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# Subliminal Response Priming in Mixed Reality: The Ecological Validity of a Classic Paradigm of Perception

## Abstract

Subliminal stimuli can affect perception, decision-making, and action without being accessible to conscious awareness. Most evidence supporting this notion has been obtained in highly controlled laboratory conditions. Hence, its generalization to more realistic and ecologically valid contexts is unclear. Here, we investigate the impact of subliminal cues in an immersive navigation task using the so-called eXperience Induction Machine (XIM), a human accessible mixed-reality system. Subjects were asked to navigate through a maze at high speed. At irregular intervals, one group of subjects was exposed to subliminal aversive stimuli using the masking paradigm. We hypothesized that these stimuli would bias decision-making. Indeed, our results confirm this hypothesis and indicate that a subliminal channel of interaction exists between the user and the XIM. These results are relevant in our understanding of the bandwidth of communication that can be established between humans and their physical and social environment, thus opening up to new and powerful methods to interface humans and artefacts.

## 1 Introduction

Subliminal stimuli can influence a wide range of behaviors, including motor responses (Schmidt, Niehaus, & Nagel, 2006), free and forced-choice between two alternatives (Eimer & Schlaghecken, 2003; Kiesel, Wagener, Kunde, Hoffmann, Fallgatter, & Stöcker, 2006), object identification (Bar & Biederman, 1998), lexical and numerical discrimination (Kunde, Kiesel, & Hoffman, 2003; Naccache & Dehaene, 2001; Damian, 2001), and esthetical preference (Zajonc, 2001).

Traditionally, as in most of experimental psychology, experiments on subliminal perception have been constrained to very rigid and controlled laboratory conditions (Boag, 2008). Hence, the generalization of this myriad of results to the real world and to ecologically valid conditions remains unclear. To address this challenge, we deploy mixed reality technologies that have been purposefully built to investigate human behavior and experience under controlled yet realistic conditions (Bernardet et al., 2010). We use this approach to investigate the

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bias of subliminal cues on decision-making in an immersive maze navigation task following the priming paradigm.

Subliminal priming allows for the controlled assessment of the coupling between the conscious and unconscious processes (Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006; Greenwald, Klinger, & Schuh, 1995). The response priming paradigm has been successfully employed in the studies on subliminal perception (Eimer & Schlaghecken, 2003; Kiesel, Kunde, & Hoffman, 2007; Schmidt, Haberkamp, & Schmidt, 2011). In the priming paradigm, subjects are asked to respond to two stimuli perceived in quick succession. The first stimulus is the prime that has been made unavailable to conscious awareness and the second stimulus is the target. The priming effect can be defined as the facilitation or inhibition of an acquired response to the target stimulus, depending on the target relation with the prime (Mattler & Palmer, 2012; Schlaghecken, Klapp, & Maylor, 2009; Eimer & Schlaghecken, 2003). By introducing the supraliminal targets, we are developing stimulus–response associations that could be activated at the unconscious level, when the participants are exposed to the subliminal primes (Damian, 2001). Bimanual input method is used to assure each stimulus has a distinct response assigned to it. The question whether subliminal priming effects depend on consciously learned stimulus–response mappings, or originate from unconscious semantic processing, is currently debated (Kiesel, Kunde, Pohl, & Hoffmann, 2006).

In order to argue that priming effects have been induced unconsciously, a stimulus has to be both presented in the visual field of the subject and remain inaccessible for conscious identification (Holender, 1986). Backward-masking and metacontrast masking (Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003) methods have been successfully validated in achieving this requirement, by showing the stimulus for a very short time ($t < 50$ milliseconds) and disrupting its presentation using a mask. The mask constitutes a visual pattern or noise designed to disrupt the retinal afterimage and is presented shortly after the onset of the prime, e.g., $\sim$50 ms (Scharlau, Ansorge, & Breitmeyer, 2006). Even though subliminal priming effects have been observed in a number of past studies (see Kouider & Dehaene, 2007 for a review), their impact on behavior is usually small and accounts for only a small, but still significant, deviation from control conditions, i.e., the absence of the subliminal prime. The behavioral impact of unconscious perception, measured as subliminal effects, depends on a number of factors including the active goal pursued by the subject (Bargh & Morsella, 2008), conscious expectations (Kunde et al., 2003), and sensory-motor learning (Schmidt et al., 2006; Hommel et al., 2001).

In the interaction with their physical and social environment, humans employ a wide range of conscious and unconscious processes; i.e., meaningful interaction with the environment requires the involvement of unconscious processes for anticipation and simulation (Hesslow, 2002; Mathews & Verschure, 2011). One more extreme view proposes that all of our actions are under the exclusive control of unconscious processes (Wegner, 2003). If there is such a significant role to be played by unconscious information processing, this creates new possibilities for constructing interfaces between humans and machines. Indeed, such an approach has been proposed to address the problem created by so-called big data where, by using both conscious and unconscious processes, we can expand the bandwidth of information exchange between humans and complex data sets through the technology that mediates between them (Verschure, 2011). As a first step toward such a system, it is necessary to understand whether artefacts can effectively communicate with unconscious processes through subliminal cues. It is exactly this question that we address here. In order to assess the interaction between unconscious and conscious processing in the context of action, we conducted an experiment in the eXperience Induction Machine (XIM), a unique immersive space constructed to measure and control human behavior in ecologically valid conditions (Bernardet et al., 2010).

To address the traditional limitations of subliminal priming research and to elevate this classical paradigm to the challenges of real-world interaction, we developed an application that uses ecologically salient stimuli in a real-time active and immersive navigation task. The objective of the task is to reach specific targets, while making as few navigation errors as possible. Behaviors relevant for goal achievement are binary navigation decisions, e.g., following or leaving the current path at discrete decision points. Each navigation choice is followed by explicit reinforcement combining operant conditioning methods with subliminal priming paradigm (Baum, 1969; Mowrer & Lamoreaux, 1946). Feedback is used as a tool to reinforce learning of stimulus–response contingencies on both conscious (in fixed-choice trials) and unconscious (in free-choice trials) level (Hommel, Müsseler, Aschersleben, & Prinz, 2001; Kiesel et al., 2006; Damian, 2001). Our experimental design thus allows us to systematically present subliminal stimuli in the context of ongoing behavior in order to investigate unconscious perceptual processes and their impact on decision-making.

