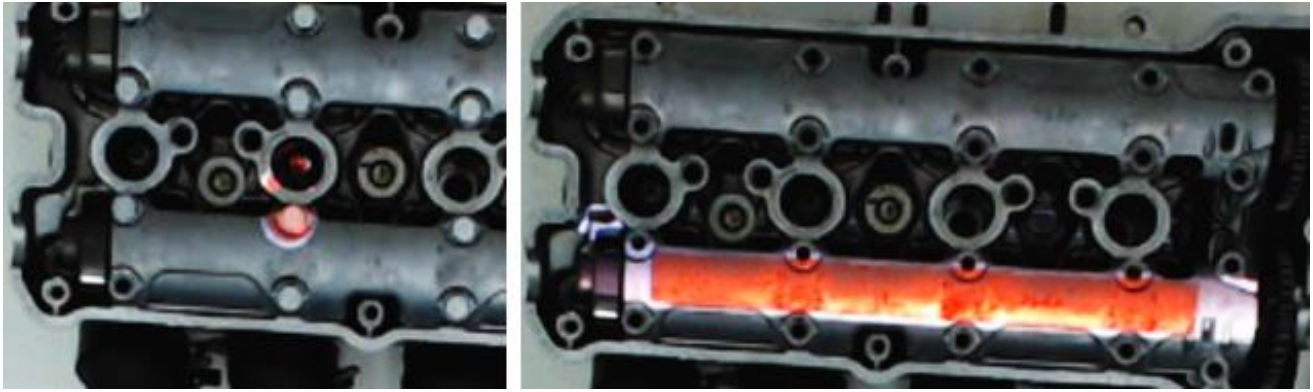


Fig. 2 Colored graphic signs used in the SAR mode to indicate a bolt (left) and a camshaft holder (right) to be removed

Table 1 Independent and dependent variables of the experiment

INDEPENDENT VARIABLES		
Participant users	16	16 males, mean age 24.6
Instruction Modes	2	Paper, SAR
Tasks	7	Dis/assembly tasks, as described in the previous section
Total trials	224	16x2x7
DEPENDENT VARIABLES		
Completion time	time (in seconds) spent for the execution of each task and the overall procedure	
Error	wrong task completion	
Users rating	votes assigned by users in a 5 points Likert scale, for each instruction mode as regards ease of use, intuitiveness and global satisfaction	

### 3.4 Measures

The experiment's independent and dependent variables, collected for the subsequent statistical analysis, are shown in Table 1. We used the following error rate definition:

$$ER\% = \frac{n.errors}{n.targets} \cdot 100$$

The  $n.errors$  is the sum of all the participants' errors observed for each task. The  $n.targets$  is the maximum number of errors that a user could make for each task, multiplied by the number of the participants that performed the experiment. For example, for Task 5, the possible errors are:

- Wrong assembly of the exhaust camshaft;
- Wrong assembly of the intake camshaft;
- Wrong assembly of a screw (for all the eighteen screws).

Then, the maximum number of errors that each user could make for Task 5 is 20 (1+1+18); multiplying this number by the number of participants (16), we have that  $n.targets=320$  for Task 5.

## 4 Analyses and results

We used two separate statistical models to analyze the effects of the instruction mode and the task type on time and error rate.

### 4.1 Completion time

Completion time was analyzed using the ANOVA. Instruction mode and task-type were modeled as fixed effects. Participant ID was modeled as a random effect. In Task 6 one user had a very bad performance due to an error in the accomplishment of the previous task. This bad performance resulted in a strong outlier (i.e. distance from the third interquartile greater than three times the interquartile distance). Thus we decided to neglect the completion times of this user for the statistical comparison of this task and the overall procedure.

To compute the ANOVA, we initially had to verify normality and homoscedasticity. If both were verified, we could proceed with a classic homoscedastic parametric ANOVA. Otherwise, we had to perform other tests.

For the normality test, since the size of the group we wanted to analyze was limited (N=16), we chose to use the Shapiro-

Wilk test. All samples positively passed normality and homoscedasticity tests.

