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Original Articles

Unconscious memory suppression

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A R T I C L E I N F O

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A B S T R A C T

Recent evidence suggests that high-level executive control can occur unconsciously. In this study, we tested whether unconscious executive control extends to memory retrieval and forgetting. In a first experiment, participants learned word-word associations and were trained to either actively recall or forget theses associations in response to conscious visual cues (Think/No-Think paradigm). Then, the very same cues were subliminally presented while participants were performing a grammatical gender categorization task on distinct word pairs. Memory retrieval tested a few minutes later was significantly influenced by conscious and masked cues, suggesting that memory recall could be manipulated unbeknownst to the participants. In a second experiment, we replicated these findings and added a baseline condition in which some words were not preceded by masked cues. Memory recall was significantly reduced both when words were preceded by an unconscious instruction to forget compared to the baseline condition (i.e. no cue), and to the unconscious instructions to recall. Overall, our results suggest that executive control can occur unconsciously and suppress a specific memory outside of one's awareness.

1. Introduction

Memory suppression corresponds to the voluntary alteration of memory retrieval by conscious cognitive control. This mechanism was first demonstrated by Anderson & Green (2001), with a "Think/No-Think" paradigm modelled on the Go/No-Go task. In the original study, participants first learned a set of word pairs. Then, they were presented with the first word of a pair (hint word) and asked, in response to a visual cue, to either retrieve the associated word (Think trials) or prevent it from coming to mind (No-Think trials). The results showed that executive control could modulate recall: recall could be improved through rehearsal, or deteriorated voluntarily, a phenomenon termed "suppression-induced forgetting" (Anderson & Green, 2001). These results have been replicated (for a review, see Anderson & Hanslmayr, 2014) and extended to non-verbal memories, using for instance emotional pictures (Depue, Banich, & Curran, 2006; Depue, Curran, & Banich, 2007; Küpper, Benoit, Dalgleish, & Anderson, 2014). Moreover, the neural substrates of this phenomenon have been clarified: fMRI studies indicated that memory suppression may involve top-down modulation of hippocampal activity by the dorsolateral prefrontal cortex (Anderson, Bunce, & Barbas, 2016).

Whether suppression-induced forgetting can be triggered unconsciously remains unknown. Indeed, long-term declarative memory has long been thought to be tightly linked to consciousness (Tulving, 1987). To date, suppression-induced forgetting has always been tested through voluntary and conscious effort to rehearse memories or purge

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them. However, recent behavioural and neuroimaging results suggested that a semantic association could be formed through unconscious processes (Reber, Luechinger, Boesiger, & Henke, 2012; vanGaal et al., 2014).

Interestingly, other studies showed that unconscious instructions could modulate high-level executive control processes, such as attention orientation (Jiang, Costello, Fang, Huang, & He, 2006), task-set preparation (Lau & Passingham, 2007; Weibel, Giersch, Dehaene, & Huron, 2013), task switching (Reuss, Kiesel, Kunde, & Hommel, 2011), error detection (Charles, Opstal, Marti, & Dehaene, 2013; Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001), conflict adaptation (vanGaal, Lamme, & Ridderinkhof, 2010) and response inhibition (vanGaal, Ridderinkhof, Fahrenfort, Scholte, & Lamme, 2008; vanGaal, Ridderinkhof, Scholte, & Lamme, 2010).

Capitalizing on these results, our study aims to test whether high-level executive control processes can unconsciously suppress a previously learned association between two words, i.e. whether suppression-induced forgetting can occur outside of one's awareness.

We designed two experiments that were modelled on the Think/No-Think paradigm (Anderson & Green, 2001), using conscious and masked cues to manipulate memory retrieval. In the first experiment, we investigated whether memory suppression could be induced by masked (unconscious) cues, which had been previously associated with conscious Think/No-Think instructions. In the second experiment, we aimed to replicate our findings with an addition baseline condition, to confirm that masked cues could induce memory suppression over and above the detrimental effect of time.

2. Experiment 1

Experiment 1 was designed as an unconscious version of the procedure developed by Anderson & Green (2001). Participants first learned word pairs (hint word – response word). Then, they performed a conscious Think/No-Think task, in which they were presented with a subset of hint words and had to actively remember (Think) or try to forget (No-Think) the associated response words, according to conscious visual shape cues. Afterwards, these conscious trials were intermixed with unconscious trials in which participants performed a distracting task on distinct hint words (a grammatical gender determination task), while the same visual shape cues were subliminally presented. The alternation between conscious and unconscious trials aimed to reinforce the association between shape cues and Think/No-Think instructions, fostering the unconscious Think/No-Think effect. A final test then probed whether participants were able to retrieve response words when presented with the hint words.

The primary aim of this experiment was to test whether masked cues could induce a Think/No-Think effect as previously evidenced in conscious settings (Anderson & Green, 2001). For methodological reasons, our experimental paradigm differs from the original in several aspects. First, in Anderson's experiments, two different methods were used to signal what task participants should perform. One method was to allocate each hint word to the Think or the No-Think conditions and to train participants until they could distinguish these words (“hint training”, Anderson & Green, 2001). Alternatively, specific colours could be associated with the Think/No-Think task such the font colour indicated the type of task participants should perform (“colour cueing”, Anderson et al., 2004). In our design, we associated shape cues (diamond and square) to Think and No-Think tasks (“shape cueing”). These cues were displayed at the beginning of each trial to indicate to participants whether they should perform a Think or a No-Think task on the subsequent word, which allowed us to then mask these visual cues in the unconscious condition. Secondly, in the original paradigm, a baseline condition was included whereby some words were not presented at all between learning and final recall, allowing active retrieval and active forgetting to be compared to a neutral condition. In Experiment 1, we did not include such a baseline, maximising the Think/No-Think effect by associating every unconscious trial with a masked cue. However, a comparable baseline condition was added to Experiment 2.

In these experiments we hypothesised that we would observe a Think/No-Think effect with both conscious and masked cues, i.e. that final recall in the No-Think condition would be significantly lower than initial recall, and significantly lower than the Think condition in final recall but not in initial recall performance.