Conducting experimental studies on ecologically valid behavior in VE is attainable only if the participants acquire a sense of presence, i.e., experience and behave in a natural and unmediated mode. Presence is defined by some as the sense of "being there" or a successful relocation of consciousness from the real world to the VE through immersion (Sanchez-Vives & Slater, 2005). However, what is missing is a clear and coherent theoretical view of how this "sense" is generated and it is not uncommon to see it explained with the notion of "the suspension of disbelief" coined by the early 19th-century poet and philosopher, Coleridge. Since the inception of the field in the early 80s, a large research effort in this area has focused on establishing the constraints governing the emergence of presence in virtual environments. Here we follow the view, going back to the psychologist Helmholtz, that perception depends on inference and that it is the consistency between perceptual predictions and action-dependent forward models and the real world that defines presence (Wyss, König, & Verschure, 2006; Bernardet et al., 2010; Verschure, 2011). The idea that the information processing of the brain is organized around prediction has reached prominence in the so-called "Bayesian Brain" or "predictive coding" frameworks (Bar, 2007; Barsalou, 2008; Clark, 2013; Friston, 2005; Verschure & Althaus, 2003). In this view, the brain systems are engaged in forms of hierarchical Bayesian inference, extracting generative models of both sensory inputs and the consequences of action, across multiple time scales and modalities (Cisek & Kalaska, 2010; Hesslow, 2002; Lau & Rosenthal, 2011). In addition, following the Distributed Adaptive Control theory of mind and brain (see Verschure, 2012 for a review), we posit that the brain coordinates these predictions across states pertaining to the world, the self, and action. Hence, "presence" resides in the balance of these multimodal predictions with the exo- and endosensory states encountered.

The reported sense of presence is positively correlated with increased attention, and motivation in participants, which are crucial factors in studies on unconscious perception and unconscious goal pursuit (Sas & O'Hare, 2003; Custers & Aarts, 2010). Only in a fully immersive framework can participants continuously attend to visual stimuli, while engaging in the interaction that is based on behavioral objectives and not purely on experimental demands (Bock & Hagemann, 2010; Sas & O'Hare, 2003). For instance, studies on grasping movement show how differently participants perform when their behavior is based on explicit experimental instructions or is being performed as a natural and implicitly controlled movement (Bock & Hagemann, 2010; Bock & Züll, 2013). Unconscious mental processes, just as overt behavior, are likely to differ under in vivo and experimental conditions. In our task, it is especially important that subjects approach the goal of avoiding aversive stimuli in the context of behavioral goals, and not only experimental instructions, for the subliminal stimuli to be effective in guiding action and influencing the decision-making. We expected that an increased sense of presence, enhancing the ecological validity of the task, would lead to stronger effects of unconsciously perceived stimuli due to changes in attitude, increased attention, and motivation of the participants (Watanabe, Náñez, & Sasaki, 2001; Tzeglov, 1997; Sas & O'Hare, 2003).

Our experiment, set up in the XIM, consists of a maze built from a series of vertical Y-junctions, where participants have to choose between two alternative paths (see Figure 1). Prior to the decision point, a subliminal stimulus (i.e., a prime) is presented for 16 ms, followed by a mask. We measure whether the presence of subliminal negative stimuli, i.e., a spider, leads to significant


**Figure 1.** *The virtual reality application developed in the XIM. This screenshot shows a frame displaying a negative subliminal prime in the vertical Y-junction in the underground maze. Participants can choose whether to go forward (i.e., follow the path), or to open the "trapdoor" to go down (i.e., avoid the path). Before the participants are asked to make a choice, the subliminal stimulus containing the spider image or a neutral image, i.e., random pattern, is displayed for 16 ms.*

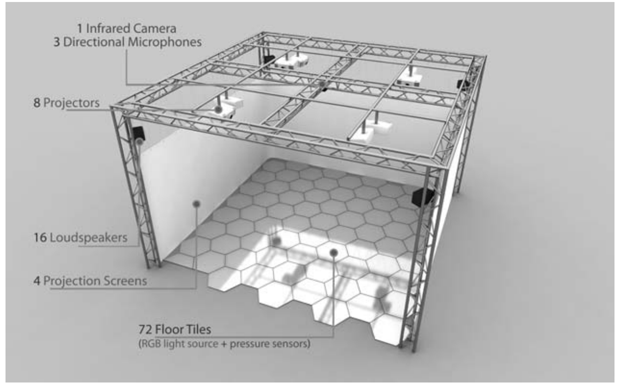


**Figure 2.** *Schematic illustration of the eXperience Induction Machine (XIM) used to conduct the experiment. The space covers an area of 5.5 by 5.5 m and is equipped with a number of effectors (8 projectors, 4 projection screens, a luminous interactive floor, and a sonification system) and sensors (marker-free, multimodal tracking system, microphones, and floor-based pressure sensors).*

changes in participants' behavior. Our hypothesis is that maze paths that are labeled with an aversive subliminal stimulus will cause the participants to modify their navigation choices and avoid those paths (see Figure 3). Our results show that participants' behavior is modulated by the exposure to the subliminal prime.

### 1.1 The eXperience Induction Machine

The XIM is an immersive space constructed to conduct empirical studies on human behavior in ecologically valid situations that involve full body interactions (Bernardet et al., 2010) (see Figure 2). It is derived from the large-scale multimodal interactive exhibition, Ada, visited by over 500,000 people (Eng et al., 2002) and has been used to study human navigation (Betella, Bueno, Bernardet, & Verschure, 2013), cooperation, and social salience (Inderbitzin, Betella, Lanatá, Scilingo, Bernardet, & Verschure, 2013), and the exploration of complex data sets (Betella, Carvalho, Sanchez-Palencia, Bernardet, & Verschure, 2012).

In this study, we used a dedicated projector with a refresh rate of 60 Hz and a resolution of 1024 by 768 px projecting on a surface of 4.5 by 3.5 m on one of the walls.

