Subliminal Cueing of Selection Behavior in a Virtual Environment

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Abstract

The performance of current graphics engines makes it possible to incorporate subliminal cues within virtual environments (VEs), providing an additional way of communication, fully integrated with the exploration of a virtual scene. In order to advance the application of subliminal information in this area, it is necessary to explore in the psychological literature how techniques previously reported as rendering information subliminal can be successfully implemented in VEs. Previous literature has also described the effects of subliminal cues as quantitatively modest, which raises the issue of their inclusion in practical tasks. We used a 3D rendering engine (Unity3D) to implement a masking paradigm within the context of a realistic scene and a familiar (kitchen) environment. We report significant effects of subliminal cueing on the selection of objects in a virtual scene, demonstrating the feasibility of subliminal cueing in VEs. Furthermore, we show that multiple iterations of masked objects within a trial, as well as the speeding of selection choices, can substantially reinforce the impact of subliminal cues. This is consistent with previous findings suggesting that the effect of subliminal stimuli fades rapidly. We conclude by proposing, as part of further work, possible mechanisms for the inclusion of subliminal cueing in intelligent interfaces to maximize their effects.

1 Introduction

Subliminal perception has recently gained attention in human–computer interaction (HCI) as an approach to prime users unconsciously. There is now a large consensus on the fact that stimuli remaining below the threshold of consciousness (i.e., subliminal stimuli) can have an impact on brain and behavior (Kouider & Dehaene, 2007). Subliminal influences have traditionally been measured through variants of the masking paradigm (Marcel, 1983). In this paradigm, a stimulus is made invisible by presenting it very briefly (i.e., only a few tens of milliseconds) and by surrounding it with masking patterns, leading to chance-level performance on discrimination tasks (objective control of awareness) and verbal reports of stimulus absence (subjective control of awareness). Nevertheless, the masked stimulus can influence subsequent decisions by biasing selection among alternatives (i.e., subliminal cueing), or by facilitating performance on subsequent, supraliminal stimuli sharing some relation with the masked cue (i.e., subliminal priming). Behavioral findings of subliminal perception revealed that a masked word, digit, or object can have an influence on sensorimotor, perceptual, and, under some conditions, even semantic and decision levels, while neuroimaging methods directly visualize the brain activation that it

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evokes in several cortical areas (for an extensive review, see Kouider & Dehaene, 2007).

While this type of research was traditionally done in limited laboratory contexts that are characteristic of experimental psychology (i.e., using simplified, nonecological modes of presentation with nothing more than a single stimulus display at a time), the use of virtual environments allows for the possibility of studying subliminal influences in more realistic contexts. Indeed, VEs are increasingly used to study realistic tasks in a variety of areas (Fox, Arena, & Bailenson, 2009), supporting the study of presence and, more recently, research in various areas of neuroscience. Over the years, virtual reality (VR) has been considered in research for investigating perception and consciousness (Sanchez-Vives & Slater, 2005). Although the use of VR to study nonconscious perception is rare (Hilsenrat & Reiner, 2009), recent advancements of software and hardware make it possible to synthetically reproduce subliminal cues for a variety of situations and tasks (Pizzi et al., 2012).

Subliminal stimuli can impact users' behavior in a VE and prevent overloading them when a large amount of data needs to be explored or remembered (Riener, Kempter, Saari, & Revett, 2011; DeVaul, Pentland, & Corey, 2003). Examples of research include subliminal cueing in support of online help in a desktop-computer text-editing task application (Wallace, Flanery, & Knezek, 1991), just-in-time memory support using subliminal cues delivered in a head-mounted display (DeVaul et al., 2003), application in a tutoring system (Chalfoun & Frasson, 2011), and aid for visual search tasks (e.g., McNamara, Bailey, & Grimm, 2008; Bailey, McNamara, Sudarsanam, & Grimm, 2009).

Affecting behavior in a VE through subliminal stimulation does not come without challenges. Many of these challenges are similar to those that are faced in subliminal persuasion in real life. For example, the influence that can be exerted with subliminal cueing in real-life situations seems to be constrained to goal-relevant behavior, such as lessening thirst (Strahan, Spencer, & Zanna, 2002) or relieving fatigue (Bermeitinger et al., 2009). Furthermore, subliminal priming is shown to be modulated by temporal (Naccache, Blandin, & Dehaene, 2002) and spatial attention (Kiefer & Brendel, 2006; Ortells, Frings, & Plaza-Ayllon, 2012). The short-lived nature of the effect of masked subliminal cues imposes additional constraints on the time window in which cueing will be effective in realistic environments (Gaillard et al., 2009; Kouider, Berthet, & Faivre, 2011; Brintazzoli, Soetens, Deroost, & Van den Bussche, 2012).

A promising way to address these challenges is to take known constraints into account when designing the interface for subliminal HCI in virtual environments (Pizzi et al., 2012), for example, by embedding subliminal cues in a goal-directed task while guiding attention during its execution. Although there is a wealth of possibilities in terms of applications, research in this direction seems to lack a systematic approach to study subliminal influences. Indeed, many attempts fall short in terms of the rigorous application of established subliminal perception paradigms from the field of experimental psychology, such as controlling carefully for the conscious visibility of masked stimuli. More effort is needed to explore subliminal influences in HCI systematically, by choosing settings that are representative, clearly specifying the techniques under investigation for specific classes of cues, and determining stimulus visibility. These efforts would ensure that results of experiments could inform subsequent research with clearer and more generalizable implications, notably in the context of virtual product experience and electronic shopping (Fox et al., 2009; Desmet, Bordenave, & Traynor, 2013; Jiang & Benbasat, 2004). In particular, it would allow demonstrating the feasibility and potential applicability of including subliminal cues to promote users' interaction with 3D objects in VEs.

In the present study, we investigated the effects of masked indices using a subliminal cueing paradigm in the context of interacting with 3D objects in a VE. We present an experiment where the effectiveness of subliminal cues to bias selection behavior was examined in a realistic task that involved selecting food items from a virtual refrigerator. Cueing effectiveness under single or repeated stimulus–presentation conditions, objective and subjective measure of stimulus visibility, and individual differences across masked objects and across experimental subjects are analyzed and discussed, with implications to practical application and future research in HCI.

Our study was designed to answer the following research question: can participants' behavior be influenced by subliminal indices in a virtual environment, within a realistic task that includes selection between objects? To address this question, we simplified the task to a series of trials of forced-choice selection between two objects to test the following general hypothesis.

Hypothesis 1. Subliminally cued objects are more frequently selected than expected by chance.

In other words, Hypothesis 1 simply proposes that there is a cueing effect. Whether the cueing effect is genuinely subliminal is established by having the same subjects perform a subsequent visibility test consisting in a forced-choice discrimination task on the masked stimulus, in accordance with standards in this research field (see Kouider & Dehaene, 2007). Based on studies of subliminal priming in the literature on experimental psychology (e.g., see Greenwald, Draine, & Abrams, 1996), we expected a small effect size for subliminal cueing on behavior. However, for the practical application of subliminal or marginally visible cues in a virtual environment, small effect-sizes may not be sufficient. Therefore, we also decided to explore cueing effectiveness under the condition of multiple expositions of masked stimuli, according to the following hypothesis.