We conducted a planned pair-wise comparison of completion time between instruction modes for each task and the overall procedure (Table 2). The results allow us to confirm the null hypothesis H1. Comparing the means, for these operations, we found a completion time improvement

with the SAR mode over the Paper mode. For the overall procedure, we found a significant [F(1,30)=22.973, p<0.001] reduction of 20.3% of completion time.

As to the substeps, we found a significant [F(1,30)=51.247, p<0.001] reduction of 32.5% of time completion for the Task 3, and a significant [F(1,30)=14.207, p=0.001] reduction of 21.6% for the Task 5.

**Table 2** Statistical analysis for the completion time

Task	One-way ANOVA		Mean completion time	
	F	p	Paper Mode	SAR Mode
Task 1	0.024	0.879	36.9 s	37.4 s
Task 2	1.723	0.199	23.3 s	20.0 s
Task 3	51.247	<0.001	<b>190.4 s</b>	<b>128.6 s</b>
Task 4	1.987	0.169	95.1 s	82.4 s
Task 5	14.207	0.001	<b>201.2 s</b>	<b>157.7 s</b>
Task 6	4.179	0.050	24.3 s	19.3 s
Task 7	3.662	0.065	48.4 s	41.3 s
Overall	22.973	<0.001	<b>610.9 s</b>	<b>486.7 s</b>

## 4.2 Error rate

To make statistical analyses about the influence of instruction mode on the accuracy of the operations, we grouped the error data of all the users involved, for each task type. Then, for each task, we computed the error rate as defined in Section 3.4. We used the method of “nx2 contingency tables” to make statistical inference.

Comparing the error rates of the experiment tasks (Table 3), we observed an error rate reduction with the SAR mode over the Paper one.

**Table 3** Statistical analysis of error rates

Task	Chi-squared test		Error rate	
	$\chi^2$	p	Paper Mode	SAR Mode
Task 1	0.000	1.000	0%	0%
Task 2	0.000	1.000	6.25%	6.25%
Task 3	21.646	<0.001	<b>5.97%</b>	<b>0%</b>
Task 4	8.085	0.004	<b>20.00%</b>	<b>2.08%</b>
Task 5	5.530	0.019	<b>3.75%</b>	<b>0.94%</b>
Task 6	0.368	0.544	6.25%	12.50%
Task 7	3.865	0.049	<b>43.75%</b>	<b>12.50%</b>
Overall	33.518	<0.001	<b>7.03%</b>	<b>1.17%</b>

This result allows us to confirm the null hypothesis H2. Instruction mode has a significant effect on the overall procedure [ $\chi^2(1)=33.518$ , p<0.001]. As to the specific tasks, we found a significant difference for Task 3 [ $\chi^2(1)=21.646$ , p<0.001], for Task 4 [ $\chi^2(1)=8.085$ , p=0.004], for Task 5 [ $\chi^2(1)=5.530$ , p=0.019], and for Task 7 [ $\chi^2(1)=3.865$ , p=0.049]. For all the other tasks, we did not find a significant difference between error rates for the two instruction modes.

**Error! Reference source not found.** reports a comparison of the results for the single tasks with their difficulty index and their complexity, as defined in Section 3.3.

