2015 IEEE International Symposium on Mixed and Augmented Reality Workshops

Visual Subliminal Cues for Spatial Augmented Reality

James Baumeister[1*] Michael R. Marner[1†] Ross T. Smith[1‡] Mark Kohler[2§] Bruce H. Thomas[1¶]

Wearable Computer Lab, University of South Australia[1]
Cognitive Neuroscience Laboratory, University of South Australia[2]

Abstract

Augmented reality systems commonly employ overt cueing to direct a user's attention and guide their actions. Spatial augmented reality based supraliminal annotations have been shown to improve user performance compared to LCD screens. This paper explores subliminal cues: annotations that exist below the threshold of consciousness. We investigate whether subliminal cueing is technically possible with standard data projectors, and if subliminal cues can further improve users' reaction time in procedural tasks. This paper describes a new technique for temporal subliminal cues in spatial augmented reality, and presents the results of three user studies evaluating the effectiveness of this technique in a button-pressing task. The results show that the presentation of annotations is indeed subliminal, in that the visual stimulus was not perceivable to users. We found a statistically significant improvement in task performance when using subliminal cues and supraliminal annotations, compared to supraliminal annotations alone, with mean trial times improving from 633.49ms to 604.64ms.

Keywords: Spatial Augmented Reality, Subliminal Cueing, User Interfaces, User Study.

Index Terms: H.5.2 [Information interfaces and Presentation]: Graphical User interfaces—Evaluation/methodology; I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction Techniques

1 Introduction

This paper presents a new subliminal cueing [36] mechanism to enhance Spatial Augmented Reality [25] (SAR) annotations. Subliminal cueing refers to the presentation of a stimulus below the threshold of awareness, for the purpose of priming or directing a behavior. This work extends investigations into the effectiveness of SAR in providing guidance for procedural tasks [18, 1]. This investigation was additionally motivated by work in providing SAR cues to automotive spot welders [37]. To our knowledge, we are the first to apply spatial subliminal cueing to spatial augmented reality.

There have been a number of investigations into how to present SAR-based information to users in domains such as automotive manufacturing [37]. There are some issues regarding the proper presentation of this information, and we have been interested in improving legibility, comprehension, attention, and reducing cognitive load [1]. To date supraliminal, consciously perceived, augmented reality cueing techniques are employed with a prominent cue to highlight the point or region of interest with projected light [24].

*e-mail: james.baumeister@unisa.edu.au
†e-mail: michael.marner@unisa.edu.au
‡e-mail: ross.smith@unisa.edu.au
§e-mail: mark.kohler@unisa.edu.au
¶e-mail: bruce.thomas@unisa.edu.au

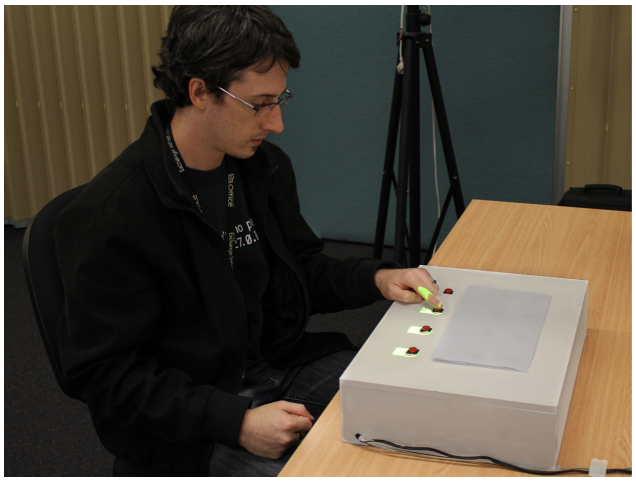


Figure 1: A participant takes part in our subliminal cueing experiment.

Subliminal cueing has a number of potential advantages over supraliminal cueing alone. Principally, subliminal cues have been shown to capture and direct attention, as well as support the semantic link between objects that results from the cued redirection of attention [6]. Subliminal processing is thought to rely on distinct, reduced neural processes compared to conscious or preconscious (carries sufficient activation for conscious awareness, but is temporarily buffered by lack of attention) processing [7]. This potentially provides a means to facilitate attention and subsequent action in a real-world scenario without compromising or diverting attention from other important functions.

There are at least three particular means of presenting visual subliminal information for which robust behavioral effects have been reported. One method involves very momentarily presented visual stimuli. Presentation was traditionally made by a tachistoscope [20], a device for carefully controlling the exposure duration of a visual stimulus. Modern display technology performs the same function. Movie advertising was made famous with this method by inserting single frames containing advertising images in the film stock. A second method is to adjust the colorimetric values of an embedded image to place the image below a user's threshold of consciousness [36]. A third method consists of embedding, hiding or masking imagery or text in a pictorial image [21].

This paper explores utilizing these psychological concepts to support application areas such as automotive assembly support and product design techniques that employ SAR-based supraliminal cues [34]. Throughout this paper, an upper limit of 50% will be applied to the detection of subliminal cues. If participant detection rates are lower than this limit,

978-1-4673-8471-1/15 $31.00 © 2015 IEEE
DOI 10.1109/ISMARW.2015.11

the cue will be deemed subliminal. This definition of subliminal cues is often used throughout the literature [35, 21, 10]. The paper investigates the two research questions:

1. How do you design and display a subliminal cue in a SAR environment?

2. Does this new SAR subliminal cue reduce the time taken for a user to complete a procedural task?

The paper presents a new spatial augmented reality subliminal cue to reduce user reaction time and direct them to press a particular button. This new cue extends the work of Marner et al. [18] by employing the same SAR cue (Figure 2) that demonstrated improved user performance with SAR over a traditional monitor presentation. Our new subliminal cue extends this with the addition of a masked subliminal cue design from psychology, as presented by Mulckhuyse et al. [23], displayed with standard projection technology.