2.1. Materials and methods

2.1.1. Participants

Forty-four healthy subjects were recruited through advertising (25 females and 19 males, mean age 24.5 years, range 21–33). All participants had normal or corrected-to-normal vision and were naive to the purpose of the experiment. No participant took part in both experiments. Participants gave written informed consent before taking part. All methods were carried out in accordance with relevant guidelines and regulations, in particular with the Declaration of Helsinki. No participants were excluded from Experiment 1.

2.1.2. Procedure

The procedure consisted of three phases: a learning phase, a Think/No-Think phase (comprising a few conscious Think/No-Think trials then intermixed with unconscious Think/No-Think trials), and a final recall test (Fig. 1a).

2.1.2.1. Learning phase. First, participants were asked to learn 30 word pairs (composed of a hint word and a response word, e.g. “candle – champagne”). Word pairs were presented in random order and each pair was presented twice. Each word was displayed on screen for 4 s. Hint words were preceded by a 200 ms fixation cross and response words were followed by a 500 ms inter-pair interval. A recall test was then performed: each hint word was displayed for 4 s (e.g. “candle”) and participants had to say aloud the corresponding response word (e.g. “champagne”). They could give an answer as soon as the hint word appeared on screen and had 4 additional seconds after it had disappeared to answer, i.e. 8 s in total to answer. No feedback was provided. A new learning phase (maximum 3) started if the minimum of 50% correct answers was not reached. All subjects reached the 50% correct answers criterion after one run of the learning phase, with an average of 80% correct answers.

2.1.2.2. Think/No-Think phase. During the Think/No-Think phase, participants were presented with the hint words preceded by Think or No-Think cues ($n = 760$ trials, 20 trials per target word, 240 conscious trials for 12 word pairs, 240 unconscious trials for 12 word pairs and 280 trials for 6 filler word pairs).

Conscious Think/No-Think trials. On conscious Think trials, participants were asked to retrieve the response word associated with the hint word, without saying it aloud. Comparatively, on No-Think trials, subjects were asked to prevent the response word from coming to mind for 3 s, while the hint word was presented on screen. No-Think instructions were unguided: no strategy was proposed to help the participants (Benoit & Anderson, 2012). A visual shape cue, in the form of either a diamond or a square, was presented at the beginning of each trial to indicate which task (Think or No-Think) the participant should perform (“shape cueing”). The association between shapes (diamond/square) and instructions (Think/No-Think) was defined at the beginning of the experiment and counterbalanced across participants. The visual sequence was as follows: fixation cross (500 ms), blank screen (300 ms), shape cue (200 ms), blank screen (166 ms), and hint word (3000 ms) (Fig. 1b).

Unconscious Think/No-Think trials. On unconscious trials, participants had to perform a grammatical gender categorization task on the hint words (i.e. determine whether it was feminine or masculine).

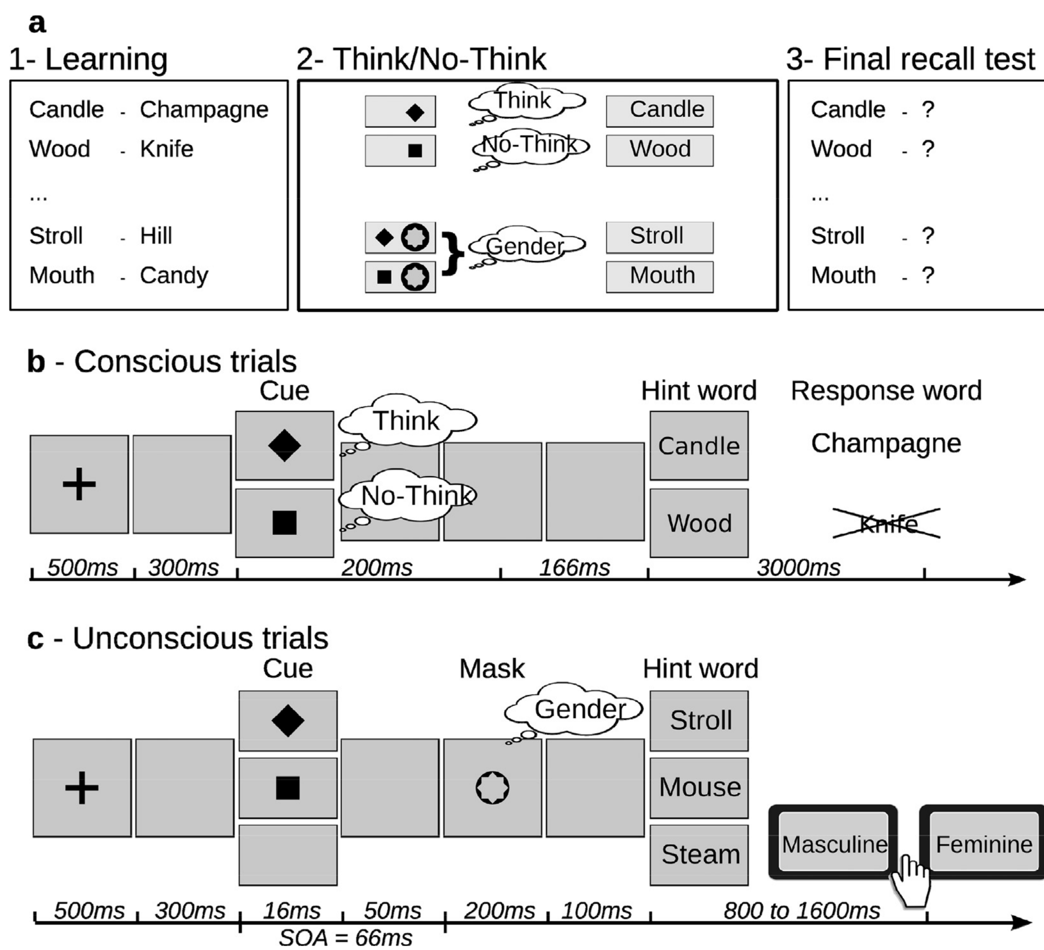

Fig. 1. Design of Experiment 1. (a) Experiment 1 consisted of three phases: (1) a learning phase, (2) a Think/No-Think phase (detailed in b and c), (3) a final test. (a1) In the learning phase, participants encoded word pairs (hint word – response word), until at least 50% of recall was reached. (b) In the Think/No-Think phase on conscious trials, participants were presented with hint words and had either to recall (Think trial) or suppress (No-Think trial) the corresponding response word. (c) In the Think/No-Think phase on unconscious trials, participants had to indicate as quickly as possible the gender of the hint word. Think and No-Think cues were presented just before the hint word and masked by a ring shape (metacontrast mask) in the unconscious condition. (a3) In the final test phase, participants' ability to retrieve response words was assessed.