### 1.2 The Virtual Maze Application

The virtual maze application was developed using the Unity 3D engine (http://unity3d.com). Participants are required to make a choice between two alternative paths in a series of vertical Y-junctions, i.e., decision points, diverging into two parallel paths (see Figure 3). At these decision points, a stimulus sequence is displayed, starting with a fixation cross, followed by a subliminal prime, a mask, and ending with a target. Participants have to avoid the alleys ending with the spider, enter alternative paths, and collect as many golden rings as possible. While navigating through the virtual maze, participants can be exposed to three types of trials: negative fixed-choice trials, neutral fixed-choice trials, or free-choice trials. These trials differ between each other with the target stimuli displayed at the decision point. Supraliminal target stimuli inform participants how to respond. In fixed-choice trials, the target stimulus specifies the correct response, i.e., either to follow the path, or to leave it. In the free-choice trials, the target represents a question mark, instructing the participants to freely decide between the two responses. Subliminal cues (i.e., primes) are presented at each decision point, 116 ms before the targets (see Figure 9). Each alley that follows this decision point can end with either a 3D animation

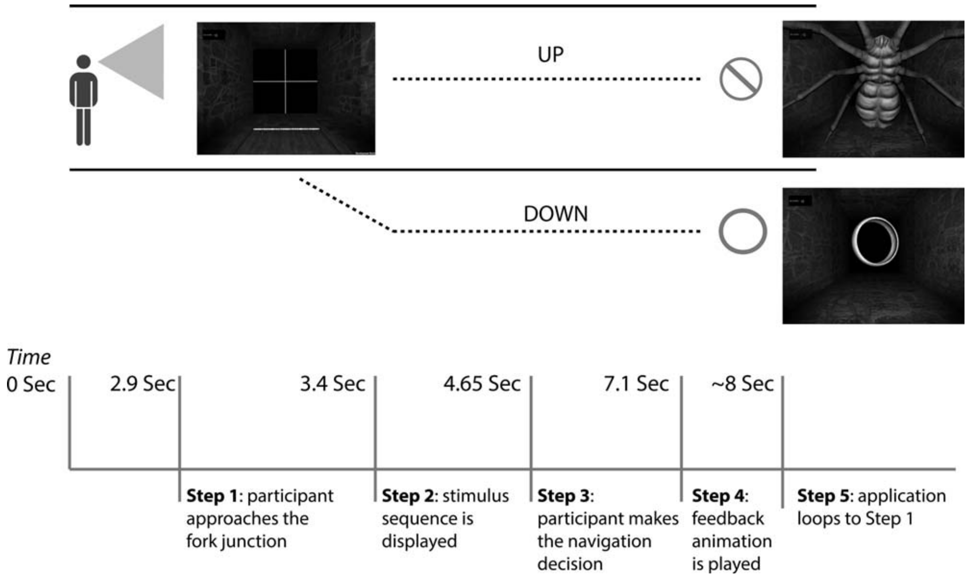


**Figure 3.** *Timeline of a single trial. Participants navigate in a maze made of a series of Y-junctions. The influence of subliminal stimuli, displayed in Step 2, is measured on their navigation decisions performed in Step 3. A single trial begins at Step 1 and ends at Step 5.*

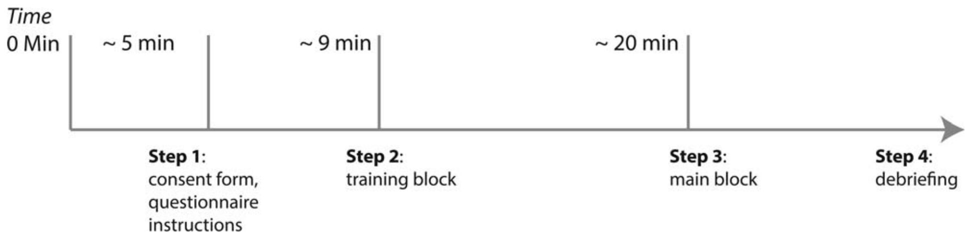


**Figure 4.** *Timeline of the experimental protocol used in Experiment 1. See text for further explanation.*

of an attacking spider (punishment) or a collectible golden ring (reward).

The experimental application consists of five main steps (see Figure 3). In the first step, the participants start at the top path and approach the Y-junction, where they see a fixation-cross displayed on a 2D texture, along with a door on the ground leading to the alternative path. In the second step, the fixation-cross disappears and a series of three visual stimuli are displayed, including the prime (see Figure 9), the mask, and the target (see Figure 10). In the third step, the participants respond, choosing one of the two alternative paths using a keyboard. In the fourth step, the feedback animation is displayed, in accordance with the alley chosen. In the fifth step, participants are relocated to the beginning of the junction to start the next trial. The animation is rendered continuously; thus, participants have a sense of moving through the maze.

## 2 Experimental Protocol

We designed two different experimental protocols, where the second experiment validates slight modifications of the protocol (see Figure 3) in terms of the organization of blocks (see Figures 4 and 6) and with respect to the stimulus sequence displayed before the decision point (see Figures 5 and 7).

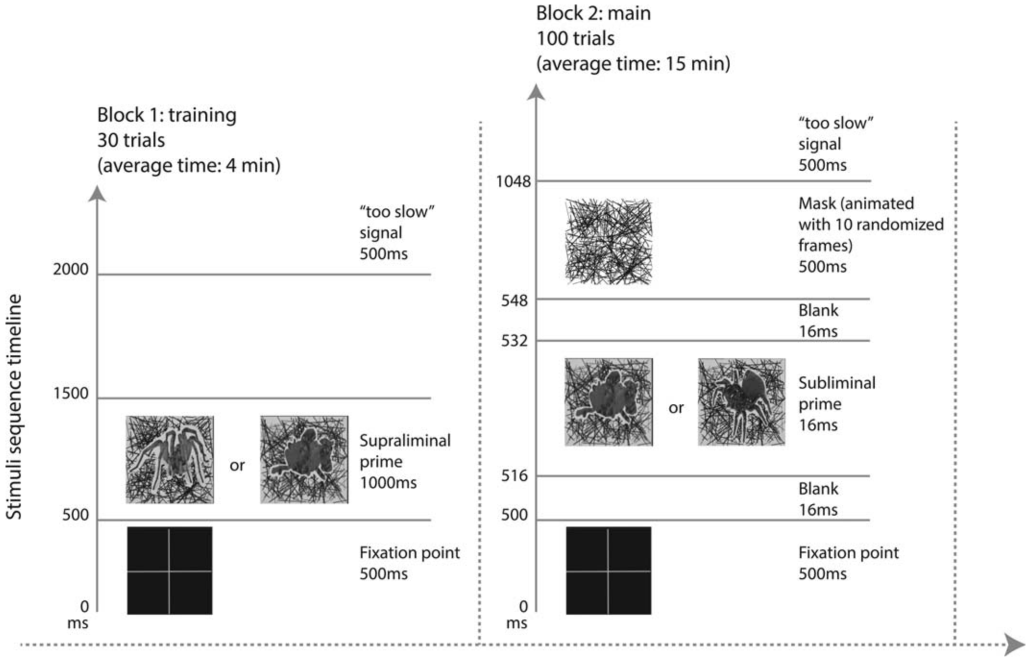


**Figure 5.** *Description of the two blocks of Experiment 1. The training block consists of uniquely supraliminal primes. The main block consists exclusively of subliminal primes, either neutral or negative. The horizontal axis represents the timeline of the experimental blocks. The vertical axes represent the timeline of the stimulus sequences displayed at each decision point.*

## 2.1 Experiment 1 Protocol

The sample consisted of 10 participants (6 women, mean age 20.8 ± 5.6 *SD*). All participants reported normal or corrected-to-normal vision. Each subject completed 30 trials in the instruction block and 100 trials in the main block (see Figure 4). The average duration of the experimental session was 20 min. Participants were seated 2.5 meters from the center projection wall. They were using a standard keyboard for the responses. Participants were instructed to press the spacebar if they wanted to switch paths and enter the lower alley (i.e., avoid the top path). Participants were informed that they had a limited time to respond: if they did not press the button in 1300 ms from the display of the mask, they would automatically go forward (i.e., follow the top path). The subliminal prime, either negative or neutral, was displayed before participants made the navigation decision. This was assured by instructing the participants to respond after the disappearance of the fixation-cross, which coincided in time with the presentation of the subliminal prime. The keyboard did not detect responses until the appearance of the subliminal prime.