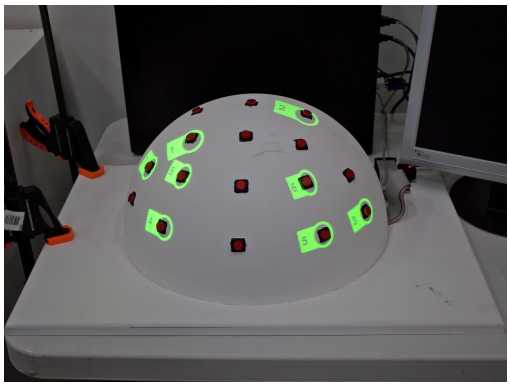


Figure 2: SAR annotations as used in a previous user study.

2 Background

This section provides an overview of subliminal cueing research as it applies to this investigation. We also give an overview of AR and SAR research that has investigated augmented annotations and user performance.

2.1 Applications of Subliminal Cueing

Subliminal cueing has been applied to a wide range of human-computer interaction domains [29], such as ubiquitous computing [28], automotive driving [27], and computer supported learning [4].

Chalfoun and Frasson [3] improved learning by employing cognitive priming, a special case of subliminal perception where the stimulus used is aimed to improve cognitive processes such as reasoning or decision making with the aim of better knowledge acquisition. They performed experiments on a traditional workstation and monitor. They found that the reasoning ability of learners is strengthened by the addition of information outside of conscious awareness, and the supplementary cognitive data does not impede or disturb current cognitive processes.

Chang and Ungar [5] employed subliminal cues for the smoothing of animation effects in graphical user interface tasks. They leveraged animator techniques of including both leading and trailing blurs to provide the user's visual system with the essential subliminal cues that are critical in maintaining the illusion of fast motion. A second effect of arcs provides a subliminal cue of organic movement.

Larsen [16] investigated the use of subliminal perception to provide help utilizing the semantic priming effect and presenting symbolic information. The author was investigating how to incorporate subliminal cues into 3D computer games as a form of continuous help. They did not find a general statistical effect, but the results indicated the effect was more prominent in particular participants.

Luboschik and Schumann [17] investigated illustrative halos in information visualization. Graphical halos improved the visual partition of objects from the background. The authors employed semitransparent, monochrome halos to investigate the use of subliminal images and suggestions that are frequently realized in artistic drawings.

Hilsenrat and Reiner investigated haptic subliminal perception in virtual reality environments [14]. They found participants modified their manual behavior in the presence of haptic subliminal cues that were presented with a PHANToM haptic device. Duval et al. [8] performed a set of visual cueing experiments using a monocular non-see-through MicroOptical QVGA clip-on HMD. The authors developed a just-in-time memory support application to improve the user's memory of face-to-name associations. There were three experimental conditions: Correct cues, misleading cues, and absent cues. They found that correct cues significantly improved performance, but that misleading cues did not significantly decrease performance.

Mulckhuyse et al. [22] developed a method for measuring participant reaction to subliminal cues. Their main experimental task had two conditions: Short stimulus-onset-asynchrony (SOA), and long SOA, which dictated the use of a delay period before displaying the target stimulus. Their procedure had participants seated in front of a computer monitor, with their head position controlled by a chin rest. Their vision was fixated upon a cross in the center of the screen. This fixation cross was removed and replaced, after a delay of 200ms, with a gray disc either to the left or right of center. This disc served as the subliminal cue and was displayed for 16ms. If the long SOA condition was being tested, all three discs were displayed for 1000ms, then a dot appeared for 80ms inside one of the discs, indicating the target. In the short SOA condition, the 1000ms delay was removed and instead, the target would appear simultaneously with the other two discs. Participants were required to press the 'space bar' as soon as the target was detected. A secondary task was also performed to detect participant cue perception ability. In this task, the participant was required to press either the 'z' or 'm' key if they detected an earlier onset of the left or right disc, respectively. Mean detection performance for the cue report task was 50%. In the short SOA condition of the main task, detection times at a cued location were significantly faster than at an uncued location; 402ms versus 413ms. Conversely, this effect was reversed in the long SOA condition.

2.2 Augmented Reality Annotation

Augmented reality annotations have long been seen as a way of increasing the user's understanding of the world around them [9], or to direct the user's focus and attention [31]. AR is able to provide in-situ annotations in the user's view. Extensive research has been carried out evaluating the effectiveness of AR annotations.

Tang et al. [33] investigated the use of AR for assembly tasks. They found users were significantly faster in completing a 56 step Duplo construction task using AR instructions compared to printed instructions. However, their results found no significant difference between AR and monitor-

based instructions. Similarly, Haniff and Baber [11] found AR instructions placed less cognitive load on the user, compared to paper-based instructions.

Henderson and Feiner also investigated the use of AR for assembly and maintenance tasks with two user studies. Their first study found AR improves task localization times compared to LCD and HUD based instructions[12]. Their follow-up study demonstrated AR can lead to better performance in the psycho-motor phase of a task [13].