Hypothesis 2. There is a larger cueing effect when subliminal objects are exposed multiple times.

We designed the experiment to explore the effects of various relevant factors on cueing effectiveness, such as reaction time, variability across multiple stimuli, and individual differences. Regarding aforementioned constraints on subliminal interfaces for HCI, reaction time is of particular interest. It follows from the short-lived nature of subliminal cueing effects that shorter reaction times should be accompanied by larger effect sizes. Repeating the cues before their effect fades may result in accumulation of the early unconscious influence (Marcel, 1983; Wentura & Frings, 2005). Although most theories of subliminal perception predict that repeated exposure leads to increasing awareness of the cues (Atas, Vermeiren, & Cleeremans, 2013), the approach is worth further exploration because of its potential practical implications. The following sections present the experimental design, procedure and analysis that allow for such an exploration.

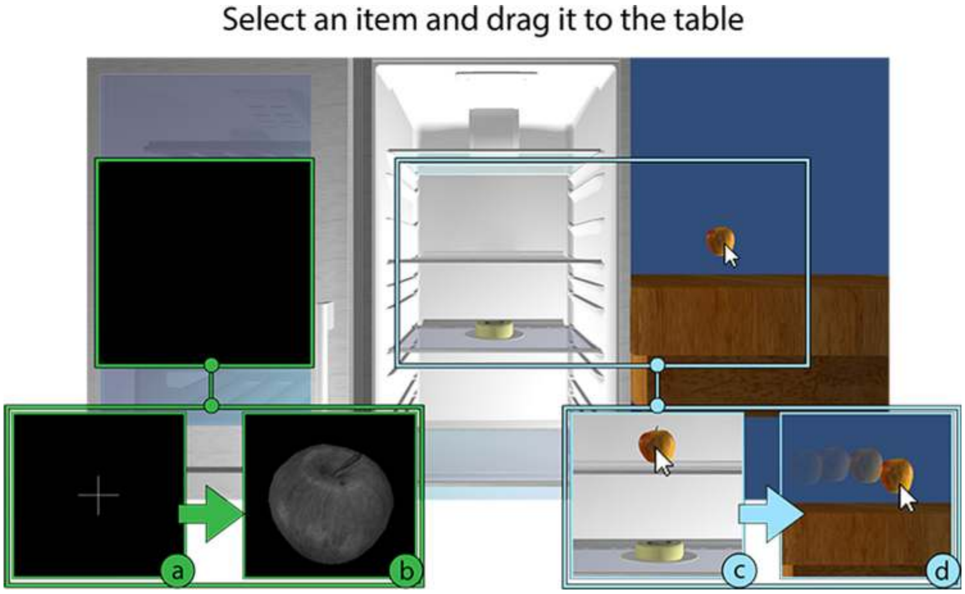
2 Experiment

2.1 Method

2.1.1 Participants. Recruitment was aimed at academic and administrative staff at Teesside University. Sixteen people participated in the experiment (9 women) with a mean age of 36.69 years ($SD = 8.14$). The mean of self-reported duration of computer use per day was seven hours ($SD = 2.52$). Participants received the equivalent of $30 vouchers as incentive.

2.1.2 Design and Procedure. We designed the experiment to compare participants' selection of objects in a series of forced-choice tasks in a virtual environment that involved the subliminal cueing of one of two objects in each trial. The task in each trial was to pick one food item (object) out of two from a refrigerator and place it on an adjacent table. Participants were instructed to select the item that corresponds to the masked object. The number of masked-stimulus presentations in each trial was included as a within-subjects factor with two levels: one or three presentations. Each participant took part in the same condition. The experiment involved three successive phases: (1) a training phase, (2) an experimental phase, and (3) stimulus visibility testing. Participants worked individually in a computer lab and the entire procedure took approximately 35 minutes to complete. The on-screen instructions for each phase of the experiment are presented in Appendix A.

In the training phase, participants completed 30 trials. The screen layout of the trials is presented in Figure 1. F1 The selection task in each trial was preceded by a cue presentation. Cue presentation took place in a fixed presentation area to reduce possible confounds arising from variations in spatial attention. Eighty percent of the training trials included a clearly visible (500 ms) stimulus and a backward mask (200 ms), while 20% of the trials included just a forward and a backward mask (200 ms each). Participants were instructed to select the object



Select an item and drag it to the table

Figure 1. *Screen layout of the training and experimental trials. The background image is a screenshot taken as a participant moves an object to the table. Each trial begins with a request for the user to click the crosshair in the cueing area (a), which triggers a cue presentation (b). The user is then asked to select an item from the fridge (c) and drag it to the table (d).*

Figure 3. *A virtual model of the appliance product used for the experiment.*

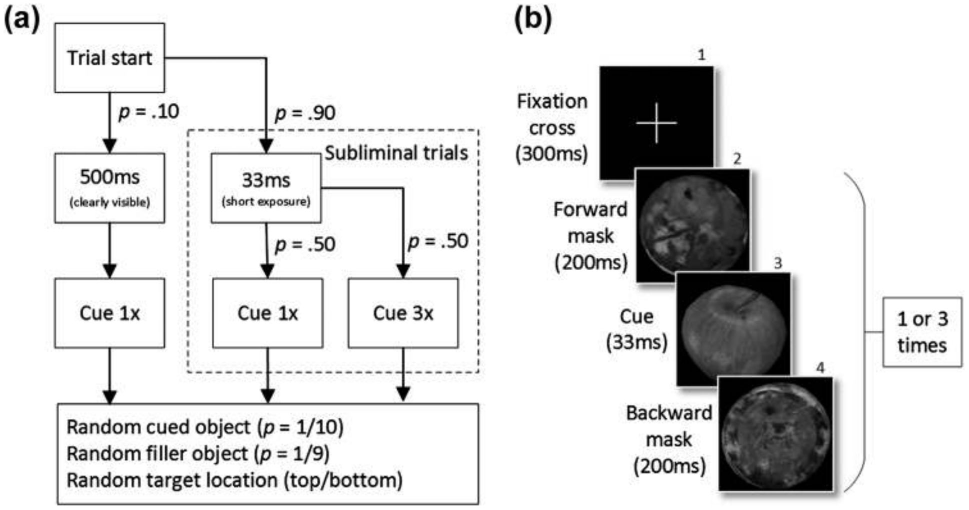


Figure 2. *Structuring of experimental trials in the masked-cueing phase (a), and cue presentation in the short-exposure trials (b).*

that corresponded to the masked object when they saw one. The training trials were included to familiarize participants with the virtual environment and to ensure that they learned to select the object they saw, and that they still selected an object even in the absence of a visible stimulus.

In the experimental phase, participants completed trials that applied the same screen layout as in the training phase. At the start of each trial, the experimental software first selected between two cueing conditions: clearly visible (500 ms) or short exposure (33 ms). Because masked-cuing paradigms typically involve cue presentation below 50 ms to ensure efficient masking, presentation duration in the short-exposure condition was set to 33 ms. The clearly-visible cueing condition had a 10% chance of being initiated and it was included to reinforce the selection task established in the training phase by re-associating the cueing area with a selection cue. Participants' performance on the clearly-visible condition was used only to check whether they carried out the selection task according to the instructions. The short-exposure condition had a 90% chance of being selected and constituted the main trials of the experimental phase.