Hint words were preceded by the same shape cues as in the conscious phase (i.e. diamond and square) but these cues were masked by metacontrast (Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003), whereby a ring appeared on screen just after the shape cue, closely fitting its contours without touching it, making the shape cue subliminal. Hint words were followed by a go-signal indicating to participants that they could give their answer for the grammatical gender determination task. The go-signal was a dot appearing on screen with a jitter in its position and timing (random position between −200 and +200 pixels above or below the screen centre and random moment between 800 and 1600 ms after the word onset). After the go-signal, participants had to answer as fast as possible by pressing the letter “k” or “d” on a keyboard. The buttons were associated with the “feminine” and “masculine” response at the beginning of the experiment and counterbalanced across participants.

Participants were not informed that masked Think/No-Think cues were presented during these unconscious trials. They were told that the main outcome of these trials was their speed and accuracy in the grammatical gender determination task. Feedback on accuracy and response times was provided every 30 gender trials. On unconscious Think/No-Think trials, the visual sequence was as follows: fixation cross (500 ms), blank screen (300 ms), shape cue (16 ms), blank screen (50 ms), ring metacontrast mask (200 ms), blank screen (100 ms), hint word (800 to 1600 ms), go signal (Fig. 1c). The Stimulus Onset Asynchrony (SOA) for the metacontrast masking was therefore 66 ms.

Trial order. Thirty-six conscious trials were first performed. Following this, unconscious trials and conscious trials were intermixed. A minimum of two conscious trials were received between every unconscious trial. To know which task they were required to perform at each trial, participants had to pay attention to conscious visual cues. When they saw a square or a diamond they had to perform a Think/No-Think task (conscious trials), and when they perceived a ring they had to perform a grammatical gender categorization task (unconscious trials).

To investigate the influence of conscious trial instructions on the following unconscious trial, unconscious hint words were divided into two groups: specific hint words were systematically preceded by a conscious No-Think trial, while others were systematically preceded by a conscious Think trial.

2.1.2.3. Final test phase. **Recall test.** After the Think/No-Think phase, participants completed a recall test identical to the one performed at the end of the learning phase.

Cue visibility assessment. At the end, participants performed 120 trials of a forced choice test designed to evaluate the visibility of the masked cues. They were told that hidden cues were presented on screen before the metacontrast masking ring, and they were asked to guess whether it was a square or a diamond. The same timing sequence as in the unconscious phase was used (Fig. 1c), except that no hint word was presented. Participants were told that only response accuracy was

Table 1
Initial and final recall rates in Experiments 1 and 2.

	Initial recall rate Mean % (sd)	Final recall rate Mean % (sd)
Experiment 1		
Conscious		
No-Think	80 (21)	77 (20)
Think	80 (21)	83 (19)
Unconscious		
No-Think	79 (25)	75 (28)
Think	83 (23)	81 (23)
Overall		
No-Think	79 (20)	76 (20)
Think	81 (17)	82 (18)
Experiment 2		
Unconscious		
No-Think	78 (22)	67 (24)
Baseline	79 (25)	81 (26)
Think	78 (26)	84 (22)

important, not response speed, and that they had to venture an answer even if they did not see the cue. Discrimination performance was assessed through d' (Macmillan & Creelman, 2005).

Questionnaire. Finally, a post-experiment questionnaire evaluated the frequency of intrusions during the unconscious condition, i.e. the frequency at which response words entered awareness during the grammatical gender determination task on hint words.

2.1.3. Materials

Stimuli. We built 30 word pairs (hint word – response word) composed of French nouns that were weakly related one to another (e.g. "candle – champagne", "wood – knife"), while unrelated to other pairs. For each subject, the 30 word pairs were randomly split into 5 sets of 6 word pairs. Four of these sets were associated with a specific Think/No-Think condition (i.e. Conscious Think, Conscious No-Think, Unconscious Think, Unconscious No-Think, n = 6 word pairs for each condition). The remaining 6 word pairs were used as filler word pairs. They were always preceded by conscious cues but not allocated to a Think or a No-Think condition: in half of the trials, they were preceded by a Think shape cue and, in the other half, by a No-Think shape cue. Therefore, participants had to continuously attend to the shape cues to know whether they should perform a Think or a No-Think task ("shape cueing") and could not only rely on hint words to identify conditions ("hint training"). Each word pair associated with a specific Think or No-Think condition was presented 20 times during the Think/No-Think phase. The randomization process was checked to ensure it did not result in an unbalanced allocation of word pairs to conditions across subjects.

Apparatus. The experiment was run on a Linux personal computer running the Psychophysics toolbox (Brainard, 1997) within Matlab. All stimuli were displayed on a CRT monitor with a refresh rate of 60 Hz, in grey on a black background. Participants sat with their head at a distance of 60 cm from the screen, so that the shape cues occupied one degree of visual angle.

2.1.4. Statistical analysis

Statistical analyses used standard repeated measure ANOVA, t-tests and linear regressions. The relevant analysis is described in the results section at the time it is first performed. Significance level was $\alpha = 0.05$, uncorrected.

All statistical analyses were performed using the "R" statistical software (R Core Team, 2013).