Screen space is a significant limiting factor when providing AR annotations. As more information needs to be presented to the user, steps need to be taken to reduce clutter, which may be a distraction [15]. SAR introduces additional factors, because the appearance of the actual physical surfaces in the world are modified [26], rather than the user's view of the world. SAR also requires physical surfaces to project onto; it is not possible to show virtual information at arbitrary locations. Rosenthal et al. [30] demonstrated that users' performance can be reduced with tasks involving projected guides. They suggest the reason for this is because the projected guides and physical objects visually conflicted with one another. Schwerdtfeger et al. [32] demonstrated the use of laser projectors in industrial applications, such as indicating weld points on car bodies, and for inspection tasks. They noted the importance of precise projector calibration, as users can detect even slight misalignments.

Marner et al. [18] have gone on to find SAR improves a user's performance for procedural tasks compared to instructions shown on an LCD screen. The results of the user study confirmed that SAR annotations lead to significantly faster task completion speeds, fewer errors, and reduced head movement, when compared to instructions shown on a monitor. The results show augmented annotations are overwhelmingly preferred by users, and have inspired our work in subliminal cueing, in an effort to further improve performance.

3 User Study

Two experiments were conducted to evaluate subliminal cueing techniques in SAR. The experimental procedure was based on the work conducted by Mulckhuyse et al. [22] and described in Section 2.1. For the purposes of our study, we wanted to inquire into whether subliminal cueing could actually increase performance in a procedural task using SAR projections. Unlike the Mulckhuyse et al. study that only measured perception of a target by having them press the 'space bar,' we required that participants push a target button. Furthermore, we required a comparison between cued and non-cued conditions.

The first experiment evaluated user performance in a button-pressing task. We used our subliminal cue technique to compare helpful cues, cues which correctly direct the user to the target; unhelpful cues, cues which direct the user to a button that is not the target; and no cue. The second experiment evaluated whether the masked cue technique does produce subliminal stimuli that are imperceptible to users. The third improved upon this perception test to provide a more comprehensive analysis of the subliminal nature of the cues. The hypotheses addressed in the experiments are as follows:

Hypothesis H1 Helpful cues lead to faster reaction time, compared to no cue.

Hypothesis H2 Helpful cues lead to faster reaction time, compared to unhelpful cues.

Hypothesis H3 No cues lead to faster reaction time, compared to unhelpful cues.

Hypothesis H4 Participants would be able to detect the cues less than 50% of the time, indicating the cues are subliminal.

Hypotheses H1, H2, and H3 were addressed by Experiment 1, and H4 was addressed with Experiments 2 and 3.

3.1 Apparatus

A typical office desk and chair were used for participants to be seated during the study. A wooden box, measuring 480mm x 330mm x 110mm, with four buttons in a straight line on top, was positioned in front of the participant, see Figure 3. Participants were seated approximately 30 cm from the button box, with their body central to the middle two buttons, as shown in Figure 1. The four buttons spanned a total of 260mm, with 62mm between each. Three of these were used as targets and the fourth as a hand origin point. One NEC NP510W projector with 1280x800 resolution and 50hz refresh rate was used to display the annotations and cues.

Participants were required to use their dominant hand during the experiment. A left and right handed arrangement of the annotations was used, as shown in Figure 4, depending on the participant. If left-handed, the origin button was the leftmost of the four and the targets the remaining three, and the reverse if right-handed. A projector was mounted overhead, angled towards the box to display the cues.

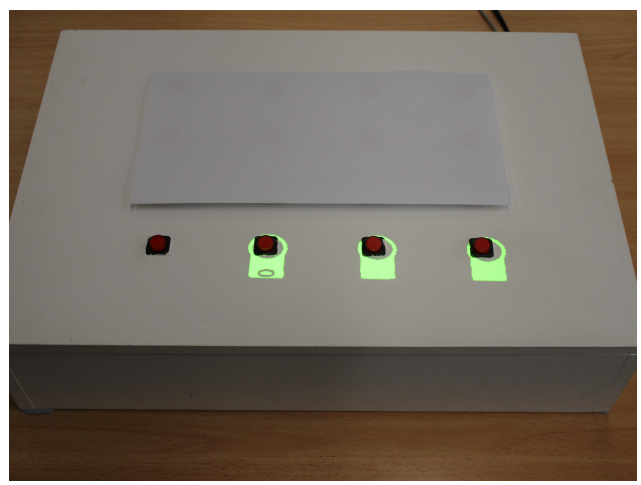


Figure 3: The button box used during the experiment. Three buttons have been highlighted with SAR annotations, with the target shown on the button second from the left.

3.1.1 Experiment 1: User Performance

The first experiment evaluated the effect the cueing technique had on task completion time in a button pressing task. The experiment consisted of three conditions: Helpful subliminal cueing, unhelpful subliminal cueing, and no subliminal cueing. Helpful cues primed the participant to their next target, whilst an unhelpful cue primed a button other than the target. The target was identified with a circle symbol (shown with arrow in Figure 4(a)) and the participants were told to press the target button as quickly as possible when it appeared.

The experiment was conducted as a within subject, repeated measures design. There were a total of 315 button press trials, broken up into 5 blocks of 63 trials, with a minimum 30 second break between blocks. Each condition was tested 21 times per trial block, with the order randomized. The target button was randomized for each trial, with each button receiving the same number of targets overall.

A practice version of the task, consisting of four sets of three targets with no subliminal cues, was presented to allow familiarization with the process and reduce any learning effects. It was stressed that the participant must use only their preferred hand, and they must keep it in the origin position until the target was identified, at which time they were to press the target button as quickly as possible. Their hand was also to return to the origin position between each press. This, along with even target dispersal between buttons, ensured consistent hand travel distance between participants.