If the short-exposure condition was selected, the experimental software randomly selected if the masked stimulus was going to be presented once or three times in the trial (50% chance for each condition). As the final step of trial structuring, the experimental software randomly selected the following properties for each condition: (1) the object to be cued (one out of a total of ten objects), (2) the alternative object to be presented in the fridge with the target (one out of the remaining nine objects), and (3) the location of the target object in the fridge (top or bottom shelf). The structuring of trials as described earlier is presented in Figure 2a. F2

Each trial started with an empty refrigerator and a white fixation cross on a black field in the cueing area (see Figure 1a), with the on-screen instructions "click on the crosshair when ready." Requiring participants to click the fixation cross ensured that their gaze was central on the area at the time of cue presentation, and participants were instructed at the start of each phase to pay attention to the presentation (see Appendix A). The participant clicking the fixation cross triggered the experimental software to structure the trial. The fixation cross remained on the screen for 300 ms and was followed by the masked stimulus (see Figure 1b). The cues and masks occupied a roughly circular area of approximately 9 cm in diameter on the screen, which corresponds to subtending an angle of 8° of participants' visual field. If the clearly-visible condition was initiated, stimulus presentation was the same as in the training phase. If the short-exposure condition was initiated with cueing only once

(1x condition), the masked stimulus presentation had the following structure: 200 ms forward mask, 33 ms stimulus, 200 ms backward mask (see Figure 2b). In the short-exposure condition with cueing three times (3x condition), stimulus presentation was the same as in the 1x condition, but repeated three times.

The target object and the other object (filler) appeared on the shelves in the refrigerator after cue presentation (see Figure 1c), with the on-screen instructions "select an item and drag it to the table." The amount of space occupied by the target objects depended on the specific food item and was affected by the camera perspective depending on its position in the fridge (top or bottom). At the extremes, the sliced lemon occupied approximately 1 by 1 cm in the bottom and the pie occupied 6 by 2 cm in the top. After the participant dragged an object to the table (see Figure 1d), the trial ended and the next trial started. The masked-cueing phase ended when the experimental software logged at least 100 completed trials for each of the short-exposure conditions.

In the visibility phase, participants received each cue 12 times, presented once or three times within each trial, in a randomized order (in the same structure as in the masked-cueing phase), resulting in a total number of 120 trials (60 trials for the 1x and 3x condition each). After the presentation of each cueing stimulus, the name of an item from the complete list of items was presented on the screen with a question mark (e.g., "apple?"), which was either congruent (50% of the time) or incongruent with the identity of the cued object (Kouider et al., 2011). Participants gave an answer by clicking a "yes" or a "no" box, positioned in the refrigerator randomly on the top or the bottom shelf where the target objects were placed in the masked-cueing phase. A one-second delay between presentation of the cue and the corresponding question was included to diminish the influence of nonconscious processes on identification performance (e.g., see Bodner & Mulji, 2010; Kiesel et al., 2006; Schlaghecken & Eimer, 2004; Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003). Furthermore, a delay gives conscious representations of the cues sufficient time to develop. In subliminal priming, a delay between prime presentation and visibility assessment increases d', preventing underestimation of stimulus visibility (Vermeiren & Cleeremans, 2012). Likewise, visibility was assessed after the experimental phase in order to avoid underestimating visibility due to training effects and familiarity with the presentation conditions (see Kouider & Dehaene, 2007).

2.1.3 System Architecture.

We developed a modular, event-driven architecture in Unity3D to support the experiment. Unity3D is a game engine: it has been designed to integrate the presentation of realistic worlds with various methods for user interaction in a dynamic environment. Unity3D provides a suitable framework for implementing VEs and provides useful abstractions that assist developers to separate components such as content, behavior, and interaction. There are high demands on modern game engines to support high frame rates even under these pressing constraints, which allows for including subliminal cue presentations as native objects in the interactive environment to explore their effects within a task setting.

As a context for the task, we used a realistic 3D model of a refrigerator from one of the largest appliance–manufacturer groups. The 3D model was simplified and with a reduced polygonal resolution in the Unity developing environment; nevertheless, the model included hundreds of units, each consisting of up to thousands of polygons. In addition, the environment was populated with various objects to assist in increasing users' sense of presence.

We modeled a large number of high-resolution, textured 3D food items that could be introduced into the scene. Food items can play an important role in providing users with information, enhancing their engagement with the fridge model. For example, it may be difficult to understand the practicality of an empty fridge drawer; however, introducing food items provides a natural and familiar reference. More specifically, incorporating models into the environment can support various tasks. The environment also included notional objects, such as cameras and lighting, to control users' experience. In particular, the camera allows precise control over various aspects that can impact the effect of subliminal cues (e.g., field of view, distracting movement, and position). A snapshot of our system including furniture, food items, and the refrigerator is presented in Figure 3. F3

Cue presentation was implemented using reusable collections of objects (prefabs) and animations, created in the Unity3D editor. Each mask and cuing image was converted to a texture and applied as a material over a surface (plane). We created a prefab for each object, consisting of the object's image and the two masks. Transforming the instantiated prefab can control the appearance of the objects prior to cue presentation. For example, the exact position of the presentation can be set, and the presentation can be scaled to compensate for certain factors that may influence cue visibility, such as fixation point and screen size. Furthermore, the objects within the instantiated prefabs can be controlled directly; for example, it is possible to rotate the backward mask (an alternative to using distinct forward and backward masks) or to disable the backward mask entirely (to test the effectiveness of the masking).

Unity3D supports extension scripts that allow seamless integration between the underlying game engine and bespoke user-defined components. We implemented various C# scripts that provide behaviors within the environment. The model of the refrigerator consists of individual components that can each be transformed individually. The scripts select from a collection of specific animations that manipulate the position and rotation of the components to realize many of the expected low-level behaviors. The scripts are triggered by events identified from user behavior (using ray casting to identify the target). The animations are controlled in distinction from the physics engine to support integration with deliberative control systems (for example, a planning system). As a consequence of these integrated behaviors, the refrigerator can be fully manipulated: the doors can be opened, the drawers can be pulled out, and the shelves can be repositioned or folded up (as in an area for tall food items). We also implemented several C# classes that managed the transactions involved in the experiment task. The components communicated through message passing to facilitate selection of appropriate modules for each task and convenient logging through event listening.

Cue presentations were made by playing an animation on the appropriate collection of objects. We implemented three animations for each object for single, triple, and clearly-visible presentations, using the alpha channels of the materials to make the masks and the cue appear correctly. We used 60 frames-per-second animations to match the screen refresh rate. The following frame counts were used to approximate the presentation times: 30 animation frames for 500 ms, 12 frames for 200 ms, and 2 frames for 33 ms. Each part of the experiment began with the camera zooming from a long view of the fridge and table to a static view that focused on the screen, shelves, and table. This initial zooming was included to facilitate users' understanding of the task context, while the static view during the trials supported maximum attention.