2.2. Results

2.2.1. Conscious and masked No-Think cues reduce memory recall

A three-way analysis of variance (ANOVA) on recall performance was performed for each participant, with cue type (Think versus No-Think), cue visibility (conscious versus unconscious) and time (initial versus final recall) as within subject factors, and subject as random factor. This analysis revealed a significant interaction between cue type and time ($F(1,43) = 5.56$, $p = 0.023$), while there were no main effects of cue type ($F(1,43) = 3.67$, $p = 0.062$), cue visibility ($F(1,43) = 0.036$, $p = 0.85$) or time ($F(1,43) = 2.90$, $p = 0.096$). A significant interaction between cue visibility and time ($F(1,43) = 4.3$, $p = 0.044$) was observed, but there was no significant interaction between cue type and cue visibility ($F(1,43) = 0.01$, $p = 0.72$), and no triple interaction between cue type, cue visibility and time ($F(1,43) = 0.47$, $p = 0.498$). The effect of cue type over time was therefore analysed irrespective of cue visibility.

Think/No-Think effects were assessed in two different ways: (1) by comparing final versus initial recall performances separately for Think and No/Think conditions, (2) by comparing Think and No/Think recall performances in the final test.

No-Think cues (conscious and unconscious) significantly reduced recall performance in the final test compared to the initial test (76% versus 79%, $t(43) = 3.10$, $p = 0.003$), whereas Think cues did not significantly improve recall performance (82% versus 81%, $t(43) = -0.42$, $p = 0.67$) (Table 1, and Fig. 2b).

In the initial test, there was no significant difference in recall between word pairs that were next allocated to the Think and No-Think conditions (initial recall of 81% and 79% respectively, $t(43) = 0.86$, $p = 0.39$). By contrast, in the final test, a significant difference in recall between the Think and No-Think conditions arose (final recall of 82% and 76% respectively, $t(43) = 2.75$, $p = 0.009$).

No significant effect of cue visibility was found, however, as an exploratory analysis, we analysed separately conscious and unconscious trials.

For unconscious trials, the two-way ANOVA on recall performance for each participant according to cue type (Think versus No-Think) and time (initial versus final recall) did not reveal a significant Think/No-Think effect (cue type × time: $F(1,43) = 1.92$, $p = 0.173$). There was no main effect of masked cue type ($F(1,43) = 2.77$, $p = 0.103$) but a main effect of time ($F(1,43) = 6.23$, $p = 0.017$). Exploratory t-tests showed that unconscious No-Think cues significantly reduced recall in the final test compared to the initial test (75% versus 79%, $t(43) = 2.90$, $p = 0.006$) and final recall was significantly lower with unconscious No-Think cues compared to unconscious Think cues (75% versus 81%, $t(43) = 2.03$, $p = 0.024$, single-sided) (Fig. 2a, Table 1).

For conscious trials, in the two-way ANOVA on recall performance for each participant according to cue type (Think versus No-Think) and time (initial versus final recall), the Think/No-Think effect did not reach statistical significance (cue type × time: $F(1,43) = 4.03$, $p = 0.051$) nor did the main effect of cue type ($F(1,43) = 1.22$, $p = 0.27$) or time ($F(1,43) = 0$, $p = 1$). Exploratory t-tests showed that final recall was significantly lower with unconscious No-Think cues compared to unconscious Think cues (75% versus 81%, $t(43) = 2.03$, $p = 0.038$, single-sided) (Fig. 2a, Table 1).

2.2.2. The memory effect is not due to cue discriminability

Discriminability, as assessed by the forced choice test, was very low in the unconscious condition, albeit significantly above zero (hit rate 55.5%, $d' = 0.35$, $t(43) = 5.01$, $p < 0.001$). Crucially, a between-subject regression analysis (Greenwald, Draine, & Abrams, 1996) demonstrated that subjects' ability to discriminate masked cues (d′) was unrelated to the cues' effect on memory (No-Think – Think recall performance in the final test) (Fig. 2c). The slope of the regression line was not significantly different from zero (slope = 0.05, $t(42) = 0.77$, $p = 0.45$), indicating that people's ability to discriminate masked cues

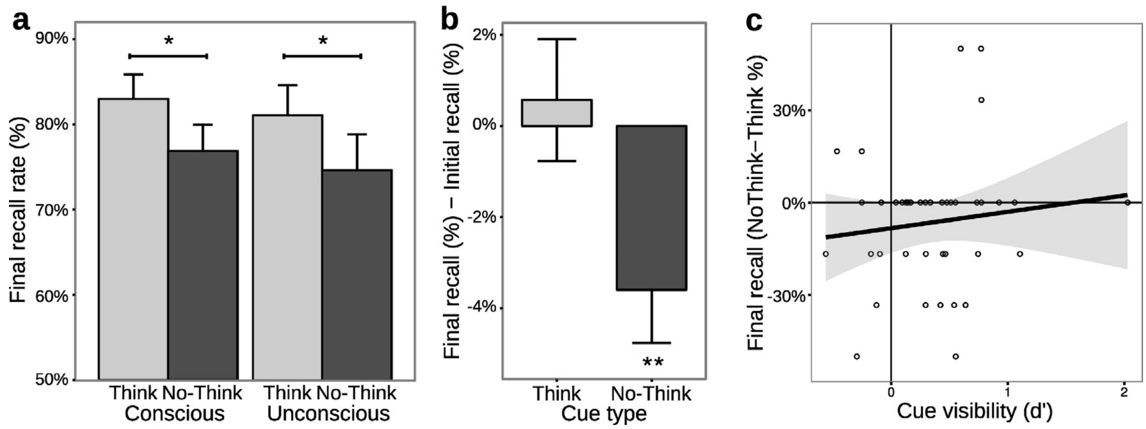

Fig. 2. Effect of cue type and visibility in Experiment 1. (a) Final recall performance was lower with No-Think cues (black) compared to Think cues (grey) when these cues were consciously visible (left) and masked (right). Error bars represent the standard error of the mean (SEM). (b) Think cues (grey) did not improve overall recall performance (final recall – initial recall, grouping conscious and unconscious trials together), whereas No-Think cues (black) significantly reduced it. Error bars represent the standard error of the mean (SEM). (c) Participants' ability to discriminate masked cues on unconscious trials, as measured by d', did not significantly alter cues effect on final recall, and the effect remained significant for people who could not discriminate masked cues (intercept = −8%). The shaded area around the regression lines represents the 95% confidence interval. * = $p < 0.05$, ** = $p < 0.01$.

did not predict their memory effect. The intercept of the regression was significantly different from zero (intercept = −8%, $t(42) = -2.08$, $p = 0.044$), indicating that people who could not discriminate masked cues still showed an effect on final recall.