When ready, the participant began the main task by pressing the origin button, identified by a red annotation. A delay of 1000ms with no annotations followed. If in the helpful or unhelpful subliminal cue condition, a cue would display for 20ms prior to the display of the annotations for the other two buttons. Figures 4 and 5(a) illustrate the timing of annotations for the helpful and non-helpful cue conditions, respectively. After the 20ms all three buttons were annotated and the target was indicated by a circle symbol. In the non-subliminal cue condition, all three annotations appeared concurrently after the 1000ms delay, as shown in Figure 5(b). When the target was pressed, the green annotations were removed and the red origin annotation reappeared. This procedure would then repeat in a cyclical fashion until the completion of each block. Data were recorded capturing the time taken to press the target button, in milliseconds, from the time the circle symbol appeared.

3.1.2 Experiment 2: User Perception

A second experimental task was designed to measure how effectively participants could perceive the earlier onset of a cue. In this task, a cue was pseudo-randomly selected to appear on any of the three target buttons. The participant was asked to press the button they believed was cued first.

This experiment consisted of four sets of 21 button presses. Upon pressing the origin button, and after a delay of 1000ms, a cue was displayed for 20ms. Following that, the remaining two annotations were displayed, without a target indicator. Participants were instructed to press the button corresponding to the annotation they believed appeared before the others. The timing of annotations for this experiment is shown in Figure 6. Only information regarding a correct or incorrect press was recorded.

The targets were pseudo-randomly allocated, but evenly dispersed between the three buttons. Mathematically, each of the three buttons had a 1/3 chance of being pressed purely at random. However, the presence of a cue was expected to influence results. The accepted definition of a subliminal cue is that the participant is able to detect it no more than 50% of the time. As there were three buttons, we therefore expected the results to be weighted such that the primed button would be selected no more than 1/3 + 1/6, or 50% of the time overall for the cue to be considered subliminal.

3.1.3 Experiment 3: Subjectively Subliminal

A third task was designed to strengthen the claim that the cues were being presented subliminally; that is, below a participant's conscious awareness. A limitation of Experiment 2 was that there were no subjective data collected. It

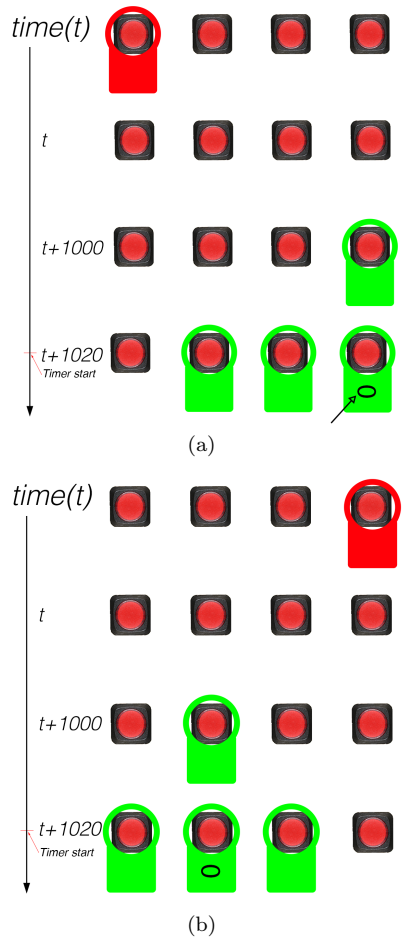
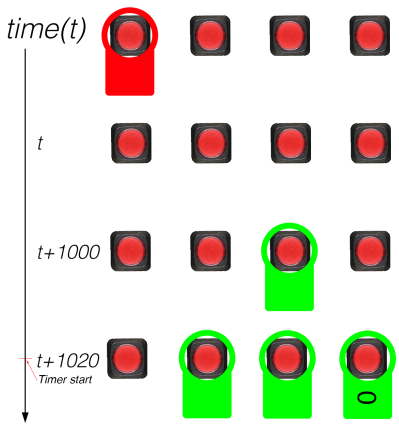


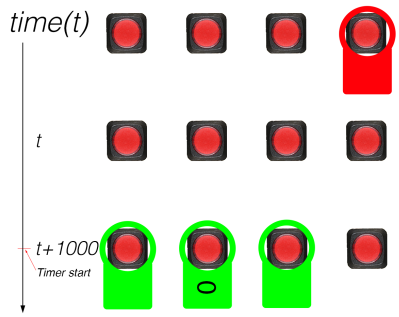
Figure 4: The timing of annotations for the *helpful cue* condition. (a) Left-handed configuration with helpful cue and arrow to indicate target. (b) Right-handed configuration with helpful cue. Note that the target button was randomized among the three buttons.

was possible that the participants might just be not attending the cue, making it pre-attentive rather than subliminal. The quantitative data that were collected in the perception analysis test were not sufficient to completely eliminate this concern, so the development of a more comprehensive test was required. This experiment incorporated a version of the perception analysis test used in Experiment 2, but with a slight adaptation of the cueing technique, and qualitative responses taken from the participant on the visibility of the cue presentation. In this version of the perception analysis new conditions were also introduced.

The cueing technique used an annotation identical to the previous study. The difference, however, is that after the 20ms presentation of the cue on the upcoming target button, identical green annotations were presented on the remaining buttons for 200ms, representing a backward masking and a modest stimulus onset asynchrony. This experiment addressed Hypothesis H4. Participants were shown images of the annotations they would see projected onto the box apparatus. The experimenter explained that they would see a series of flashes and that there was a subliminal cue that would be displayed for a brief time. The exact sequence of the flashes was explained to the participants. The experi-



(a)



(b)

Figure 5: Timing of annotations for the *unhelpful cue* and *no cue* conditions. (a) Left-handed configuration with unhelpful cue, the right-handed configuration was mirrored like in Figure 4(b). (b) Right-handed configuration with no cue. The left-handed configuration was mirrored like in (a).

menter also explained that they were to specifically look for the subliminal cue and respond yes or no as to whether they had seen the cue.