We developed a framework that supports various mappings between user actions and behaviors; for example, in previous work we mapped gestures to user actions (Pizzi et al., 2012). We opted for a mouse-controlled, click-and-drag interaction in order to focus the experiment toward investigating cueing effects, but our system is compatible with gesture interaction. To support manipulation, the food items and yes/no labels were tagged and given colliders, and the area of the screen that displayed the table was defined as the drop zone. To avoid the frustration of mouse-control issues, objects that were dropped during dragging would remain hovering, and could be selected again. An outline of the system architecture is presented in Figure 4. F4

2.1.4 Materials and Equipment. The experimental software was implemented in Unity3D (version 4.0.1f2) and was run on a Dell Precision T7600 computer (CPU: Intel Xeon E5-2609 2.40 GHz; 32 GB RAM; GPU: NVidia GeForce GTX 680; OS: MS Windows 7 Enterprise 64-bit) with a 24-in Dell U2412M monitor (60-Hz refresh rate, 1920 by 1200 resolution). Participants were seated 65 cm from the screen. The timing of cue presentation was checked by recording presentations with a Panasonic Lumix TZ30 high-speed camera (220 fps) and counting the number of frames the cues were present on the screen. We counted six clear and two partially visible frames for each cue, corresponding to between 27.27 ms and 36.36 ms exposition time, which we deemed an acceptable fit to the intended 33

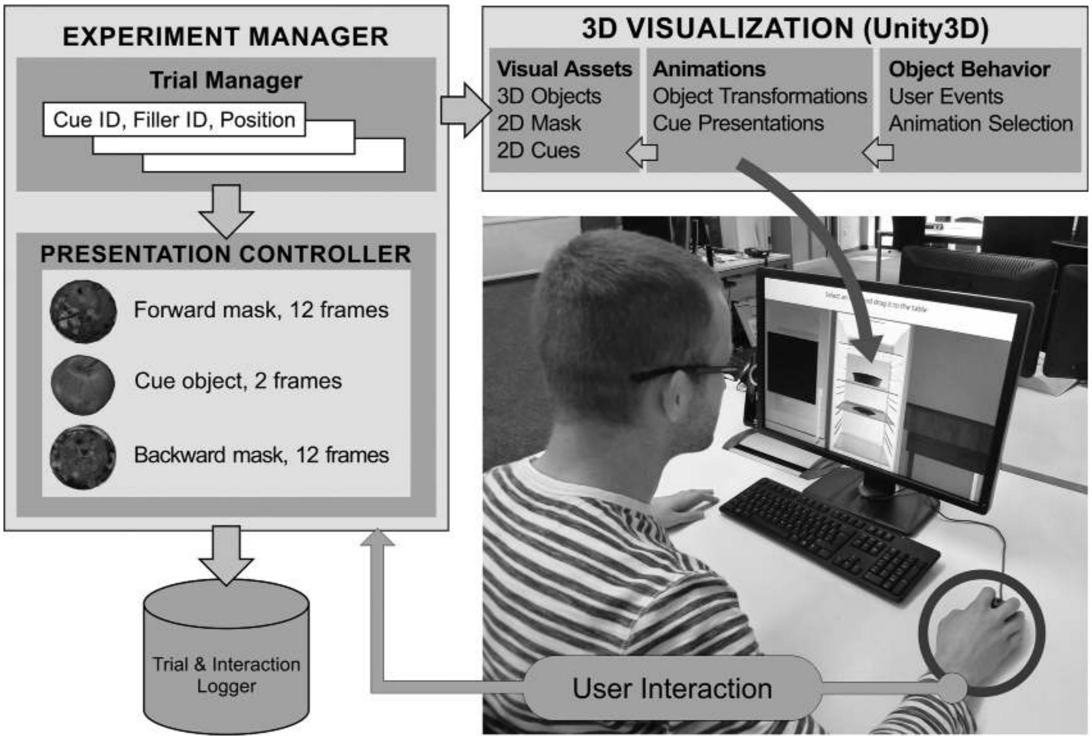


Figure 4. *An overview of the experimental system implemented in Unity3D.*

ms. We used IBM SPSS Statistics Version 20 software for all statistical analyses. Examples of experimental stimuli are presented in Figure 5. F5

Ten food items were used in the study: apple, burger, cheese, fish, lemon, pear, pepper, pie, pizza, and tomato (see Appendix B). Each object was constructed as a 3D model with an average of 500 polygons and detailed using a uniquely mapped 8-bit RGB diffuse and 8-bit grayscale specular texture. Colors used in the diffuse textures were chosen from real-life photographic reference and their histogram levels were clamped so that they could be represented consistently in both RGB color and grayscale within Unity3D. We created a corresponding cue for each object with the following properties: (1) in grayscale, matched for luminosity and contrast across cues, (2) normalized in size, and (3) displayed from an angle so that it appeared roughly circular (see Figure 5a). The cues had a mean image brightness of 37% and the mean for the masks was 29%. These properties allowed for using the same masks for each target object, thereby avoiding possible confounds attributable to mask properties. The masks were created in Adobe Photoshop CS6 by overlaying the deconstructed, contrast-equalized images of the cues after using a Perlin noise mask for each cue (see Figure 5b).

2.2 Results

2.2.1 Cueing Effectiveness. Participants were explicitly instructed to select objects from the fridge that are congruent with the cued images. Success rate on the clearly-visible trials was 100% for 12 participants and between 94% and 97% for the remaining 4 participants, which indicates that they carried out the selection task according to the instructions in the masked-cueing phase. In support of Hypothesis 1, a one-sample *t*-test concluded that the overall success rate ($M = 55.28\%$, $SD = 8.17$) was significantly different from 50% expected by chance, $t_{(15)} = 2.59$, $p = .02$ (two-tailed), $r = .56$ (large[1]). The average success rate was 53.01% in the 1x

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[1] Cohen's (1988) effect-size conventions are used: .10 – small, .30 – medium, and .50 – large.