To further isolate the inhibition effect in unconscious No-Think trials, we performed a regression analysis (Greenwald et al., 1996) on final versus initial recall performance (final No-Think – initial No-Think performance), as a function of cue discriminability (d'). This analysis yielded a similar result with an effect of cues that was unrelated to people's ability to discriminate masked cues (slope = 0.01, $t(42) = 0.32$, $p = 0.75$). This effect remained significant for people who could not discriminate masked cues (intercept = −5%, $t(42) = -2.47$, $p = 0.017$).

2.2.3. Recall performance in unconscious trials was not affected by the preceding conscious trial

Final recall performance for unconscious trials was not influenced by the type of cue presented in the preceding conscious trial. There was no significant effect of conscious Think/No-Think trials on the subsequent unconscious trials (main effect of preceding conscious trial: $F(1,43) = 0.01$, $p = 0.91$, interaction between current masked cue type and previous conscious cue type: $F(1,43) = 0.10$, $p = 0.76$).

2.2.4. Performance in the grammatical gender determination task

Participants reported a low level of intrusions during the word gender determination task (16.5% based on post-session questionnaires), suggesting that the word gender determination task efficiently drew their attention away from conscious memory task during unconscious trials.

Performance in the word gender determination task did not significantly differ according to unconscious cue type: gender response accuracy was 99.3% and 99.2% with the Think and No-Think masked cues respectively ($t(43) = -0.53$, $p = 0.60$), and reaction time was 365 ms and 361 ms respectively ($t(43) = 0.43$, $p = 0.67$).

2.3. Discussion

Experiment 1 showed that a Think/No-Think effect could be induced by conscious and masked shape cues. Crucially, in the unconscious condition, word pairs had never been consciously associated with Think/No-Think instructions.

While the Think/No-Think effect of cues irrespective of cue visibility was confirmed by a significant three-way ANOVA and subsequent t-tests, further exploratory ANOVA and t-tests on unconscious cues separately and conscious cues separately provide further contrasts. The two-way ANOVAs on unconscious and conscious cues separately failed to reach statistical significance, but exploratory t-tests show a difference in final recall between Think and No-Think cues both for unconscious and conscious trials, when such differences were not present in initial recall. These exploratory results require confirmation to ascertain that unconscious cues taken alone significantly alter recall, which was the object of Experiment 2.

Interestingly, no main effect of cue visibility (conscious versus masked) was observed, whereas a stronger effect in the conscious condition was expected (Dehaene & Changeux, 2011). A possible explanation is that the distracting task performed by participants in unconscious trials may have elicited forgetting through interference (Tomlinson, Huber, Rieth, & Davelaar, 2009), thus strengthening the No-Think effect in the unconscious condition. This hypothesis is supported by the main effect of time which is only observed in the ANOVA restricted to unconscious trials. Moreover, no enhancement of recall was observed in the Think condition between the initial and final recall test. This result is not fully compatible with the previous literature on Think/No-Think effects (Anderson & Huddleston, 2012) and suggests a global detrimental effect of time.

In previous studies, conscious Think and No-Think effects on recall were compared to a baseline condition (Anderson & Green, 2001; Anderson et al., 2004): a subset of words that were not presented between the learning phase and the final test to reflect the pure detrimental effect of time. In this experiment, we did not include such a condition, therefore we could not disentangle an enhancement of recall due to the Think condition from a suppression effect due to the No-Think condition. Moreover, we could not measure the interference effect of the distracting task (Tomlinson et al., 2009) and its interaction with the Think/No-Think cues. Therefore, to confirm that unconscious No-Think cues have a genuine suppression effect on recall performance, we replicated this experiment, including a baseline condition.

3. Experiment 2

Experiment 2 was a replication of Experiment 1, which included unconscious baseline trials where no masked cue was presented before the hint word. The aim of this experiment was to reproduce and extend Experiment 1 results, and to prove that masked cues can induce a genuine suppression effect. This experiment was also designed to control for any detrimental effects of time and to rule out interference from the distracting task in the measured No-Think effect, since the only difference between the unconscious baseline condition and the No-Think condition is the absence/presence of masked cues.

Capitalizing on previous studies and the results of Experiment 1, we did not aim to replicate conscious Think/No-Think effects in this experiment. Instead, conscious trials were used to induce and maintain a strong association between shape cues and Think/No-Think instructions. To this end, conscious hint words were not associated with a specific Think or No-Think task: they were equally preceded by Think and No-think cues. The purpose of this change was to encourage participants to focus on cues in conscious trials and therefore to maximize the Think/No-Think effects in unconscious trials ("shape cueing"). Furthermore, it was not possible to include a baseline in conscious trials equivalent to the baseline designed for unconscious trials. Indeed, presenting a hint word without any conscious cue would have undoubtedly led participants to either think or repress the corresponding response word without any way for us to control this parameter.

We hypothesised that a Think/No-Think effect would occur with masked cues, i.e. that final recall would be significantly lower than initial recall with unconscious No-Think cues, and that there would be a significant difference in final recall performance with No-Think cues compared to both Think cues and baseline, in the absence of any such difference in initial recall performance.

3.1. Materials and methods

3.1.1. Participants

Thirty one healthy subjects were recruited through advertising (23 females and 8 males, mean age 24.0 years, range 18–33). All participants had normal or corrected-to-normal vision and were naive to the purpose of the experiment. No participant took part in both experiments. Participants gave written informed consent before taking part. All methods were carried out in accordance with relevant guidelines and regulations, in particular with the Declaration of Helsinki. One subject was excluded because they did not understand the instructions and stopped the experiment before completion.