## 4.3 Subjective evaluation

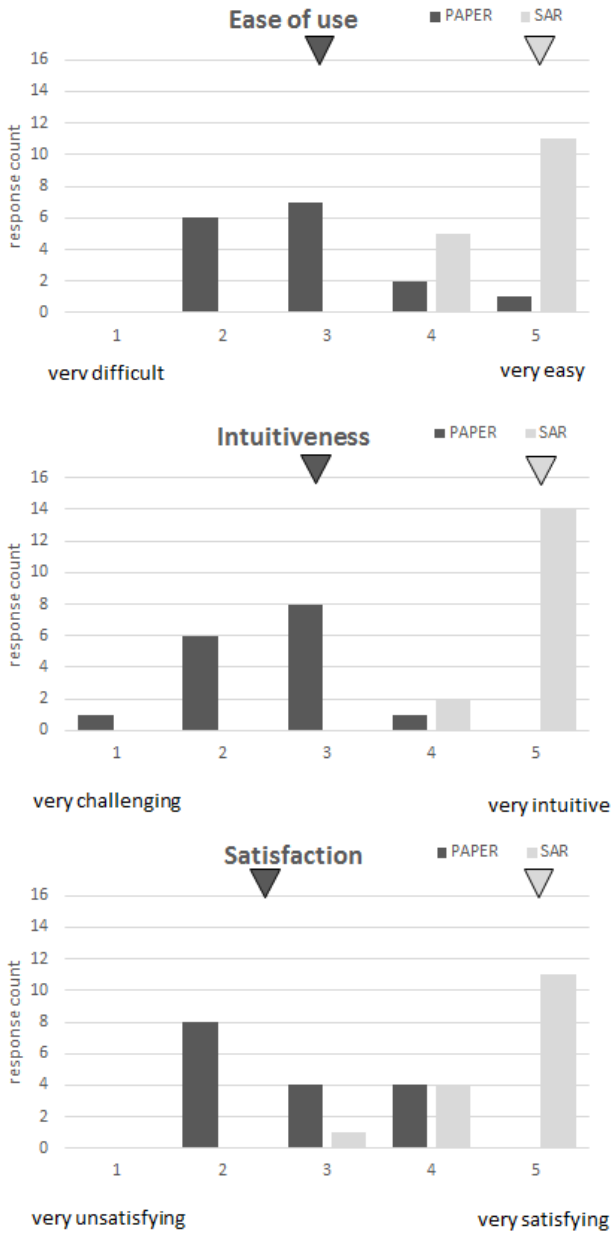
The post-experiment questionnaire featured five-point Likert scale questions (1 = most negative; 5 = most positive) to evaluate ease of use, satisfaction level, and intuitiveness for each Instruction Mode. The summary results from these ratings are reported in Fig. 3.

Medians of the ratings for SAR mode were always higher (5) than Paper mode (3 for ease of use and intuitiveness, 2.5 for satisfaction) for any of the three characteristics.

**Table 4** Comparison of task difficulty, complexity and performance improvement

Task	Difficulty	Complexity		Significantly different?	
		Paper	SAR	Completion time	Error rates
Task 1	*	*	*	NO	NO
Task 2	*	**	*	NO	NO
Task 3	***	***	*	YES	YES
Task 4	***	***	**	NO	YES
Task 5	***	***	*	YES	YES
Task 6	*	**	*	NO	NO
Task 7	**	***	*	NO <sup>1</sup>	YES

<sup>1</sup> towards significance (p=0.065)



**Fig. 3** User ratings about ease of use (top), intuitiveness (middle), satisfaction (bottom). Median values for each condition are shown as triangles

## 5 Discussion and conclusions

The results showed that SAR presentation mode is significantly better than paper one in completion times (reduction of 20.3% in overall completion time) and error rates (83.3% fewer errors with the SAR mode) confirming H1 and H2. Subjective evaluation supported H3 (at least 2 points higher for SAR mode), confirming good user acceptance of SAR technology for conveying technical instructions.

Tasks with low difficulty (tasks 1, 2 and 6) show no significant difference — both for completion times and for error rates.

Tasks with high difficulty (tasks 3, 4, 5 and 7) show a significant difference in error rates. Tasks with high difficulty show a significant difference for completion times only if there is a substantial reduction in complexity due to SAR.

Tasks 3, 5 and 7 require the understanding of a correct sequence of the bolts. Indeed, using the paper manual, either the mental workload associated with these instructions is high if users tried to memorize the sequence of the bolts, or the cognitive distance is high if users switched from information space (the manual) to physical space (the engine) for every bolt or both. The SAR highly reduces the complexity of these tasks because the technical information is conveyed illuminating the bolt to be pulled out/inserted. With the SAR, we have then two great benefits: 1) the reduction of the mental workload associated with a task because only the task-relevant information is displayed; 2) the reduction of the cognitive distance because the information space and the physical space coincide. This result is consistent with what suggested and proved by Kim and Dey [20].