Prior to the experiment, the participants were given the instructions about the task. The instructions were both presented by the experimenter and displayed on the screen. Participants started the experimental session with a training block (see Figure 5). They were asked to respond to supraliminal targets, in order to establish stimulus–response associations (Hommel, 2000). No subliminal stimuli were displayed in the training block. Following the first block, participants had to complete the main block, where they were asked to perform navigation choices (i.e., forward or down) after being exposed to subliminal primes. Each stimulus sequence ended with a mask (i.e., there was no target). Participants were instructed to respond as soon as the mask was detected. We measured the response bias, a tendency to choose the responses instructed by the subliminally presented prime, i.e., the prime compatible responses, which in our case was to avoid the aversive stimulus and switch paths.

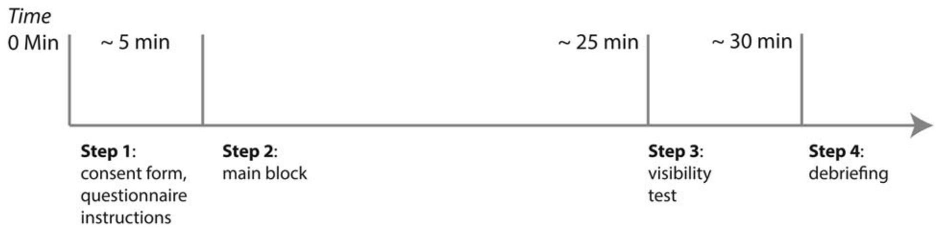


**Figure 6.** *Timeline of the experimental protocol used in Experiment 2.*

## 2.2 Experiment 2 Protocol

The main difference in respect to Experiment 1 was the introduction of supraliminal targets and fixed-choice trials that informed participants about the correct response to negative and neutral stimuli. The sample consisted of 22 participants (11 women, mean age 25.4 ± 4.4 *SD*). All participants reported normal or corrected-to-normal vision. Participants were seated 2.5 meters from the projection wall. They used a standard keyboard for their responses. The keyboard was rotated 90 degrees clockwise. White tape with arrows was placed on the top of the “w” and “o” keys, depicting arrow up and arrow down, respectively. This setup ensured a bimanual responding method, which allowed for the development of sensory-motor contingencies, i.e., assignment of stimulus–response mappings to two different hands (Kiesel et al., 2007; Schmidt et al., 2006; Hommel, 2000).

Participants were naïve, i.e., not informed about the presence of subliminal stimuli. After the instructions, the main experimental block started (see Figure 6). This block consisted of 150 trials, out of which 60 were free-choice trials, 45 were negative target-fixed trials, and 45 were neutral-target fixed trials (see Figure 7). The main block lasted approximately 20 min. After the main block, an intermediate screen was displayed, with instructions for the visibility test block. The visibility test block assessed whether the primes were genuinely subliminal.

## 2.3 Fixed and Free-Choice Trials Description

In the fixed-choice trials, the target stimulus specified the response to be performed by the participant; i.e., the navigation choice was fixed to the stimulus. Participants were instructed to press the arrow key down (i.e., to avoid the top path) when the negative target was displayed (see Figure 10, left). When the neutral target was displayed, they were instructed to press the arrow up (i.e., to follow the top path) (see Figure 10, middle).

## 2.4 Free-Choice Trials

In free-choice trials, participants were not informed about the correct path to choose; i.e., there was no response assigned to the target stimuli. The free-choice target instructed participants to freely choose between the two paths (see Figure 10, right). Response accuracy was measured as either a prime compatible or prime incompatible answer. We measured the response bias the subliminally presented image of a spider can induce, i.e., whether participants were more likely to press the arrow down following the presentation of the negative prime in order to avoid the aversive stimulus. In free-choice trials, we defined compatibility as the relation between the prime and the response.

## 2.5 Feedback

Each trial ended with a feedback animation, which was used either as a reward or as a punishment for the choice made by the participant. This procedure was used to instruct the participants how to respond correctly to supraliminal stimuli in fixed-choice trials, and to observe if the responses learned on the conscious level are also performed unconsciously. Feedback animation could be either positive or negative, depending on the response. Prime and target compatible responses were followed by a feedback animation consisting of a golden ring that the participant collected. Prime and target incompatible