3.1.2. Procedure

The procedure consisted of the same three phases as in Experiment 1: a learning phase, a Think/No-Think phase (760 trials, 20 trials per target words: 240 unconscious trials for 12 word pairs and 520 conscious trials for 12 filler word pairs) and a final recall test (Fig. 3).

The learning phase was the same as in Experiment 1, except that word pairs allocated to the conscious condition were presented one additional time (i.e. three times) in order to yield a higher initial recall rate. Thus, participants could do the conscious Think/No-Think task on a maximum number of items.

In both the initial and the final recall test phases, hint words were presented on the screen for 4 s. However, contrary to Experiment 1, participants had to provide their answer before the word disappeared from the screen (i.e. within 4 s versus 8 s in Experiment 1). This change aimed to highlight differences between Think and No-Think in the final recall rate. Two subjects did not reach the minimum recall performance of 50% after one run of learning phase and were thus presented with word pairs an additional time.

Conscious and unconscious Think/No-Think trials consisted of the same tasks and the same visual time sequence as in Experiment 1, except that an unconscious baseline condition was added. In baseline trials, no shape cue was presented before the metacontrast mask (ring): the diamond and square shapes were replaced by a blank screen (Fig. 3). As in Experiment 1, the Think/No-Think phase started with 36 conscious trials before conscious and unconscious trials were intermixed.

We revealed the presence of masked cues at the end of the experiment and assessed cue visibility (d') using the same procedure as in Experiment 1 (i.e. forced choice on the identity, square or diamond, of the masked shape cue).

3.1.3. Materials

We used 24 pairs of French nouns: a hint word and a response word that were weakly related one to another whilst unrelated to other pairs, as in Experiment 1. Four word pairs were used for each of the 3 unconscious conditions: Think, No-Think, and baseline (for a total of 12 word pairs allocated to the unconscious condition).

Contrary to Experiment 1, in the conscious condition, hint words were not associated with a fixed instruction: they were preceded by a Think shape cue in half of the trials, and by a No-Think shape cue in the other half. That is, we extended to all conscious word pairs what was done on a subset of 6 conscious word pairs in Experiment 1. Consequently, the Think/No-Think effect of conscious shape cues could not be assessed in Experiment 2. The main purpose of this change was to force participants to focus on cues and, by doing so, to maximize Think/No-Think effects in unconscious trials ("shape cueing"). Twelve word pairs were allocated to the conscious condition. As in Experiment 1, each word pair allocated to the unconscious condition was presented 20 times during the Think/No-Think phase. As in Experiment 1, the 24 word pairs were randomly allocated to conditions for each subject, and the randomization process was checked to ensure it did not result in an unbalanced allocation of word pairs to conditions across subjects.

In Experiment 1, preceding conscious trials had no effect on subsequent unconscious trials. Therefore, in Experiment 2, conscious trials were randomized so that each unconscious trial was preceded by the same number of conscious Think and conscious No-Think trials. The computer, screen and programs used to run Experiment 2 were identical that used in Experiment 1 (see Material and methods of Experiment 1).

3.1.4. Statistical analysis

Statistical analysis in Experiment 2 followed the same methods as in Experiment 1, except that we restricted analyses to unconscious trials only. Indeed, in conscious trials, word pairs were not associated with a specific Think or No-Think condition as hint words were equally preceded by Think and No-Think cues.

Effect sizes were computed with Cohen d to compare the two experiments.

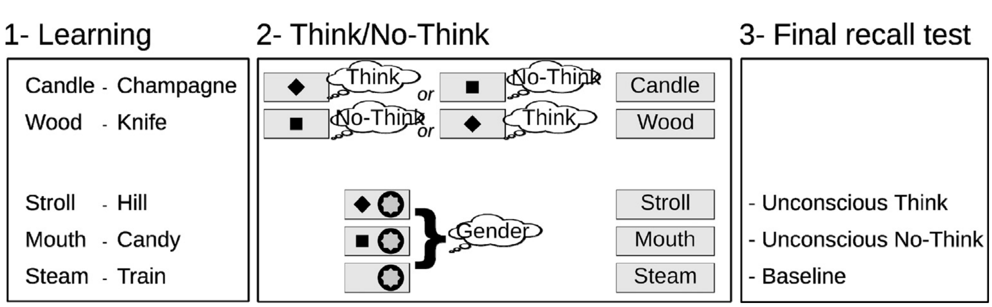

Fig. 3. Design of Experiment 2. A baseline condition was added to the unconscious condition. Therefore, in unconscious trials, either a diamond, a square or a blank screen could be presented before the metacontrast mask (ring). In the conscious condition, all hint words were equally preceded by Think shape cues and No-Think shape cues (i.e. word pairs were not associated with a specific instruction). In the final test, the recall performance was assessed only for the words that were used in the unconscious condition.