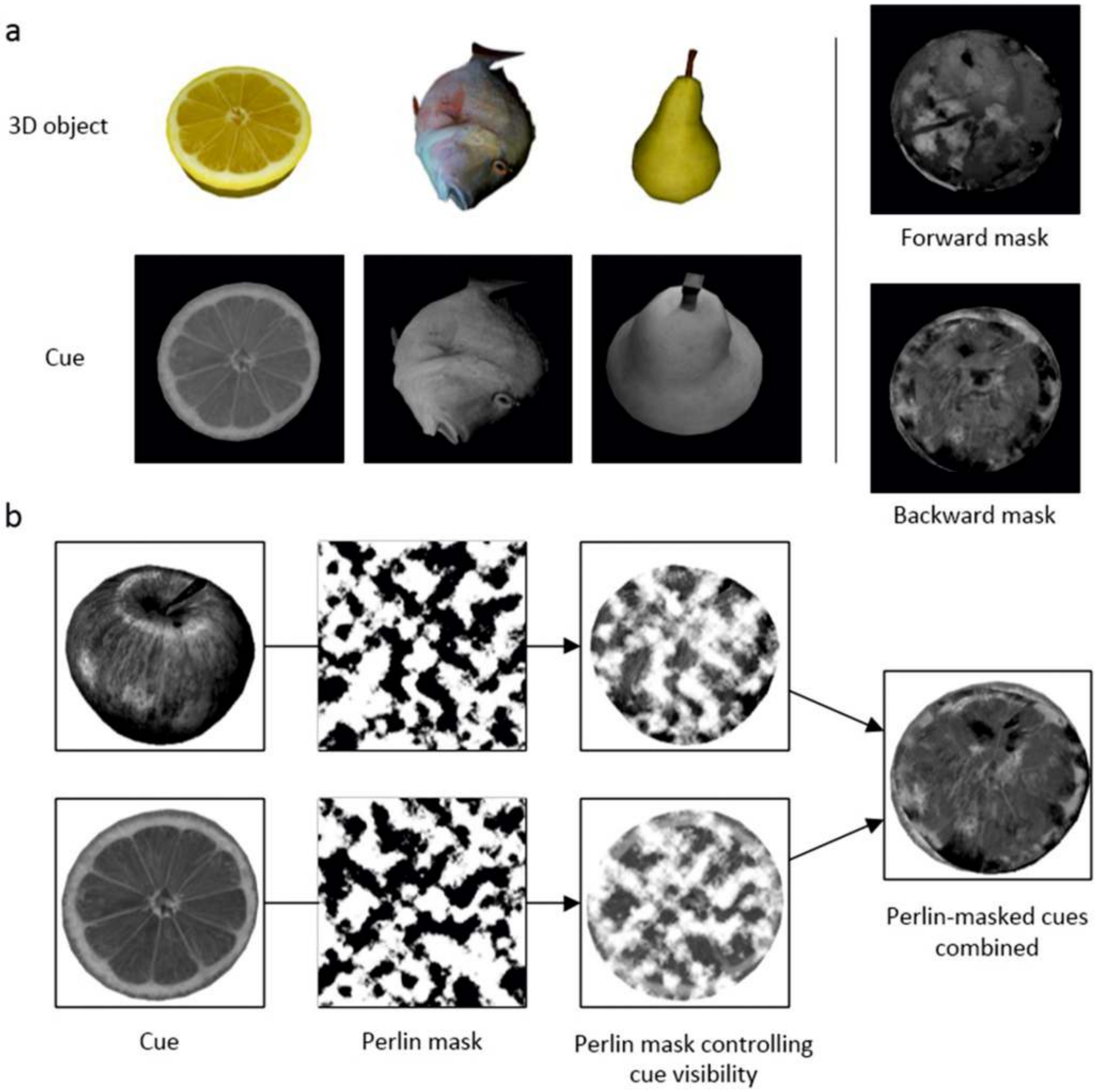

Figure 5. *Objects, cues, and masks used in the experiment. (a) Examples of 3D objects, their corresponding cueing images, and masks (see Appendix B for the full set of objects and cues). Note that the cues are in greyscale, normalized for contrast and size, and roughly circular to allow for using the same masks. The 3D objects are matched in size and rotated for presentation only. (b) An illustration of the process for creating masks with two cue images. A separate Perlin mask was used to control the alpha channel of each cue and these were combined to produce the masks. Note that the masks used in the experiment were created including cues and separate Perlin masks from four objects each.*

AQ1

condition ($SD = 7.60$), which was not significantly different from 50%, $t_{(15)} = 1.59$, $p = .13$, $r = .38$ (medium). However, the average success rate of 57.61% ($SD = 10.21$) in the 3x condition was significantly different from 50%, $t_{(15)} = 2.98$, $p < .01$, $r = .61$ (large). The within-subjects difference between the 1x and 3x conditions was significant, $t_{(15)} = 2.55$, $p = .02$, $r = .55$ (large), supporting Hypothesis 2. Additionally, while success rate in the 3x condition was normally distributed ($D_{(16)} = .17$, $p = .20$), its distribution in the 1x condition was significantly non-normal, $D_{(16)} = .30$, $p < .001$; in particular, the distribution had a significant positive skew ($z = 2.28$), which indicates a build-up of low scores. These findings indicate that multiple presentations of masked cues can increase cueing success.

In order to express the magnitude of effect in a more tangible way and on a scale that has a meaningful zero point, we expressed success rate in terms of the percentage of successful trials that are attainable above chance by dividing the percentage of successful trials attained above chance by the probability of trials attainable above chance.[2] Although the effect-size in the 1x condition indicates that even a slight increase in sample size would result in the success rate being significantly above chance level,[3] participants on average had only 6% above-chance performance. By comparison, participants had an average of 15% above-chance performance in the 3x condition.

With regards to reaction time (RT), object selection in both presentation conditions was significantly quicker in successful trials than in non-successful trials; 1x condition: mean difference between successful ($M = 1.45$ [seconds], $SD = 0.69$) and non-successful ($M = 1.57$, $SD = 0.65$) = 0.11 seconds, $t_{(1741)} = 3.53$, $p < .001$, $r = .08$ (small); 3x condition: mean difference between successful ($M = 1.43$, $SD = 1.11$) and non-successful ($M = 1.53$, $SD = 0.67$) = 0.10, $t_{(1654)} = 2.12$, $p = .034$, $r = .05$ (small). This finding can be interpreted within the diffusion decision model (Ratcliff & McKoon, 2008), where the subliminal cue provides information for a choice between the two alternatives, resulting in a faster selection decision. Furthermore, we performed a median split on the basis of reaction time by subjects in both presentation conditions to explore the relationship between success rate and reaction time. Participants had significantly higher success rates in trials where their reaction time was below median RT; 1x condition: $M_{\text{below}} = 57.83\%$ ($SD = 8.43$), $M_{\text{above}} = 48.20\%$ ($SD = 8.52$), $t_{(15)} = 5.14$, $p < .001$; 3x condition: $M_{\text{below}} = 61.83\%$ ($SD = 13.20$), $M_{\text{above}} = 54.38\%$ ($SD = 11.11$), $t_{(15)} = 2.49$, $p = .03$.

Although the observed overall cueing effect was statistically significant, its magnitude was not large enough for practical interface applications. However, research indicates that the effect of masked cues can degrade very quickly with time, and cueing effects can decrease substantially if the subliminal cues are not acted upon in the first second or so (Dupoux, Gardelle, & Kouider, 2008; Greenwald et al., 1996; Kouider & Dehaene, 2007). Therefore, we used the collected reaction–time data to refine the analysis of cueing effectiveness. First, we considered only those trials where participants selected an object within one second following the end of cue presentation. The resulting improvement in success rate was substantial and statistically significant. In the 1x condition (222 trials with RT $\leq$ 1 second), success rate improved by 13.05% ($M = 66.06$, $SD = 19.70$), $t_{(13)} = 3.051$, $p = .009$, which represents 32% of trials attained above chance and a large effect size ($r = .65$). In the 3x condition (278 trials with RT $\leq$ 1 second), success rate improved by 12.07% ($M = 69.68$, $SD = 13.68$), $t_{(14)} = 5.57$, $p < .001$, which represents 39% of trials attained above chance and a large effect size ($r = .83$). Additionally, success rate was no longer significantly different between the 1x and 3x conditions when only RT $\leq$ 1 second trials were considered, $t_{(13)} = 0.52$, $p = .61$.