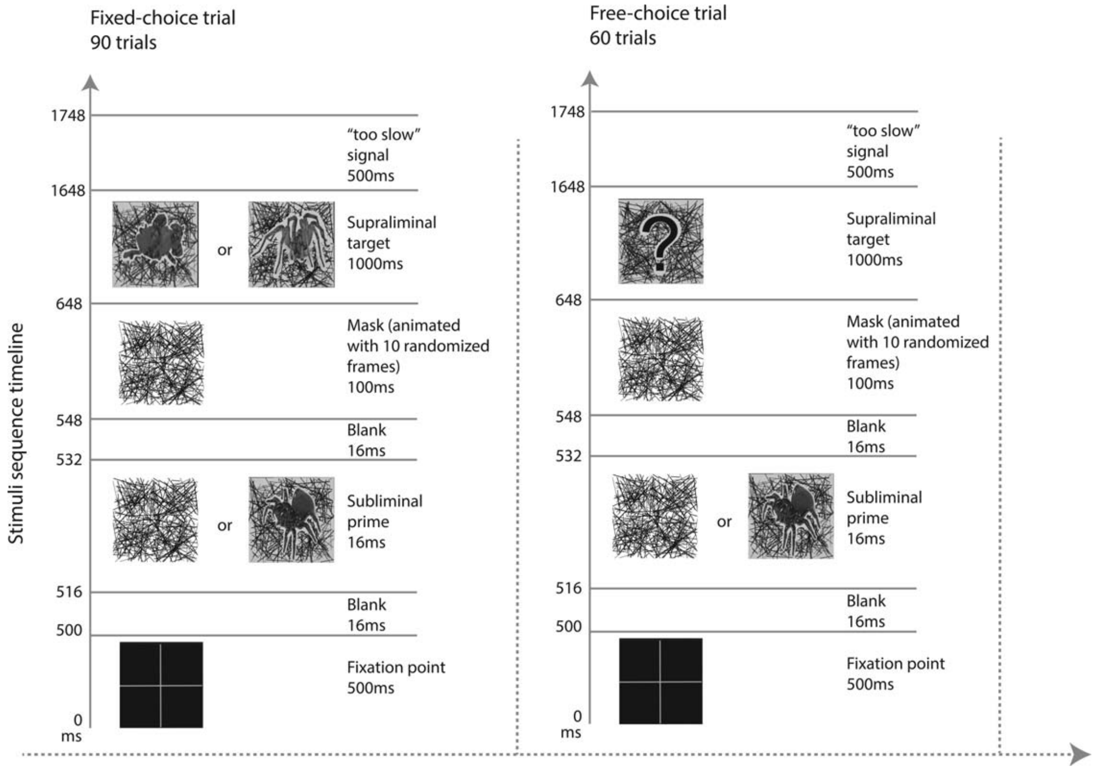


**Figure 7.** *Description of the fixed- and free-choice trials in Experiment 2. There are 150 trials in total; each trial can be either fixed- or free-choice. The order of individual trials is mixed and randomized; i.e., the trials are not separated in individual blocks. In fixed-choice trials, subjects were instructed to press the arrow down in response to the negative target and to press the arrow up in response to the neutral target. In the free-choice trials, subjects were instructed to freely decide between the two alternatives (arrow up or arrow down). The order of targets was semi-randomized; i.e., every trial could be either fixed or free with a proportion of 3/2. The type of the prime stimulus (negative or neutral) was randomized over all trials.*

**Figure 8.** *Spider image selected for the subliminal prime. (Public domain, released under the GNU free Documentation License: http://en.wikipedia.org/wiki/File:Mouse_spider.jpg.)*

responses were followed by an animated 3D spider, which appeared to be attacking the participant (see Figure 3). The participant score, displayed at the top left corner of the screen, was incremented in the former case and decreased in the latter.

In fixed-choice trials, the accuracy of the response to the target (i.e., target compatibility of the response) determined the feedback type. In free-choice trials, since the target did not specify a response, the prime compatibility of the response determined the feedback type.

### 2.6 Prime Visibility Assessment

To measure whether participants were able to identify the subliminal stimuli, we measured the prime visibility on a prime discrimination task. After the main experi-

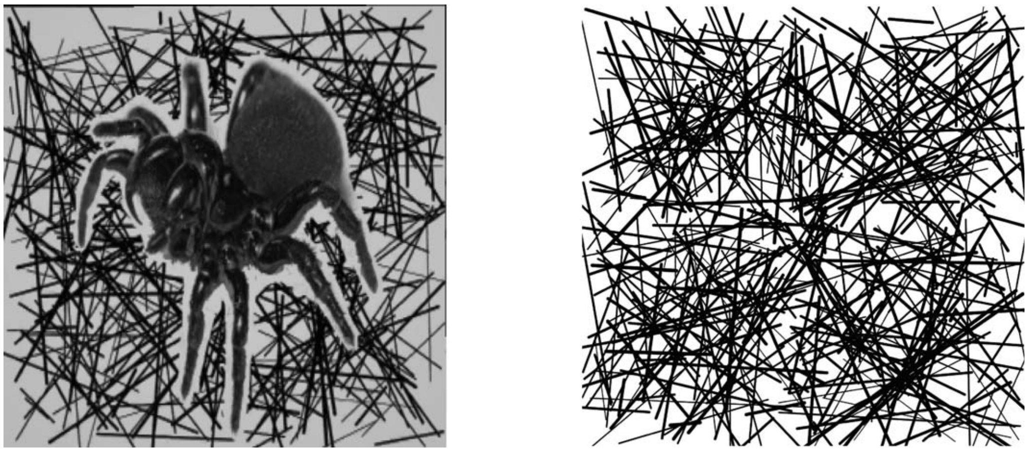

**Figure 9.** *Illustration of the subliminal stimuli displayed for 16 ms. Negative prime (left); neutral prime (right).*

mental block, each participant completed the visibility test block, which measured whether the primes were genuinely subliminal. In the visibility block, the navigation component of the task was excluded and the participants were responding to the continuously appearing stimulus sequences. The stimulus sequence did not include the target and ended with the display of the mask. Participants were asked to focus on the images and to try to detect their contents. Using the arrow keys, but with reversed mapping in comparison to the main block (i.e., arrow up assigned to the negative prime and arrow down assigned to the neutral prime), subjects indicated whether they thought they saw a spider or a random shape in the stimulus sequence.

### 2.7 Stimulus Selection

Previous studies have produced subliminal effects using images and videos of faces (Kouider, Berthet, & Faivre, 2011; Faivre, Charron, Roux, Lehericy, & Kouider, 2012), words (Greenwald et al., 1995; Marcel, 1983; Dijksterhuis & Aarts, 2010), numbers (Naccache & Dehaene, 2001), arrows (Schlaghecken et al., 2009; Schlaghecken & Eimer, 2004), animal pictures (Dell'Acqua & Grainger, 1999; Ohman & Soares, 1994), and graphical depictions of objects (Bar & Biederman, 1998). The subliminal stimulus used in this study was an image depicting a spider (see Figure 9). This selection was made in order to relate the stimulus to an ecologically salient object related to avoidance behavior, i.e., a threatening animal (Ohman & Soares, 1994). Different images were used for the prime and target stimuli, to avoid perceptual learning extending from the target to the prime.

The subliminal prime stimulus was chosen from a pool of nine pictures. The pictures were divided into three categories, each containing three pictures. The first category was composed of the pictures of spiders taken from the IAPS database (Lang, Bradeley, & Cuthbert, 2008). The second category was composed of high-resolution pictures of spiders on white backgrounds. The third category was composed of simple spider images, edited with a graphic filter to consist of contours and converted to the grayscale.

Ten subjects (4 women, mean age 26 ± 2.4 *SD*) rated the pictures indicating the "most fearful" in each category and choosing one image across all categories. The image from the second (high-resolution) category was selected as most fearful within the category by 60% of participants and as the most fearful from all the images by 40% of participants, thus obtaining the highest score on the stimuli selection questionnaire.