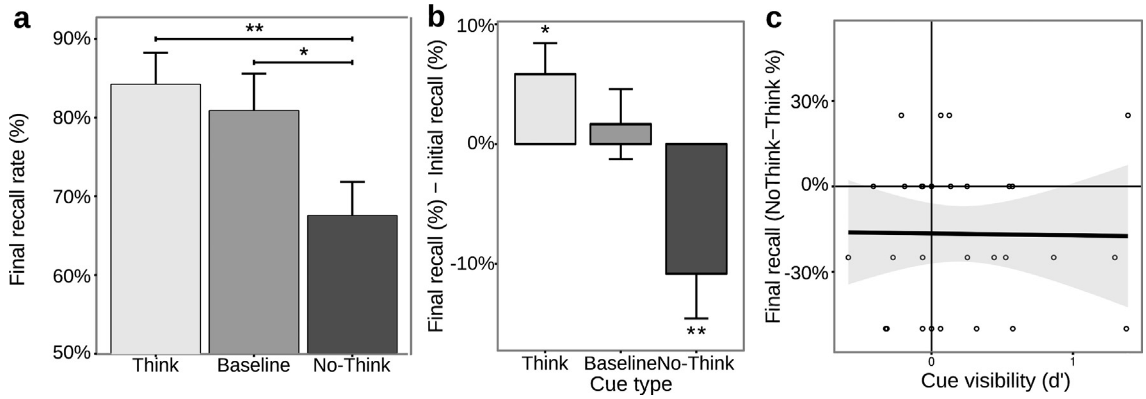

Fig. 4. Effect of masked cues in Experiment 2. (a) Final recall was lower with No-Think cues (black) compared to Think cues (light grey) and the Baseline condition (dark grey), with no significant difference between Think and baseline conditions. Error bars represent the standard error of the mean (SEM). (b) No-Think cues (black) significantly reduced recall performance (final recall – initial recall), Think cues (light grey) improved recall performance, and recall performance did not significantly change in the baseline condition (dark grey). Error bars represent the standard error of the mean (SEM). (c) The level of cue discriminability, as measured by d' in unconscious trials did not significantly alter the effect of masked cues on final recall, and the effect remained significant when visibility was nil. The shaded area around the regression lines represents the 95% confidence interval. * = $p < 0.05$, ** = $p < 0.01$.

3.2. Results

3.2.1. Masked No-Think cues reduce recall performance compared to Think cues and to baseline

A two-way analysis of variance (ANOVA) on recall performance was performed for each participant, with cue type (Think versus No-Think) and time (initial versus final recall) as within subject factors, and subject as random factor. This analysis revealed a significant interaction between cue type and time ($F(2,58) = 7.63$, $p = 0.001$).

Masked No-Think cues significantly reduced recall performance in the final test compared to the initial test (67% versus 78%, $t(29) = 2.90$, $p = 0.007$). On the contrary, masked Think cues significantly improved recall performance in the final recall compared to the initial test (84% versus 78%, $t(29) = -2.25$, $p = 0.032$). For the baseline condition, no significant difference between initial and final recall was observed (81% versus 79%, $t(29) = 0.57$, $p = 0.57$) (Fig. 4b).

In the initial test, there was no significant difference in recall between words that were allocated to the different unconscious conditions (No-Think: 78%, Baseline: 79% and Think: 78%, $F(2,58) = 0.02$, $p = 0.98$). By contrast, in the final test, a significant difference in recall performance emerged with a main effect of cue type (No-Think: 67%, Baseline: 81% and Think: 84%, $F(2,58) = 4.65$, $p = 0.013$), and final recall performance was significantly lower when words were preceded by both No-Think cues compared to Think cues (difference: 17%, $t(29) = 3.55$, $p = 0.0013$) and baseline (difference: 13%, $t(29) = 2.08$, $p = 0.047$). However, there was no significant difference in recall performance between Think and baseline conditions (difference: 3%, $t(29) = 0.55$, $p = 0.59$) (Fig. 4a and Table 1).

3.2.2. The memory effect is not due to cue discriminability

Discriminability, as assessed by the forced choice test, was again very low in the unconscious condition but significantly above zero (hit rate 58.1%, $d' = 0.21$, $t(29) = 2.23$, $p = 0.033$). As in Experiment 1, a between-subjects regression analysis (Greenwald et al., 1996) demonstrated that subjects' ability to discriminate masked cues (d') was unrelated to the cues effect on memory (No-Think – Think final recall performance). The slope of the regression line was not significantly different from zero (slope = −0.007, $t(28) = -0.07$, $p = 0.94$), indicating that people's ability to discriminate masked cues did not predict their memory effect. The intercept of the regression line was significantly different from zero (intercept = −16%, $t(28) = -3.20$, $p = 0.003$), indicating that people who could not discriminate masked cues still showed an effect on final recall (Fig. 4c).

To further isolate the inhibition effect, we conducted the same regression analysis for final recall performance in unconscious No-Think trials versus baseline as a function of cue discriminability. Again, the effect of cues was unrelated to people's ability to discriminate masked cues (slope = −0.12, $t(28) = -0.91$, $p = 0.37$). The intercept was negative, but failed to reach statistical significance (intercept = −11%, $t(28) = -1.56$, $p = 0.13$).

We repeated the above analysis on final versus initial recall performance for No-Think word pairs, as a function of cue discriminability (d'). This analysis yielded a similar result with an effect of cues that was unrelated to people's ability to discriminate masked cues (slope = −0.11, $t(28) = -1.56$, $p = 0.13$). The effect of cues remained significant even for people who could not discriminate masked cues (intercept = −8%, $t(28) = -2.15$, $p = 0.040$).

3.2.3. Performance in the grammatical gender determination task

Performance in the word gender determination task did not significantly differ according to masked cue type (No-Think: 99.3%, Baseline: 99.5% and Think: 99.4%, $F(2,58) = 0.21$, $p = 0.81$), nor did reaction time (No-Think: 369 ms, Baseline: 394 ms, Think: 365 ms, $F(2,58) = 2.83$, $p = 0.07$).

3.2.4. Comparison of effect size in Experiment 1 and Experiment 2

We computed the effect size (Cohen d) for the difference between unconscious Think and unconscious No-Think cues in the two experiments. These amounted to 0.25 in Experiment 1 and 0.72 in Experiment 2. An ANOVA on recall performance, with cue type (Think versus No-Think) and Experiment (1 versus 2) as factors showed a significant main effect of cue type ($F(1,73) = 15.1$, $p < 0.001$) but no significant effect of Experiment ($F(1,72) = 0.15$, $p = 0.7$), suggesting that effect size was comparable in the two experiments.