In task 4 the reduction in complexity is lower than in the other tasks. Task 4 shows contrasting results: there is a significant and relevant decrease of the error rate but the difference in the completion times is not significant. Task 4

1 is also a difficult task, but the textual information is the same  
2 for paper and SAR, and therefore the time needed to read  
3 and understand the instruction is similar. However, SAR  
4 provides explicit component identification (green  
5 illumination of the portion of the engine to control), thus  
6 reducing error rates.

7 From these results, we can conclude that the use of SAR  
8 brings more advantages for difficult tasks than for simple  
9 ones. The main advantage of SAR is related more to the  
10 reduction of error rates than to completion times. These  
11 results were never found before in the literature for SAR,  
12 thus supporting the motivation for our research.

13 For traditional AR, in which 3D CAD models are used for  
14 displaying information, we found works where AR reduces  
15 both times and error rates and works showing only error rate  
16 reduction. Our result agrees with what found by Tang et al.  
17 [14]: in their experiments, AR does not appear to have an  
18 advantage in time of completion comparing with other  
19 traditional media; nevertheless, they observed a strong  
20 reduction of error rates. The tasks in our and their  
21 experiment are very similar, based on the identification of a  
22 specific part and its positioning in a specific position.  
23 However, we achieved this result without using the CAD  
24 model of the assembled parts (screws), but just that of the  
25 engine used as occlusion model and as a projection mapping  
26 reference geometry, with a strong effort reduction in the  
27 authoring phase. Indeed, we experienced authoring times  
28 much shorter in modeling and positioning of the colored  
29 graphic signs than in modeling and animating virtual  
30 screws.

31 Thus, we can conclude that SAR, similarly to traditional  
32 AR, always ensures low error rates and consequently  
33 guarantees operator accuracy. This result is important  
34 because it is in line with the objectives of Industry 4.0 and  
35 supports the role of AR as a key technology for a smart  
36 factory. Our industrial partners always considered  
37 overriding the reduction of the errors made by the operators  
38 and optional the reduction of times.

39 The result of this work for maintenance dis/assembly  
40 operations should be read together with what found in the  
41 literature for other manufacturing processes, such as data  
42 visualization of CNC machines [21], spot-welding  
43 operations [17], human-robot collaboration [22], and other  
44 manufacturing processes. Therefore, we can feel that SAR

technology can be integrated shortly into industrial  
processes and product lifecycle. In particular, the SAR  
prototype presented in [12] could be, with further  
improvements, a good candidate for a future introduction of  
SAR in a smart factory. However, the advantages of SAR  
found with our validation are just the starting point to be sure  
of the path taken. Other problems remain open such as the  
authoring of contents, the tracking, the usability, the  
interface design. In the authors' view, when all these issues  
will be addressed, industries will accept the introduction of  
SAR in their practices.

The SAR solution proposed and tested can be used for both  
training new maintenance operators and assisting operators  
in ordinary maintenance. In fact, we designed a multilevel  
tree-like structure of the procedure-instructions. It allows  
regular technicians a fast and effective browsing of  
instructions, by skipping well-known details and by  
accessing specific information only if necessary. While for  
new operators, there is the possibility to provide further  
detailed information to learn new procedures. In our work,  
the information detail is high because both text, images and  
graphic signs were used and users were asked to browse all  
the procedure steps.

Even if the case study used here is very basic, there are some  
tasks, as Task 3 and Task 5, where the mental workload is  
high because a dis/assembly order should be memorized. In  
these cases, SAR is helpful also for experienced  
maintenance operators, who usually can perform the  
procedures even without the support of instructions because  
they learned them over time. Furthermore, in the age of  
Industry 4.0 manufacturing is mainly based on mass  
customization. Thus, even experienced operators could  
work on many various products or versions of the same  
product, and they could not memorize all the relative  
procedures.