The perception analysis test consisted of four blocks of ten button presses. The same four-buttoned apparatus used in Experiments 1 and 2 was used, with the rightmost button representing the trial start button, and the other three as potential targets for the subliminal cue. Pressing the trial start button, as identified by a red annotation, started each trial. After a delay of 1000ms the cue would be displayed. After the cue was displayed, all the target buttons were annotated with a blank, green label. The participant was then required to verbally acknowledge whether or not they saw the subliminal cue by stating yes or no. The researcher then recorded this response. Then, irrespective of the response, the participant was asked to guess where the cue appeared by pressing the button on which they believed the subliminal cue to have been displayed. The annotations were then all removed and the next trial began. This was repeated for 10 trials. Between each block of 10 presses, the participant was required to press the start trial button, identified by a red annotation.

The subliminal cues were divided randomly amongst the potential target buttons. In 80% of the trials there was a subliminal cue. The remaining 20% acted as catch trials. Thus, the response and guess combinations gave the following possibilities:

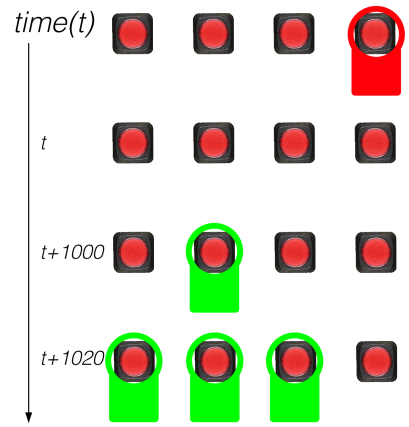


Figure 6: Timing of annotations for Experiment 2. Note that there is no target button annotation in this experiment, participants were instructed to press the button with the annotation they thought appeared first.

- "yes" response with a correct guess,
- "yes" response with an incorrect guess,
- "no" response with a correct guess,
- "no" response with an incorrect guess, and
- the catch trial with a "yes" or "no" response.

In order to claim that the presented cues were truly subliminal, less than 40% of the responses would need to be yes with a correct guess. The 40% is due to 20% of the trials being catches, and the definition of subliminal being accepted as perceived less than 50% of the time.

4 Results

Twenty-one participants took part in Experiments 1 and 2, and ten took part in Experiment 3. All participants were recruited from the general public and staff and students at the University of South Australia's School of Information Technology and Mathematical Sciences. Of the group of twenty-one, seventeen participants were male, and four were female. Three participants were left handed, with the remaining eighteen right handed. The participants were aged between 22 and 54 years of age, with a mean age of 29.5 years (SD = 7.9). Of the ten participants for Experiment 3, ages ranged from 18 to 30 years with a mean age of 26.40 years (SD = 3.75), and five were female. All participants had normal or corrected to normal vision.

4.1 Experiment 1: Reaction Time

The mean reaction time across all fifteen conditions was 623.52ms (SD = 88.42). The overall means for each of the cueing conditions are as follows: helpful = 604.64ms (SD = 81.30), unhelpful = 632.43ms (SD = 76.36), and no-cue = 633.49ms (SD = 103.12).

A five (trial block) by three (cueing condition) repeated measure ANOVA was performed to determine differences in reaction time across trials and between conditions. Sphericity was violated, $\chi^2(2) = 11.81$, $p = .003$, therefore a Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.68$ for the

cueing effect) was used. There was a significant main effect for cueing condition, $F(1.37, 27.34) = 16.08, p < 0.001$, with faster reaction times in the helpful cue condition compared to both unhelpful cue and no-cue (both $p < 0.001$) (Figure 7). No overall differences were observed between unhelpful and no-cue condition. There was also a significant main effect for trial, $F(2.31, 46.29) = 5.03, p < 0.01$, however, no overall reaction time differences between pairs of trials were found in post hoc analysis. Finally, a significant condition by trial interaction was found, $F(2.72, 54.44) = 3.13, p < 0.05$. Post hoc comparisons suggest this effect was due to the slower reaction time observed for the no-cue condition at trial one compared to other trials, however, this difference was only significant when comparing trial one to trial four, $p < 0.05$.

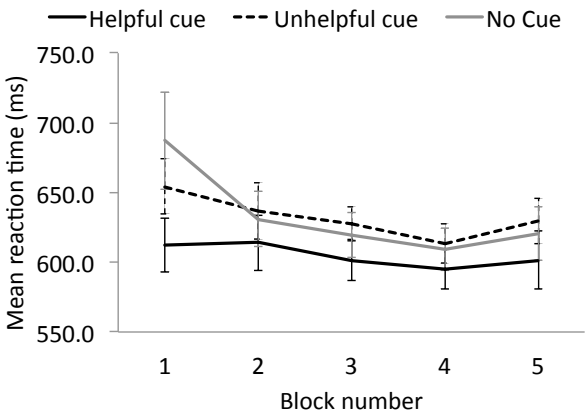


Figure 7: Mean reaction times for each block of trials. Reaction times were significantly faster for helpful cue across all trials when compared to unhelpful cue, and significantly faster when compared to no-cue during first and last trial blocks only.