In order to further explore differences in success rate due to reaction time to trials and presentation version, we grouped trials according to reaction time into three categories (within one second, between one and two seconds, and more than two seconds), and performed a two-way within-subjects ANOVA (see Figure 6). There was a significant main effect of reaction time, $F_{(2,\,26)} = 14.45$, $p < .001$, but there was no significant main effect

F6

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[2] $(P_{\text{successful}} - P_{\text{chance}}) / (1 - P_{\text{chance}})$

[3] In fact, due to the directional hypothesis, using one-tailed significance is justified, which is $p = .07$ with the current $N = 16$ sample size. However, we report two-tailed p values to minimize Type I error.

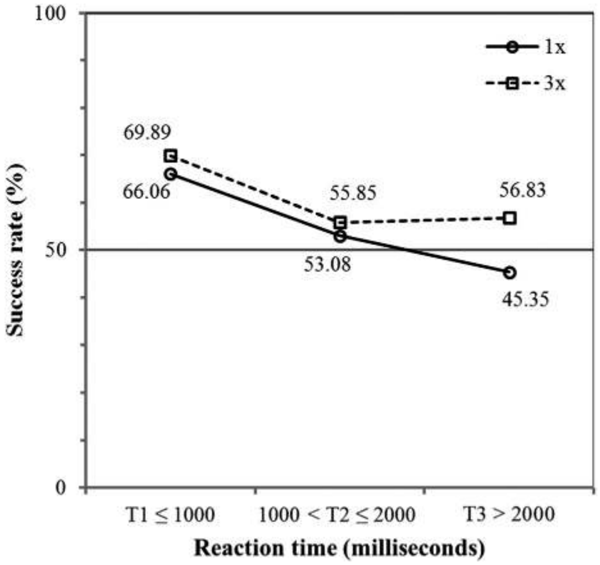

Figure 6. *The relationship between reaction time and success rate across cue-presentation conditions. Note that success rate is significantly above chance level at T1 in both conditions, and at T2 in the 3x condition. Fourteen out of 16 participants had trials at T1 in both conditions, and the number of trials was 500 at T1 (1x = 222; 3x = 278), 2410 at T2 (1x = 1260; 3x = 1150), and 489 at T3 (1x = 261; 3x = 228), which indicate an adequate sample size both in terms of participants and trials at each point in the analysis.*

of presentation condition ($F_{(1,\,13)} = 2.31$, $p = .15$) and there was no interaction effect ($F_{(2,\,26)} = 0.55$, $p = .59$). As presented earlier, success rate was significantly different from chance level when only trials within one second reaction time were considered. For trials with between one and two seconds reaction time, success rate was significantly better than chance in the 3x condition ($t_{(15)} = 2.16$, $p = .05$), but not in the 1x condition ($t_{(15)} = 1.30$, $p = .21$). Finally, success rate was not significantly different from chance level in either condition when only trials with more than two seconds reaction time were considered (1x: $t_{(15)} = -0.93$, $p = .37$; 3x: $t_{(15)} = 1.31$, $p = .21$). These findings have significant implications for interface design by indicating the importance of the temporal positioning of subliminal cues close to subsequent user action.

2.2.2 Cue Visibility. A genuinely subliminal cueing effect cannot be asserted without assessing the visibility of cues. We included 120 visibility trials in the experimental protocol (60 for each presentation condition) to assess the objective visibility of masked cues. Using signal–detection theory (Macmillan & Creelman, 2004), the hit rate and false-alarm rate were used to calculate the d' sensitivity index (Stanislaw & Todorov, 1999). Although several participants had close to zero d' and the average d' was low in magnitude, objective visibility was significantly nonzero in both conditions; 1x condition: average $d' = .45$ ($SD = .38$), $t_{(15)} = 4.69$, $p < .001$; 3x condition: average $d' = .59$ ($SD = .53$), $t_{(15)} = 4.46$, $p < .001$. These findings suggest that participants may have seen the cues, but only in a few trials, while they did not see the cues in the majority of trials. Objective visibility was not significantly different between the two presentation conditions, $t_{(15)} = 1.40$, $p = .19$, which indicates that although the multiple presentation of masked-cues improved success rate, the improvement was not due to increased cue visibility.

We regressed objective visibility onto a measure of above-chance performance (see Footnote 2 for its calculation) and extrapolated the regression line to the objective threshold of null sensitivity ($d' = 0$) to infer implicit perception (Greenwald, Klinger, & Schuh, 1995). According to this approach, a statistically significant intercept is considered evidence for the presence of a cueing effect in the absence of cue visibility. The value of the intercept was zero in both conditions, which indicates that above-chance performance cannot be attributed to a subliminal cueing effect. However, the method of extrapolating to null sensitivity may be too strict or even inappropriate, for example, when the assumptions of linearity and homoscedasticity are violated (see Hannula, Simons, & Cohen, 2005). Although objective visibility was correlated to success rate in the 3x condition ($r = .70$, $p < .01$), the correlation was nonsignificant in the 1x condition ($r = .34$, $p = .19$), and the distribution funneled out when plotting the residuals against predicted values in the regression, indicating heteroscedasticity[4] (see Field, 2009). Therefore, we also calculated a

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[4] Heteroscedasticity indicates that the prediction accuracy of the regression model is inconsistent across different levels of the predictor, which in the present case invalidates extrapolation to the zero value on the predictor.

Table 1. *Descriptive Statistics of Pooled Trials*

	Presentation condition		
Success	1x	3x	Clearly visible
Match	924 (52.8%)	953 (57.5%)	394 (98.7%)
No match	822 (47.2%)	703 (42.5%)	5 (1.3%)
Total	1743 (45.9%)	1656 (43.6%)	399 (10.5%)

NOTE. Percentages in the final row are cumulative across conditions.

less strict measure for objective visibility by testing the difference of the hit rate from chance level in the visibility trials. The hit rate was not significantly different from the 50% level expected by chance (1x: $M = .45$, $SD = .18$, $t_{(15)} = -1.13$, $p = .28$; 3x: $M = .52$, $SD = .22$, $t_{(15)} = 0.33$, $p = .75$). Based on this less strict measure, we can assume the presence of a subliminal cueing effect.

Furthermore, we collected subjective-visibility ratings from each participant on a single-item Likert scale (1 to 7). Subjective visibility received rather low ratings ($M = 2.69$, $SD = 0.95$, Mode = 2) and it was uncorrelated to objective visibility (1x: $r = .30$, $p = .26$; 3x: $r = .10$, $p = .71$). These findings indicate that although the cues had some objective visibility, they were subjectively rated as very hard to see and that this limited visibility had been associated only with the higher success rate in the 3x condition.

2.2.3 Cueing Effectiveness across Objects and Participants. We pooled the trials across participants to explore the determinants of trial success on a large sample of trials. A total of 3798 trials were completed by the 16 participants (see Table 1). Trial success in the clearly-visible condition was 98.7%, which indicates that participants carried out the selection task according to the instructions in the masked-cueing phase. These trials are not analyzed further.