However, in this study, we did not consider as a variable the  
experience of operators, as well as the learning effect due to  
the repetition of a procedure at different times, or the  
possible fatigue of operators using SAR. In a follow-up  
study, it would be interesting, to evaluate the effect of these  
variables on user performance with SAR. We aim to test our  
SAR system in our industrial partners' facilities and carry  
out some pilot studies in a real scenario with actual workers.

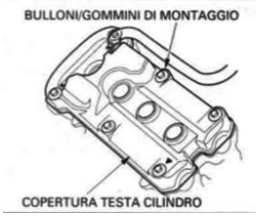
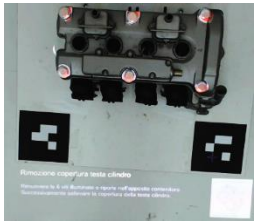

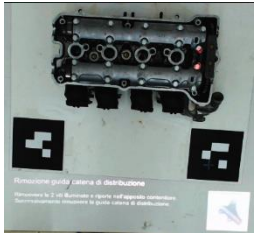
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## 6 Appendix

	Paper mode		SAR mode	
	Textual content	Visual cues	Textual content	Visual cues
Task 1	<ul style="list-style-type: none"> <li>Remove the 6 screws of the cylinder head cover and place them in the container;</li> <li>Lift the cylinder head cover.</li> </ul>		<ul style="list-style-type: none"> <li>Remove the 6 illuminated screws and place them in the container;</li> <li>Lift the cylinder head cover.</li> </ul>	
Task 2	<ul style="list-style-type: none"> <li>Remove the 2 screws of the distribution chain guide, and store them in the container;</li> <li>Remove the distribution chain guide.</li> </ul>		<ul style="list-style-type: none"> <li>Remove the 2 illuminated screws and place them in the container;</li> <li>Lift the cylinder head cover.</li> </ul>	

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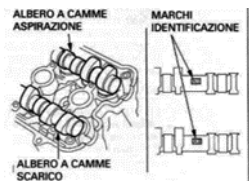
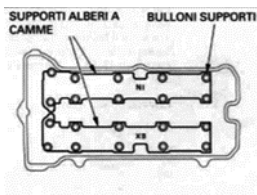
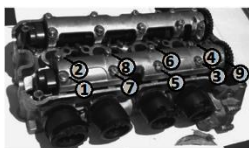
Task 3

Paper mode

Textual content

Visual cues

- Remove the screws of the intake camshaft holder, identified by the mark IN, in the following order and store them in the container:  
1-8-3-9-2-4-7-5-6;
- Remove the screws of the exhaust camshaft holder, identified by the mark EX, in the following order and store them in the container:  
8-9-3-2-1-7-5-4-6;
- Remove the intake camshaft holder, identified by the mark IN.
- Remove the exhaust camshaft holder, identified by the mark EX.
  
- Remove the intake camshaft, identified by the mark IN.
  
- Remove the exhaust camshaft, identified by the mark EX.

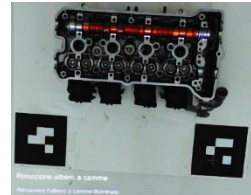
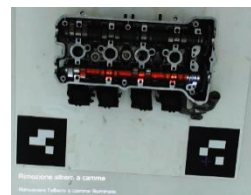
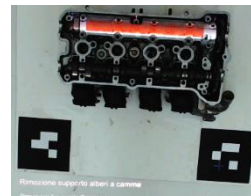
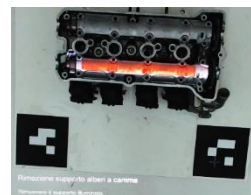
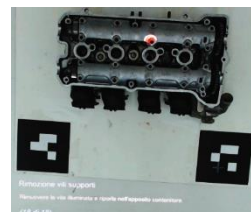
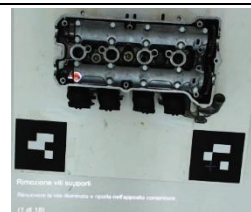


SAR mode

Textual content

Visual cues

- Remove the illuminated screw and place it in the container. (1 of 18);
- Remove the illuminated screw and place it in the container. (18 of 18);
- Remove the illuminated camshaft holder;
- Remove the illuminated camshaft holder;
- Remove the illuminated camshaft;
- Remove the illuminated camshaft.