Further pair-wise post hoc analysis shows that reaction times were consistently faster in the helpful cue condition compared to the unhelpful cue condition at every trial (all $p < 0.01$). However, reactions times were significantly faster for the helpful cue compared to no-cue condition in the first and last trials only (all $p < 0.05$). Examination of response errors, to determine any possible trade-off between response time and response accuracy, showed a very small error rate ranging from 0.3% to 0.8% across trials (average = 0.5%). Chi-squared analysis indicated there was an even distribution of errors across participants ($p > 0.05$).

4.2 Experiment 2: Test for Perception

The mean number of correct responses was 9.91 (SD = 4.32) or 47.2% and mean number of incorrect responses was 11.10 (SD = 4.32) or 52.8%. A one way ANOVA was conducted on the results. This analysis shows there was no change in number of correct (or incorrect) responses across trials ($p > 0.05$).

4.3 Experiment 3

Overall, "yes" responses were given in less than 50% of the 40 presentations. Table 1 shows the mean scores and standard deviations for the six possible responses listed above, for each of the apparatus and label conditions. Each of the cue styles was presented in 40 trials. Of those, eight were catch trials. For each for the cueing styles, and on both apparatuses, the combination of a yes response and a correct guess occurred in less than 50% of the trials with a subliminal cue.

Table 1: Mean number of verbal responses

	Box Apparatus
"Yes" Correct	M = 8.50, SD = 4.06
"Yes" Incorrect	M = 7.20, SD = 5.43
"No" Correct	M = 6.10, SD = 4.12
"No" Incorrect	M = 10.20, SD = 2.78
"Yes" Catch	M = 1.90, SD = 1.60
"No" Catch	M = 6.10, SD = 1.60

5 Discussion

This paper has successfully, and for the first time, demonstrated the application of subliminal cueing to facilitate procedural task performance in a SAR environment. These findings provide a strong indication for the potential use of subliminal cueing in other augmented reality display methods. The findings are as follows:

1. Standard consumer grade projection devices are sufficient to support subliminal cueing.

2. Subliminal cues presented as a primer, improve a user's reaction time for a procedural task.

3. Subliminal cues are effective for spatial augmented reality annotations.

5.1 Discussion of Results

To demonstrate standard consumer grade projection devices are sufficient to support subliminal cues, we performed a threshold test to determine if the presented cues were subliminal or supraliminal. A subliminal threshold is typically determined by the ability to detect a stimulus on average 50% of the time. We performed two tests for perception with our experiment participants, collecting both quantitative and qualitative measures. Consistent with this definition, the results for our assessment of participants perception of the subliminal cue were reported at just under 50%.

In addition, the results clearly indicate that the subliminal cues improved the reaction time of a user selecting a particular button highlighted with a spatial augmented reality annotation. Specifically, reaction times were faster in the cued condition than either a cue in an incorrect location (unhelpful cue) or no-cue at all. All effects were adequately powered (all above 0.9) and effect sizes were large. These results are consistent with the psychological literature demonstrating a valid subliminal cue facilitates target identification in non-SAR spatial tasks [6, 19]. Figure 7 depicts the relative mean reaction times for each time over the five blocks. While there is an indication of a subtle training effect beyond the practice task given to participants, the change in reaction time across trials within each condition was relatively small, and statistically non-significant. Closer analysis revealed that response times were consistently faster in the helpful cue condition compared to unhelpful cue across the trial blocks, however differences between helpful cue and no-cue conditions were only robustly established in first and last trial blocks. This result may be explained by carry-over learning effects in the first trial whereby helpful priming

facilitated the learning process as well as leading to maintenance of boosted performance across trials. Conversely, task fatigue would be expected to be maximal by the final trial block, where again helpful cueing could be expected to provide maximal benefits. The implications of this latter finding are that application to cueing in real-world scenarios that are fatiguing (e.g. shift-work) and require fast and accurate responses may particularly benefit.

While projectors have been previously employed to depict subliminal cues, these were typically in cinema, or cinema-like settings [23]. The key difference between this format and SAR annotations is that in the cinema the user only focuses on the virtual information (i.e. the film), and in an AR setting the user must focus on both virtual information and the physical world. This investigation demonstrated that projected information onto physical objects can contain subliminal information. The second major presentation of subliminal information in the literature is with a workstation monitor. In the literature the most common experiments were in the form of the user viewing information on a workstation monitor and asked to respond via a keyboard or mouse button press. The user in these previous experiments had to view virtual information and then they physically responded to this information with an input device not in their field of vision. Our investigation required to the user to view virtual information in-situ with the physical world (i.e. control panel with the physical button to be pressed).

5.2 Applications

Our new SAR subliminal cue works as a primer to improve reaction time to press a button in a procedural task. We believe subliminal cues have the potential to improve other aspects of augmented reality annotations, but acknowledge these ideas require rigorous future investigations.

One potential avenue stems from the fact that by their very nature subliminal cues are less attention grabbing than overt supraliminal cues. In their model of visual processing, Dehaene et al. [7] propose that subliminal processing involves weak bottom-up stimulus strength, but can influence behavior based on the presence or influence of top-down modulated attention. Attended subliminal processing has short-lived effects, with no reportability by individuals and seemingly no durable fronto-parietal brain activation. In contrast, preconscious or conscious processing involves strong bottom-up stimulus strength, and more widely and intensely distributed neural activation, extending to durable parieto-frontal networks under conditions of directed attention. The implication of such activation differences is that given a measured effect on behavioral outcome, subliminal cueing provides a means to facilitate patterns of behavior with minimal or reduced interference of important conscious processes that may also be required. This study demonstrates that SAR provides a novel and applied means to investigate such potential further.