#### 2.7.1 Prime and Target Stimuli.

The original spider image was placed over a mask composed of random lines, to decrease the visibility of the prime against the mask background. We used the image containing the spider as the negative prime (see Figure 9, left). An image containing only random lines was used as the neu-

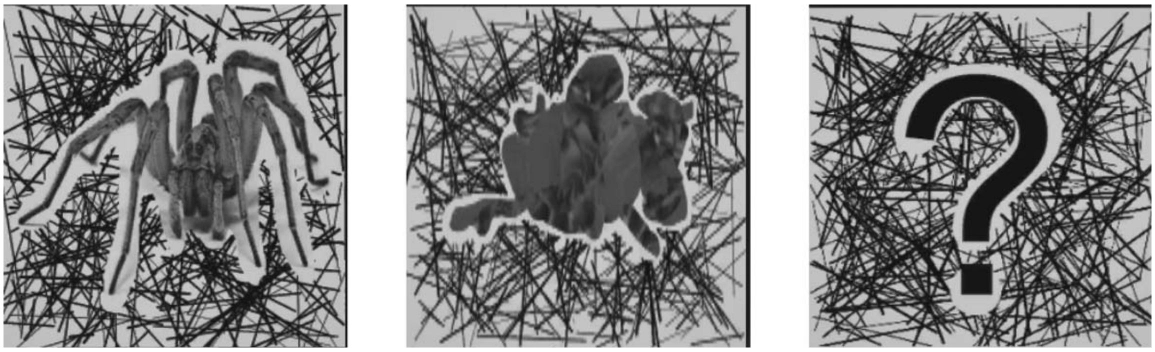

**Figure 10.** *Illustration of the supraliminal target stimuli displayed for 1000 ms. Negative target (left); neutral target (middle); free-choice target (right).*

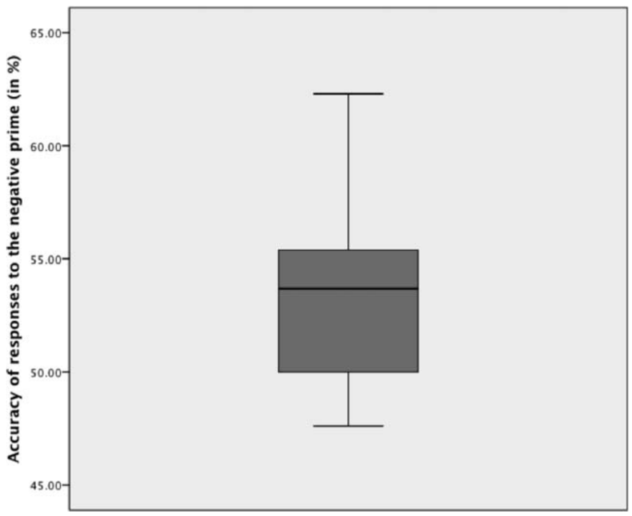


**Figure 11.** *Accuracy of responses to the negative prime. The y-axis represents the percentage of accurate answers. The 50.00 value represents the response accuracy score expected to occur in the absence of priming effects. The mean of the priming effects is 53.78%.*

tral prime (see Figure 9, right). The primes were not exposed during both experiments; i.e., the participants never saw them consciously. Participants were naïve, i.e., were not informed about the presence of the subliminal stimulus until the end of the experiment.

During the experiment, participants could see only the target stimuli. Each target stimulus was displayed in the end of the stimulus sequence, instructing the participants how to respond. There were three types of target stimuli, each instructing the participant to perform a different type of response (see Figure 10).

### 2.8 Measure of Stimuli Exposure

To ensure a high accuracy in the subliminal stimulus display time (16 ms), we synchronized the application with the refresh rate of the video projector (V-sync). The projector used for the display was running at 60 Hz; thus the stimulus shown for one frame was visible for 16.6 ms. In addition, we conducted a series of tests of our system using a phototransistor (TSL235R by TAOS, USA) connected to a high-frequency data sampler. We recorded 30 minutes of high-resolution data at 5 MHz. The results of our test confirmed that the subliminal stimuli were displayed for exactly 16.6 ms and that no frames were lost.

## 3 Results

### 3.1 Experiment 1

In Experiment 1, we focused on establishing an avoidance reaction to the negative subliminal stimuli in a go/no-go task. We computed the sum of the responses compatible with the negative prime (i.e., when participants pressed the spacebar key after the display of the spider prime in order to switch paths and avoid the aversive stimulus) and divided it by the total number when participants pressed the spacebar key, hence obtaining the response accuracy ratio. We compared the response accuracy ratio of each participant to the expected chance level of 50% (see Figure 11). We ran a one-sample *t*-test, to determine whether the mean accuracy of responses to the negative stimuli occurred at the chance level, or if there

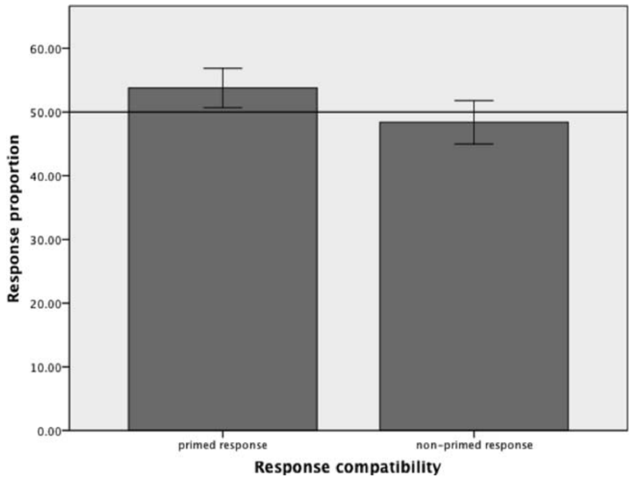


**Figure 12.** *Mean number of accurate and inaccurate responses for all participants. Accurate response is one compatible with the prime. Example of accurate response: negative prime was displayed and the participant pressed the spacebar key, avoiding the path. The error bars represent the 95% confidence interval.*