We conducted a binary logistic regression analysis to predict the probability of trial success from the following categorical variables: presentation version (1x or 3x), cued object ID (10 food items), filler object ID (10 food items), and target object location (top or bottom shelf). The model was a good fit, $\chi^2_{(20)} = 763.41$, $p < .001$; $R^2 = .20$ (Cox & Snell), .27 (Nagelkerke).[5] The prediction accuracy of 55.1% (no model) was increased to 70.5%. Each variable had a significant contribution to the model. The model is summarized in Table 2. Note that, for brevity, only the significant categories within the predictors are presented in Table 2, and the effect of target location has been removed for its low effect size and lack of substantive importance (odds ratio top/bottom = 1.19 [1.02; 1.39]). Apple was used as a reference object for expressing effect sizes, because this object had the lowest objective-visibility rating pooled across participants, and the 48% overall success rate for apple was close to chance.

The odds of trial success were 1.31 times higher in the 3x condition than in the 1x condition. The odds of trial success was 3.26 times higher if cheese was the target object than the odds when apple was the target, 5.64 times higher if pie, 2.47 if pizza, and 1.99 if lemon, while the odds of trial success were higher when apple was the target object as opposed to fish (2.70 [1/0.37]) and pepper (2.04 [1/0.49]). As presented before when discussing cue visibility, the moderate correlation between d' and success rate (3x: $r = .70$, $p < .01$; 1x: $r = .34$, *ns*) indicates that higher objective visibility alone cannot account for the differences in odds between the objects.

The significant effect of the type of filler (i.e., not-cued) object on trial success indicates that participants were also influenced by what was *not* cued in a trial.[6] For example, if a participant received a filler object that had a relatively highly visible cue associated with it, he/she could select the correct object by elimination, without actually seeing the cue of the target object. Furthermore, note that the odds of trial success were lower if pie or pizza was the filler object than if the filler was apple, while the odds of trial success were significantly higher if pie or pizza was the target, which suggests that participants had a preference for selecting these objects, regardless of the cue. This may be explained by the relatively

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[5] See Field (2009) for a detailed description of measures of goodness of fit in logistic regression.

[6] However, the identity of the cued object was a much better predictor of trial success; while cued-object ID increased prediction accuracy of the outcome by 10.2%, filler ID increased it by only 5.3%.

Table 2. *Significant Predictors of Trial Success*

Variable	Category	B (SE)	Odds ratio	95% CI
Presentation condition		***2.71 (.08)	1.31	[1.13; 1.53]
Cued object[a]	Cheese	***1.18 (.18)	3.26	[2.31; 4.59]
	Fish	***−0.98 (.18)	0.37	[0.26; 0.53]
	Pepper	***−0.71 (.17)	0.49	[0.35; 0.69]
	Pie	***1.73 (.20)	5.64	[3.83; 8.30]
	Pizza	***0.91 (.17)	2.47	[1.76; 3.47]
	Lemon	***0.69 (.17)	1.99	[1.42; 2.79]
Filler object[a]	Fish	***1.27 (.19)	3.58	[2.45; 5.22]
	Pear	**0.51 (.17)	1.66	[1.19; 2.32]
	Pepper	***0.86 (.18)	2.36	[1.67; 3.34]
	Pie	***−1.09 (.17)	0.34	[0.24; 0.47]
	Pizza	***−0.87 (.17)	0.42	[0.30; 0.58]

[a] Reference category: apple.

**$p < .01$. ***$p < .001$.

strong visual resemblance between the (clearly-visible) masks and these objects (see Figure 5 for the masks). However, the selection of other objects was apparently not affected by their visual similarity to the masks.

In order to test the effect of individual differences between participants on the observed cueing effect, we regressed participant ID (categorical predictor) onto trial success (binary outcome). Although the model was a significant fit, $\chi^2_{(15)} = 87.22$, $p < .001$, this was due to the high number of trials ($N = 3399$); participant ID improved the effectiveness of predicting the probability of trial success by only 0.9% ($R^2 = .03$ [Cox & Snell], .03 [Nagelkerke]). The odds of trial success were significantly higher for three participants than those of the reference participant (who had near-zero performance above chance). These findings indicate that although there were some participants with significantly better performance than the rest, the overall effect of individual differences was small; therefore, it was not considered further.

Finally, in order to test for a possible learning effect in the masked-cueing phase, the serial number of each trial was regressed onto trial success. The model-fit was non-significant $\chi^2_{(1)} = 0.78$, $p = .38$, *ns*, which indicates that participants did not get more successful due to practice within the masked-cueing phase. We propose that this technique of using logistic regression to express variability in cueing effectiveness due to differences in cued objects and across participants in terms of odds ratios is useful in identifying (and quantifying) objects from an object pool that may be more successfully applied for subliminal cueing, and potential high performers or outliers among subjects.

3 Discussion, Limitations, and Future Work

The main contribution of the current study is the successful application of a masked-cueing paradigm in a virtual environment to influence participants' behavior within a realistic object-selection task. Hypothesis 1 was supported: there was a significant overall cueing effect, that is, participants performed above chance level in the selection tasks. Hypothesis 2 was also supported: there was a significantly larger cueing effect when cues were exposed multiple times.

When all experimental trials were considered, participants' performance in the 1x condition (where cues were presented only once) only approached statistical significance (due to low sample size) and had a small effect size, while in the 3x condition (where cues were presented three times), their performance was significantly above chance level with medium effect size. Based on previous literature, the subliminal cueing effect was expected to degrade quickly. We therefore used reaction–time data to further explore priming effectiveness. When we considered only trials where participants selected an object within one second following the end of cue presentation, success rate was significantly above chance level with a large effect size in both cue-presentation conditions. Furthermore, when trials with reaction times within only one second were considered, the advantage of presenting cues multiple times disappeared. A possible interpretation is that presenting cues multiple times helps to prolong the quickly fading cueing effect. However, we did not control for the differences in sequence duration between the two conditions. Given the role of temporal attention in priming effects (Naccache et al., 2002), this could have had an influence on the results. Participants may have paid more attention to masked cues later in the sequence, leading to a larger cueing effect without a significant influence on awareness. Yet, it should be noted that our interface has been designed to guide users' attention in both conditions.

We ensured users' temporal and spatial attention to the cues by presenting them in a fixed area on the screen immediately after participants clicked the center of this area; dragging the mouse to the center of the fixation cross required them to look there, and clicking ensured that they knew when to expect the prime. A fixed presentation area allowed for a high level of experimental control and served to avoid the need to include cueing location as an independent variable, which would have led to a substantially more complex experimental design. Additionally, using a fixed presentation area may also increase the applicability of results obtained in a VE to interface design for real-world appliances, such as the fridge in our experiment. However, there are ways to avoid the need for a fixed interaction area to present subliminal indices in HCI. One way would be to monitor users' gaze behavior using eye-tracking technology to drive the flexible placement of subliminal indices. Another way would be to utilize the movement and input from a pointing device (e.g., mouse or gesture control) to the same purpose. Future research could make use of feedback from user behavior to ensure that the placement of subliminal indices coincide with users' temporal and spatial attention.

An important implication of a short-lived cueing effect for interface design is that the subliminal effect can be substantially increased by positioning subliminal cues close to subsequent user action (or implicit input collected by the system), preferably within one second in time. However, if this is not possible, multiple presentations of subliminal cues may prolong or otherwise increase the cueing effect, without significantly increasing cue visibility. Obviously, this assumes inferring impending user action from real-time user behavior. When no user action is forecasted, the implication is that subliminal cueing is expected to have a substantial influence on user behavior for a short time only, with a rapidly decreasing magnitude of effect.