A second potential avenue is to provide subtler cueing for expert users. One aspect from our investigations with the automobile industry is that SAR annotations require different forms of presentation to expert users and novice users. In particular, a number of annotations should not distract their workflow. This is well known in human computer interaction research and as Buxton [2] states, experts and novice users require a different user interface to computer applications. We envision subliminal cues as part of an expert version of a SAR annotation scheme to provide a more elegant and effective annotation scheme to expert users. These annotations would be less intrusive and less distracting.

Finally subliminal SAR cues have the potential to provide annotations on surfaces with highly complex geometries and intricately colored textures, such as the cockpit instrument panel of a modern passenger plane. Supraliminal cues require a user to direct their attention to the cue, understand the cue, and respond to the cue. Current methods of highlighting a particular button or dial in these environments are an unsolved research problem. The use of subliminal cues may mean that such a structured, iconic presentation is not required or its use can be minimized. For example, a subliminal presentation through a tachistoscopic device over a particular button may provide enough cueing to guide the user to the correct button to press in an emergency or under high cognitive load conditions. The visual background may not have as much bearing on the cue as the cognitive processing differs [7].

In future work we may explore employing spatial priming subliminal cues to influence a user's selection of specific buttons instead of improving reaction time. This may be useful for training scenarios such as childhood education. For example, in a simple quiz with multiple choice answers subliminal cues may be employed to guide the user to the correct answer. Subliminal cues have previously been shown to be effective for learning tasks on traditional workstation monitors [3, 4].

6 Conclusion

This paper presents the first investigation into using subliminal cues in spatial augmented reality. These results represent fundamental research into cognitive psychological processes of human computer interaction with spatial augmented reality. We have demonstrated that subliminal cues are possible using standard data projectors with a 50Hz vertical refresh rate. This was achieved by employing a masking technique, adopted from cognitive psychology, making it possible to display a single frame subliminal cue on one of three buttons that is not perceivable by users. Our threshold analyses confirmed the subliminal cue was detectable less than 50% of the time. We also present findings to support that subliminal cues can improve user reaction time performance when asked to press sequences of target buttons. Three cue conditions were presented: Helpful, unhelpful and no cue. A significant result demonstrated a performance increase between the helpful and no-cue condition.

We believe subliminal cues are useful for augmented reality system designers to assist with mission critical applications and supporting optimal efficiency user interface designs. We envisage future implementations will leverage higher performance projectors allowing a full range of subliminal cue techniques to be presented in spatial augmented reality that will further increase user performance.

Further investigations are required to determine if these findings hold for other augmented reality display technologies such as head mounted displays (optical see-through and video see-through) and hand-held display technologies. Based on the existing success with flat display technologies we foresee it will be possible to apply the techniques in this paper to these display technologies.

References

[1] J. Baumeister and B. H. Thomas. Crossing spatial augmented reality with psychology. In *Information Technology and Applications (ICITA), 2014 9th IEEE International Conference on*, 2014.

[2] W. Buxton. Chunking and phrasing and the design of human-computer dialogues. In *Proceedings of the IFIP*

World Computer Congress, page 475480. North Holland Publishers, 1986.

[3] P. Chalfoun and C. Frasson. Optimal affective conditions for subconscious learning in a 3D intelligent tutoring system. In J. A. Jacko, editor, *Human-Computer Interaction. Interacting in Various Application Domains*, number 5613 in Lecture Notes in Computer Science, pages 39–48. Springer Berlin Heidelberg, Jan. 2009.

[4] P. Chalfoun and C. Frasson. Cognitive priming: assessing the use of non-conscious perception to enhance learner's reasoning ability, 2012.

[5] B.-W. Chang and D. Ungar. Animation: From cartoons to the user interface. In *Proceedings of the 6th Annual ACM Symposium on User Interface Software and Technology*, UIST '93, pages 45–55, New York, NY, USA, 1993. ACM.

[6] W. L. Chou and S. L. Yeh. Subliminal spatial cues capture attention and strengthen between-object link. *Consciousness and cognition*, 20(4):1265–71, 2011. Chou, Wei-Lun Yeh, Su-Ling Conscious Cogn. 2011 Dec;20(4):1265-71. doi: 10.1016/j.concog.2011.03.007. Epub 2011 Apr 2.

[7] S. Dehaene, J. P. Changeux, L. Naccache, J. Sackur, and C. Sergent. Conscious, preconscious, and subliminal processing: a testable taxonomy. *Trends in cognitive sciences*, 10(5):204–11, 2006. Dehaene, Stanislas Changeux, Jean-Pierre Naccache, Lionel Sackur, Jerome Sergent, Claire England Trends Cogn Sci. 2006 May;10(5):204-11. Epub 2006 Apr 17.

[8] R. W. DeVaul. *The memory glasses: wearable computing for just-in-time memory support*. PhD thesis, 2004.

[9] S. Feiner, B. MacIntyre, T. Hllerer, and A. Webster. A touring machine: Prototyping 3D mobile augmented reality systems for exploring the urban environment. *Personal Technologies*, 1(4):208–217, Dec. 1997.

[10] S. Gayet, S. Van der Stigchel, and C. L. Paffen. Seeing is believing: Utilization of subliminal symbols requires a visible relevant context. *Attention, Perception, & Psychophysics*, 76(2):489–507, 2014.

[11] D. J. Haniff and C. Baber. User evaluation of augmented reality systems. In *Information Visualization, 2003. IV 2003. Proceedings. Seventh International Conference on*, pages 505–511. IEEE, 2003.