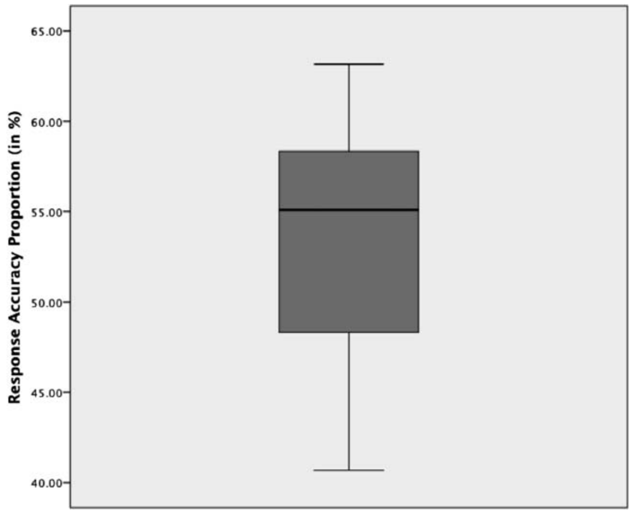


**Figure 13.** *Response accuracy in free-choice trials. Accuracy is defined as a prime compatible response. The 50.00 value represents the chance level for choosing an accurate response.*

existed a prime compatible effect. We observed a prime compatible modulation of the response accuracy of 3.78%, which was significantly higher than chance, $t(9) = 2.776$, $p < .05$. The magnitude of the modulation we obtained is comparable with that reported in the literature on subliminal priming (Bodner & Mulji, 2010).

In addition, an independent sample $t$-test was conducted to compare the mean response frequency between primed and nonprimed responses. We observed that the prime compatible choices obtained a significantly higher response frequency. The mean frequency of primed responses ($M = 53.8\% \pm 4.31$ $SD$) was significantly higher than the frequency of nonprimed response ($M = 48.4\% \pm 4.75$ $SD$); the mean difference was 5.4%, $t(18) = 2.654$, $p < .05$ (see Figure 12).

### 3.2 Experiment 2

In Experiment 2, we addressed the specific question of the behavioral impact of subliminally perceived stimuli. We calculated the proportion of prime compatible and incompatible responses of each participant in the free-choice trials obtaining the accuracy scores. The scores were computed by dividing the sum of compatible responses by the sum of all responses. Using a one-sample $t$-test, we compared the compatibility ratio of each participant against a value of 50.0, i.e., the expected outcome in the absence of priming effects (see Figure 13).

**3.2.1 Response Patterns.** The results of the one-sample $t$-test (see Figure 13) show the presence of a significant priming effect. The average accuracy calculated from the individual subjects' scores was 53.61 % ($\pm$ 6.65 $SD$). The difference from the expected mean was significant and represented a 3.61% higher accuracy than expected by chance, $t(22) = 2.479$, $p < .05$. These findings show the presence of a tendency, i.e., a response bias, for participants to choose the prime compatible responses.

For the second analysis, we considered as the sample the total number of free-choice responses of all the participants (see Table 1). We used a Chi-square test to determine whether there was a relation between the prime type and the navigation choice. We found a deviation of the observed values in the prime compatible direction. Prime compatible choices were performed more frequently by approximately 7%; hence, they were significantly higher than expected in the absence of priming effect (see Table 1). This priming effect is statistically significant, $X^2$ (1, N = 1289) = 6.119, $p < .05$. These results show that subliminally presented primes

**Table 1.** *Distribution of Responses in Free-Choice Trials*

| Prime Array | | Response Array: 0–arrow down (avoid the path) | Response Array: 1–arrow up (follow the path) |
|---|---|---|---|
| 0–negative prime | Observed value | 267 | 363 |
| | Expected value | 245.4 | 384.6 |
| | % within response array | **53.20%** | **46.10%** |
| 1–neutral prime | Observed value | 235 | 424 |
| | Expected value | 256.6 | 402.4 |
| | % within response array | **46.80%** | **53.90%** |

NOTE: 0–0 and 1–1 cells represent prime compatible choices. 0–1 and 1–0 cells represent prime incompatible choices. The differences between prime compatible and prime incompatible cells indicate that subliminal primes were successful in the induction of a compatible response bias. Expected value cells indicate the result in absence of priming effects, i.e., when the responses are distributed equally. Response array cells define the proportion of compatible and incompatible responses for neutral and negative stimuli.

had an effect on the navigation choice in the prime compatible direction.

**3.2.2 Visibility Test Scores.** We analyzed the responses collected in the visibility test block of Experiment 2 to determine whether the participants could consciously identify the primes. We submitted the data to a one-sample *t*-test to compare the mean accuracy of individual participants to chance level. The *t*-test was statistically not significant, indicating that the accuracy of responses in the visibility test block was at the chance level, $t\,(21) = -.124$, $p = .9$ and that subjects were not able to consciously discern the prime.

Taking into account the total number of responses, we applied a Chi-square test to determine whether there was a relation between the displayed prime and the participants' response. The Chi-square test was statistically not significant, $X^2\,(1, \mathrm{N} = 879) = .01$, $p > .1$.

We used a Pearson's *r* test to measure the correlation between individual participant scores on the visibility test and the accuracy of their responses in the main block. The correlation was statistically not significant, $r = .142$, $\mathrm{n} = 22$, $p = .264$. The higher scores on the visibility test were not causing higher accuracy of responses in the main block.

Taken together, these results demonstrate that the priming effects were genuinely subliminal and not mediated by conscious perceptual processes.

**3.2.3 Response Times.** Additionally, we submitted the response times to statistical analysis. Response times were measured from the onset of the prime to the execution of the response. We compared the difference in mean response times between the prime compatible and incompatible answers in fixed-choice trials and obtained no statistically significant results (see Figure 14).

To analyze the data collected on fixed-choice trials, we used two independent sample *t*-tests, comparing the mean response times between prime compatible and incompatible trials for neutral and negative targets. The mean response time for compatible negative trials ($M =$ 846 ms $\pm$ 97 *SD*, N = 440) was smaller than for the incompatible negative trials ($M =$ 855 ms $\pm$ 93 *SD*, N = 451); however, the difference was not statistically significant, $t\,(889) = -1.328$, $p > .1$. The 2-ms difference between the response times in compatible neutral trials ($M =$ 902 ms $\pm$ 109 *SD*, N = 425) and incompatible neutral trials ($M =$ 900 ms $\pm$ 105 *SD*, N = 400) was not statistically significant, $t\,(828) = .271$, $p > .1$.