The use of a planning system, for example, could play a key role in determining critical points for influencing users during interaction. This is supported by previous work that has demonstrated an effective exploitation of shared context between deliberative factors, such as the importance of the current decision within the task, and a reactive context, which includes how susceptible the user might be in a particular configuration and indications of impending user action from low-level behaviors or implicit signals (Pizzi et al., 2012). The present findings suggest that subliminal cues cannot be expected to provide an exact communication with the user; instead, they can provide a less obtrusive and suggestive communication mechanism for guiding the user with less important decisions. For example, subliminal cues could be used when early choices may save some resources, or in suggesting actions that could enhance the users' interaction; specifically, in situations that are not critical in completing a task.

With regards to the subliminal nature of cueing within the current study, we closely examined the objective visibility of the stimuli in the applied presentation paradigm. In particular, we included a large number of cue-visibility trials for both cue-presentation conditions separately and applied signal–detection theory to assess objective visibility while also assessing overall subjective visibility. Although the d' measure of objective visibility was significantly nonzero, it was low in magnitude, which suggests that participants had seen the cues a few times, but the cues remained invisible in the majority of trials. Furthermore, the hit rate in the cue-visibility trials was not significantly different from chance level. It is also worth noting that participants knew to look for the cues they had been familiarized with in the clearly-visible trials, on a particular area of the screen, right after they initiated cue presentation by clicking on the presentation area, and they were expressing conscious effort to identify the cues. Therefore, it is expected that the cues would go mostly undetected under more natural conditions.

Although we could not demonstrate a subliminal effect using the strict criterion of regressing cueing effect to zero visibility, our sample size was low for a regression analysis with stable parameter estimates, there was no significant linear relationship between objective visibility and the cueing effect in the 1x condition, and the assumption of homoscedasticity was also violated. However, the nearly perfect (99%) mean success rate on the clearly-visible trials, as opposed to the substantially lower (55%) mean success rate on short-exposure cueing trials, the moderate correlation between d' and success rate, and low subjective visibility together indicate that objective visibility alone cannot account for participants' performance. In other words, we would have expected a much larger observed cueing effect if the cues were clearly visible. For example, Participant 4 had the largest d' value in our data, while he/she performed exactly at chance level in the 1x condition and performed perfectly on the clearly-visible trials at the same time. Therefore, we can conclude that the cues were not clearly visible and, using the softer criterion of hit-rate probability, there was a subliminal cueing effect.

It is worth noting that we used an identification task in the visibility phase as a measure of awareness. Although detection measures are more sensitive in general, we argue that identification was the appropriate measure in the present context, because the identity of the cues is informative to the successive selection task, while the perceived presence or absence of the cues alone is not (Vermeiren & Cleeremans, 2012). This raises the question whether performance on the main task could be explained by partial awareness of the cues (see Kouider & Dupoux, 2004; Kouider, Gardelle, Sackur, & Dupoux, 2010), undetected by a visibility protocol that requires identification of objects as a whole. Our extensive analysis of the influence of cue identity on selection behavior revealed that participants may have been able to exploit differences and similarities between cues in terms of low-level features. Crucially, participants were unable to reconstruct object identity based on these features, despite thorough familiarity with the limited amount of choices available. We used a restricted set of 10 objects and our participants knew exactly what these objects were from the clearly visible trials. They could thus have used any clearly visible property of the cues for identification just as well as for discrimination. Neither success rate on the main task, nor the results from the visibility test, suggest that this was the case. If the cueing effect had been due to partial awareness, success rate would not have been expected to drop after the first second.

There are two key implications of our cue-visibility results for future research. First, future studies could aim at increasing cueing duration and masking effectiveness at the same time, thereby promoting a more robust cueing effect and preventing cues from reaching sufficient activation for conscious processing. Additionally, when analyzing the difference in cueing effectiveness between the objects, we found that particular objects' similarity to the masks may influence target selection, which further illustrates the importance of expending extra effort in mask development. Second, subjective visibility could be assessed separately for each object in future research. Note that although a rigorous testing of objective visibility is required when making claims for subliminal effects in a laboratory context, this may not be necessary in the case of practical application. For example, partially visible but effective cues may be preferable over completely invisible and ineffective cues in an applied context, where the emphasis is on influencing behavior without substantially increasing cognitive load (Riener et al., 2011). This departure from a strict visibility constraint can be accepted, as we have already established the effect of subliminal cues in research that incorporated rigorous visibility testing. Additionally, it could be counterproductive to include a thorough visibility protocol in a practical application, as it could interfere with the task at hand.

An additional contribution of the present work is that rather than just detecting the proposed effects, we took a step further to quantify the magnitude of these effects at each step using a wealth of metrics, such as variance explained by effect, percentage correct, percentage correct within above-chance trials, and odds ratios. Furthermore, we conducted additional analyses to break down the detected cueing effect to its significant determinants, such as reaction time, differences in cued objects and filler objects, and differences across participants. Although these differences can be expressed in simpler ways within the sample, for example, by listing standardized scores for each object and subject and looking for extreme values (usually $-2 \geq z \geq 2$), expressing effect size in terms of odds ratios with associated confidence intervals provides a more tangible interpretation about the expected magnitude of effect in the population. Additionally, these more detailed analyses allow for a deeper interpretation of the available data, such as strategies used by participants for object selection (e.g., using a target's similarity to the mask as a decision criterion).

Limitations of the current study include task properties, sample of objects and subjects, and type of subliminal cueing. The forced-choice object selection task we applied was realistic in the present context, but it was necessarily simplified for the needs of the research. Future research needs to establish the extent to which our findings can be applied to more complex tasks and other contexts. Similarly, we limited the number of objects (food items) in the current study for practical considerations (e.g., including more objects would have increased the required number of trials, putting an increased load on participants). Although the sample size was sufficient to answer our research questions, a larger sample in general would benefit analysis (e.g., appropriate sample size for regression to extrapolate success rate to null visibility) and promote the exploration of differences across individuals, in particular, identifying those especially sensitive to subliminal cueing.

4 Conclusion

In conclusion, the experiment presented in this paper demonstrated significant cueing effect of subliminal cues within a realistic task in a virtual environment, using a masked-cueing paradigm, where the cueing effect was especially pronounced when participants responded within one second. Our findings support the feasibility of including subliminal cues to influence interaction with 3D virtual objects and provide insight into the properties of the processes involved, with implications for practical application and future research. This work has several implications in terms of designing user interfaces that incorporate subliminal cueing. The first one is that, to incorporate subliminal cueing, the attention of the user should be focused prior to the stimulus, and the system should be compatible with a user response < 1000 ms. This suggests the use of intelligent interfaces that can track the user context to determine the most appropriate timing for subliminal cueing (Pizzi et al., 2012). Another implication derives from the actual magnitude of the observed effect. In order to support realistic applications, it is necessary to leverage the choice effect. This can be achieved in systems where specific states are associated with a nontrivial level of perplexity, or where the user has an option for repeated choice (Pizzi et al., 2012).

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