[12] S. J. Henderson and S. Feiner. Evaluating the benefits of augmented reality for task localization in maintenance of an armored personnel carrier turret. In *Mixed and Augmented Reality, 2009. ISMAR 2009. 8th IEEE International Symposium on*, pages 135–144. IEEE, 2009.

[13] S. J. Henderson and S. K. Feiner. Augmented reality in the psychomotor phase of a procedural task. In *Mixed and Augmented Reality (ISMAR), 2011 10th IEEE International Symposium on*, pages 191–200. IEEE, 2011.

[14] M. Hilsenrat and M. Reiner. The impact of unaware perception on bodily interaction in virtual reality environments. *Presence: Teleoper. Virtual Environ.*, 18(6):413420, Dec. 2009.

[15] S. Julier, M. Lanzagorta, Y. Baillot, L. Rosenblum, S. Feiner, T. Hollerer, and S. Sestito. Information filtering for mobile augmented reality. In *IEEE and ACM International Symposium on Augmented Reality, 2000. (ISAR 2000). Proceedings*, pages 3–11, 2000.

[16] C. larsen. Subliminal perception in 3D computer games - towards an invisible tutorial. In *ACM CHI*, Paris, 2013.

[17] M. Luboschik and H. Schumann. Illustrative halos in information visualization, 2008.

[18] M. R. Marner, A. Irlitti, and B. H. Thomas. Improving procedural task performance with augmented reality annotations. In *Mixed and Augmented Reality (ISMAR), 2013 12th IEEE International Symposium on*, Adelaide, South Australia, 2013.

[19] P. A. McCormick. Orienting attention without awareness. *Journal of experimental psychology. Human perception and performance*, 23(1):168–80, 1997. McCormick, P A J Exp Psychol Hum Percept Perform. 1997 Feb;23(1):168-80.

[20] P. Milgram. A spectacle-mounted liquid-crystal tachistoscope. *Behavior Research Methods, Instruments, & Computers*, 19(5):449–456, 1987.

[21] T. E. Moore. Subliminal advertising: What you see is what you get. *The Journal of Marketing*, pages 38–47, 1982.

[22] M. Mulckhuyse and J. Theeuwes. Unconscious attentional orienting to exogenous cues: A review of the literature. *Acta Psychologica*, 134:299–309, 2010.

[23] M. D. J. Mulckhuyse. Grabbing attention without knowing: Automatic capture of attention by subliminal spatial cues. *Visual Cognition*, 15(7):779–788, 2007.

[24] S. R. Porter, M. R. Marner, R. T. Smith, J. E. Zucco, and B. H. Thomas. Validating spatial augmented reality for interactive rapid prototyping. In *Mixed and Augmented Reality (ISMAR), 2010 9th IEEE International Symposium on*, pages 265–266. IEEE, 2010.

[25] R. Raskar, G. Welch, and H. Fuchs. Spatially augmented reality. In *In First IEEE Workshop on Augmented Reality (IWAR98)*, page 1120, 1998.

[26] R. Raskar, G. Welch, K.-L. Low, and D. Bandyopadhyay. Shader lamps: Animating real objects with image-based illumination. In *Rendering Techniques 2001*, pages 89–102. Springer, 2001.

[27] A. Riener. Subliminal persuasion and its potential for driver behavior adaptation. *Intelligent Transportation Systems, IEEE Transactions on*, 13(1):71–80, 2012.

[28] A. Riener, M. Reiner, M. Jeon, and P. Chalfoun. Methodical approaches to prove the effects of subliminal perception in ubiquitous computing environments, 2012.

[29] W. Ritter. Benefits of subliminal feedback loops in human-computer interaction. *Advances in Human-Computer Interaction*, 2011:1, 2011.

[30] S. Rosenthal, S. K. Kane, J. O. Wobbrock, and D. Avrahami. Augmenting on-screen instructions with micro-projected guides: when it works, and when it fails. In *Proceedings of the 12th ACM international conference on Ubiquitous computing*, pages 203–212. ACM, 2010.

[31] B. Schwerdtfeger and G. Klinker. Supporting order picking with augmented reality. In *Mixed and Augmented Reality, 2008. ISMAR 2008. 7th IEEE/ACM International Symposium on*, pages 91–94. IEEE, 2008.

[32] B. Schwerdtfeger, D. Pustka, A. Hofhauser, and G. Klinker. Using laser projectors for augmented reality. In *Proceedings of the 2008 ACM symposium on Virtual reality software and technology*, pages 134–137. ACM, 2008.

[33] A. Tang, C. Owen, F. Biocca, and W. Mou. Comparative effectiveness of augmented reality in object assembly. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '03, pages 73–80, New York, NY, USA, 2003. ACM.

[34] B. H. Thomas, G. S. Von Itzstein, R. Vernik, S. Porter, M. R. Marner, R. T. Smith, M. Broecker, B. Close, S. Walker, S. Pickersgill, et al. Spatial augmented reality support for design of complex physical environments. In *Pervasive Computing and Communications Workshops (PERCOM Workshops), 2011 IEEE International Conference on*, pages 588–593. IEEE, 2011.

[35] M. Wiener and P. H. Schiller. Subliminal perception or perception of partial cues. *The Journal of Abnormal and Social Psychology*, 61(1):124, 1960.

[36] A. Williams Jr. Perception of subliminal visual stimuli. *The Journal of Psychology*, 6(1):187–199, 1938.

[37] J. Zhou, I. Lee, B. Thomas, R. Menassa, A. Farrant, and A. Sansome. In-situ support for automotive manufacturing using spatial augmented reality. *International Journal of Virtual Reality*, 11(1), 2012.