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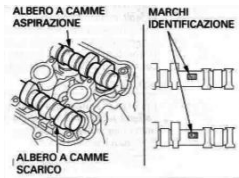
Task 4

Paper mode

Textual content

Visual cues

- Install the camshafts on the cylinder head with the cam lobes # 1 facing upwards as shown in the figure.
- NOTE: Install the camshafts in the correct position using the identification marks:
- “IN” – intake camshaft
- “EX” – exhaust camshaft
- Install the intake camshaft.
- Install the exhaust camshaft.
- Check that the bearings are aligned with their seats.



SAR mode

Textual content

Visual cues

- Install the intake camshaft in the illuminated seat. The intake camshaft is identified by the mark “IN”;
- Install the exhaust camshaft in the illuminated seat.
- The exhaust camshaft is identified by the mark “EX”;
- Check that illuminated cam lobes face upwards and outwards;
- Check that illuminated cam lobes face upwards and outwards;



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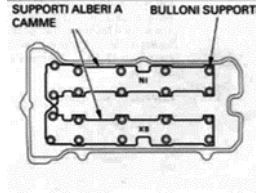
**Paper mode**

**SAR mode**

**Textual content**

**Visual cues**

- Install the camshaft holders in the correct position using the identification marks:
- “IN” – intake camshaft holder
- “EX” – exhaust camshaft holder
- Install the intake camshaft holder.
- Install the exhaust camshaft holder.
- Install the screws of the intake camshaft holder, in the following order: 1-8-3-9-2-4-7-5-6;
- Install the screws of the exhaust camshaft holder, in the following order: 8-9-3-2-1-7-5-4-6.



Task 5

- Install the distribution chain guide;
- install the two screws of the distribution chain guide.

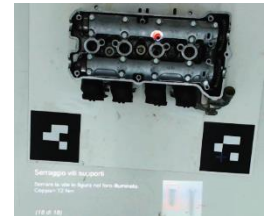
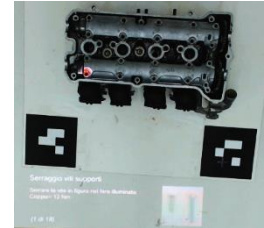
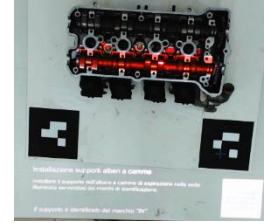


Task 6

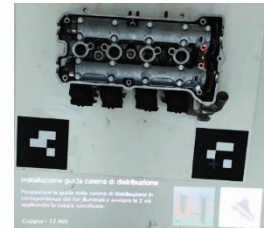
**Textual content**

**Visual cues**

- Install the intake camshaft holder in the illuminated position using the identification mark:
- “IN” – intake camshaft holder
- Install the exhaust camshaft holder in the illuminated position using the identification mark;
- “EX” – exhaust camshaft holder
- Insert the screw in the illuminated hole (1 of 18);
- Insert the screw in the illuminated hole (18 of 18).



- Place the distribution chain guide in correspondence with the illuminated holes and install the two screws.



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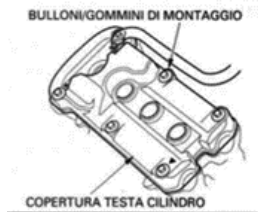
Task 7

Paper mode

Textual content

- Install the cylinder head cover.
- Install the special screws of the cylinder head cover
- Caution: Install first the screws in the holes marked by “Δ.”

Visual cues



SAR mode

Textual content

- Install the cylinder head cover as in figure;
- Insert the screw in the two illuminated holes. (2 of 6);
- Insert the screw in the four illuminated holes. (6 of 6);

Visual cues