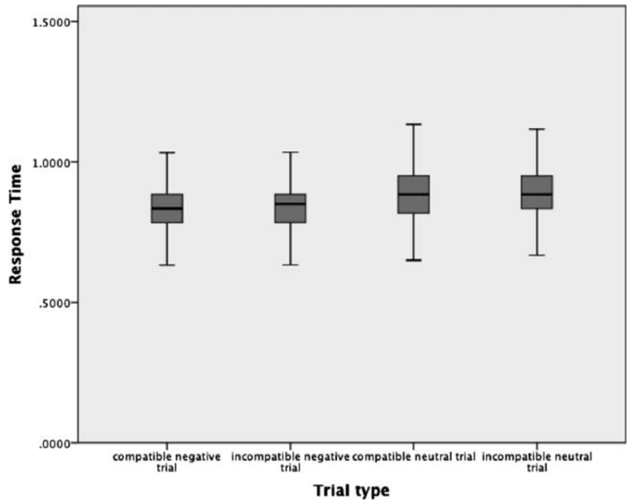


**Figure 14.** *Mean of the response times (in milliseconds) in fixed-choice trials. The difference between the means occurred between negative and neutral targets and did not occur between compatible and incompatible trials.*

## 4 Discussion

In this study, we have investigated the impact of subliminal stimuli in an ecologically valid navigation task. Using the XIM infrastructure, we have asked subjects to navigate through a maze composed of binary vertical choice points. We exposed the subjects to a series of negative and neutral subliminal stimuli to measure changes in their behavior while performing the navigation task. Our results show that the subliminal stimuli can indeed induce a compatible response bias, i.e., increase the accuracy of performance in the navigation task. The prime visibility test results confirmed that the effects we observed were genuinely subliminal. Our results indicate that the unconsciously perceived stimuli do affect conscious behavior.

The difference between unconscious automatic reaction and conscious volitional behavior lies not in the level of intentional control over the behavior but in the type of output that is produced by the psychological processes (Tzeglov, 1997). Studies of unconscious learning of sequences (Dienes & Berry, 1997), artificial grammar (Whittlesea & Dorken 1997), and contextual cueing (Jiang & Leung, 2005) question the classical dichotomy between conscious and unconscious information processing. Instead, it is suggested that in the case of the automatic processing of information, percepts are not consciously accessible as symbolic representations, but as qualia-like or "feelings of" representations (Whittlesea & Dorken; Tzeglov). It is the level of confidence in knowledge or metacognitive access to the learning process that defines the border between conscious and unconscious representations. Thus the expression of learning can be accessible to consciousness in a low-confidence qualia form, while the process of learning itself escapes subjects' attention and awareness (Dienes & Berry). Experimental procedures used to investigate unconscious perception often fail to measure these expressions of learning because subjects underestimate their low-confidence knowledge and withhold its use in the experimental test (Whittlesea & Dorken). Studies on unconscious perception have to aim to create a sense of presence in order to encourage the participants to base their decisions on low-confidence and qualia-like knowledge, which is the only accessible output of subliminal priming.

To explain the observed results, it is necessary to locate subliminal priming effects in an explanatory model of perception and action. According to the literature, there are two main models, and their differences remain the central controversy in subliminal priming research (Kouider & Dehaene, 2007). The first view states that unconsciously perceived stimuli are processed all the way up to the semantic level; i.e., their meaning is unconsciously understood (Naccache & Dehaene, 2001). The second approach explains subliminal effects as automated response mechanisms mediated by nonsemantic processes (Damian, 2001; Vorberg et al., 2003). These two models focus on the issue of depth of information processing occurring at unconscious stages of perception. However, they do not present a more inclusive perception-to-action model. If human behavior can be unconsciously affected only by the processing of the information contained in a particular stimulus, in the absence of these stimuli there could be no priming effects. Our findings suggest this is not the case. Hence, this suggests a third alternative where different levels of processing are dynamically coupled or uncoupled depending on the task requirements (Mathews et al., 2011).

Priming effects originate from the learned associations between the target stimulus and the response, which can be activated on the unconscious level by the subliminal prime (Kiesel, Kunde et al., 2006; Hommel, 2000). Thus, when the participants respond to a negative target (such as a spider), they learn to respond in the same way to the negative prime. Most importantly, the negative prime that was depicting a different spider image than the negative target still induced priming effects. This means that the presence of a spider, independent of its specific visual features, was enough to lead to an unconscious activation of the assigned response, i.e., to leave the path. Additionally, the neutral prime was not similar to the neutral target. The neutral prime was nearly identical to the mask; thus, it did not specify any response (see Figure 9, right). We have observed that the neutral prime activated the opposite response than the negative prime and thus caused a prime compatible response bias (see Table 1). Since the neutral prime represents the absence of the stimulus, the priming effect (i.e., response bias) cannot be explained as a case of stimulus–response translation, because the stimulus itself carries no information.

However, it is possible that the priming effects observed on the neutral stimuli were caused by the preference of participants to go forward, since the overall frequency of the "arrow up" response was larger than half of the total number of responses. We argue that at the unconscious level of perception, a degree of understanding of the consciously pursued task exists; otherwise, results for the neutral prime would also be neutral, i.e., without any response bias.

Absence of statistically significant effects observed on the measures of response times might be due to two factors. First, the direction and strength of the priming effects modulating the response times changes with the SOA (stimulus onset asynchrony), i.e., with the time between the presentation of the prime and the target. In our case, the SOA was 116 ms, which in previous studies was identified as a point around which response facilitation changes into response inhibition (Vorberg et al., 2003; Mattler & Palmer, 2012; Eimer & Schlaghecken, 2003). Response facilitation with subliminal prime has been observed under short SOAs, i.e., under 100 ms; thus, the time course of the stimuli sequence used in our study might have reduced the priming effects. Secondly, the time pressure of the speeded response signal (i.e., 1216 ms from the offset of the prime) could have possibly shortened all the performed responses, introducing a bias confounding with the priming effects.

The experiment was conducted on naïve participants who were not expecting nor looking for subliminal stimuli. Hence, since we observed the priming effects, we can conclude that unconscious perception does affect behavior without necessary recruitment of conscious cognitive mechanisms. Additionally, since we used different spider images for the supraliminal target and subliminal prime, we can argue that the mind is capable of category learning on the unconscious level.

Our main goal was to induce the subliminal priming effects under ecologically valid conditions. To do so, we developed new experimental methods for the study of the unconscious mind employing reward and punishment as well as goal-oriented navigation tasks. Our results indicate that the application of VE-based experimental methods can offer new insights about the coupling and adaptive mechanisms of conscious and unconscious cognition.

## 5 Future Improvements

The question regarding the processing depth of subliminally presented stimuli remains debated. Our experimental paradigm provides an interesting opportunity to investigate this issue, for example, by comparing different types of prime stimuli, such as words and images. We plan to enhance our paradigm by allowing full body interaction with the maze, hence augmenting the ecological validity of the experimental task. In future, we plan to further improve our paradigm by measuring EEG data in order to find direct insights about the time course of the relation between subliminal perception and conscious behavior.

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