4. General discussion

Taken together, the results of this study demonstrate that memory suppression through executive control can be unconsciously triggered on specific memories. Borrowing from Anderson's Think/No-Think paradigm (Anderson & Green, 2001), participants were trained to actively recall or repress word-word associations, in response to conscious visual cues. Then, the very same cues were subliminally presented while participants were doing a grammatical gender determination task on other hint words. Experiment 1 showed that recall performance was significantly lower with No-Think cues compared to Think cues, be they conscious or masked. Crucially, word pairs used in the unconscious condition were different from those used in the conscious condition, therefore, they had never been preceded by conscious Think/No-Think cues or consciously associated with these instructions.

In Experiment 1, the difference between the Think and No-Think conditions could either be due to a recall enhancement by Think cues and/or to a suppression effect by No-Think cues. Indeed, Experiment 1 did not comprise a baseline condition. Experiment 2 replicated the effect of masked cues on recall performance, and further demonstrated that this includes a suppression-induced forgetting component. Indeed, the recall of word pairs was lower when preceded by masked No-Think cues than in a neutral baseline condition (i.e. no cue). Therefore, the memory suppression effect was independent of any detrimental effect of time, or an interference with the distracting task. Furthermore, other controls ruled out a difference in initial encoding or a residual capacity to discriminate the cues.

In both experiments, d' values were significantly above zero. As proposed by Greenwald et al. (1996), we therefore performed a regression analysis in order to check whether subliminal priming relies on residual visibility. This method has been discussed using simulations (see e.g. Miller, 2000, but also Greenwald's reply in Klauer & Greenwald, 2000) and is routinely used even when d' are not significantly different from zero. We showed that the behavioural measures of interest were not correlated to d' and that the intercepts were significantly different from zero. This result suggests that subliminal cues impact memory independently of participant's ability to discriminate them.

The unconscious memory effect did not significantly differ between Experiment 1 and Experiment 2 although experimental modalities were slightly different, suggesting that this effect is robust and reproducible. Surprisingly, effect size was not significantly different between the masked and the conscious conditions in Experiment 1 (6% difference between Think and No-Think conditions with both conscious and masked cues). Previous work suggested that masked cues had a weaker effect than conscious cues (Dehaene & Changeux, 2011 for a review). However, opposing studies have shown that priming effects could be comparable with low-visibility cues and high-visibility cues (Vorberg et al., 2003). Similarly, electrophysiological studies found that N400 waves associated with semantic processing had the same amplitude under conscious and unconscious conditions in attentional blink and masking paradigms (Kiefer, 2002; Luck, Vogel, & Shapiro, 1996; vanGaal et al., 2014). These contradictory findings are potentially linked to the masking procedure itself. Indeed, Vorberg et al. (2003) used a long stimulus onset asynchrony (SOA) to increase the cue effect, and a long mask duration to maintain a low visibility of the stimulus. Following this procedure in the present experiment (SOA = 66 ms and mask duration = 200 ms), we obtained consistent results, i.e. strong effects of low-visibility cues.

Alternatively, the relatively large effect of masked cues we observed might be the result of the peculiar nature of the task. Indeed, we found a low intrusion rate (i.e. thinking about the response word while the instruction is to determine the gender of the hint word) in the unconscious condition (16.5% on average) compared to what is usually found in the conscious version of the Think/No-Think paradigm (60% at the beginning of the procedure and 30% at the end of the experiment, see Levy & Anderson, 2012). Several studies pointed to the importance of intrusions in the inhibition process (Benoit, Hulbert, Huddleston, & Anderson, 2015; Gagnepain, Hulbert & Anderson, 2017; Hellerstedt, Johansson, & Anderson, 2016; Levy & Anderson, 2012). However, intrusions could also induce a paradoxical reinstatement or reinforcement of the memory the subject tries to suppress. The conscious No-Think effect may therefore result from two opposing trends: a high inhibition that is tempered by automatic recall (as reflected by intrusions). By contrast, the unconscious memory effect may arise from a lower but unchallenged inhibitory effect, leading finally to a net effect similar to the one obtained under the conscious condition.

Our results are in line with previous publications suggesting that inhibition can be induced by subliminal stimuli. These studies demonstrated that cognitive control could be influenced by subliminal priming (Boy, Husain, & Sumner, 2010), error detection processes could proceed without awareness (Charles et al., 2013) and that inhibition, even intentional, could be triggered unconsciously (Parkinson & Haggard, 2014; vanGaal et al., 2010). Moreover, unconscious memory suppression further adds to the strongly debated question of the long-lasting effects of unconscious cues on cognitive processes. In most priming studies, the effect of masked cues sharply decreases with time and vanishes within less than a second (Dehaene & Changeux, 2011). Nonetheless, recent studies suggested that a stimulus subjectively judged as unseen could be maintained in neuronal activity for more than 1 s (King, Pescetelli, & Dehaene, 2016). In addition, subliminal visual stimuli have been shown to affect familiarity judgements (Sweeny, Grabowecky, Suzuki, & Paller, 2009; Voss & Paller, 2009; Voss, Baym, & Paller, 2008) or preference judgement (Kunst-Wilson & Zajonc, 1980) several minutes, hours or days later, and emotional words trigger cerebral changes over several minutes (Gaillard et al., 2007). In the present experiment, the lower recall performance in the unconscious No-Think condition supports the idea that masked cues have a detrimental effect that affects performance several minutes after they were presented (i.e. in the final test). To the best of our knowledge, only one previous study demonstrated a long-lasting detrimental effect of unconscious cues by measuring the attractiveness of masked cues in a reinforcement learning paradigm (Pessiglione et al., 2008).

Finally, working memory has already been demonstrated to be influenced by unconscious effects (Soto & Silvanto, 2014; Trübutschek et al., 2017). To ensure that our effects concerned long-term declarative memory processing, we used a large number of word pairs (30 in Experiment 1 and 24 in Experiment 2), far exceeding working memory capacity (Squire & Wixted, 2011).

To summarize, these experiments showed that it is possible to suppress specific memories unbeknownst to participants, in a minimal laboratory setting. As people encounter repeated occasions to recall or repress memories throughout their lifetime, the mechanism described here could explain why one may occasionally experience the inability to recall unwanted memoires, while unaware of any conscious will to reject it (Naccache, 2006).

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.cognition.2018.06.023.

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