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Conscious control over the content of unconscious cognition

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Abstract

Visual stimuli (primes) presented too briefly to be consciously identified can nevertheless affect responses to subsequent stimuli – an instance of unconscious cognition. There is a lively debate as to whether such priming effects originate from unconscious semantic processing of the primes or from reactivation of learned motor responses that conscious stimuli afford during preceding practice. In four experiments we demonstrate that unconscious stimuli owe their impact neither to automatic semantic categorization nor to memory traces of preceding stimulus-response episodes, but to their match with pre-specified cognitive action-trigger conditions. The intentional creation of such triggers allows actors to control the way unconscious stimuli bias their behaviour.

Keywords: Unconscious cognition; Number processing; Action control

1. Introduction

Ever since the early days of scientific psychology unconscious information processing has been a fascinating and controversially debated topic. Indeed, the phenomenon that stimuli might bias our behaviour in the absence of awareness of them and the mental machinery that mediates their impact provides a challenge, both for intuition and psychological theorizing.

Fig. 1 illustrates a widely acknowledged experimental demonstration of the basic phenomenon. Participants are to indicate as quickly as possible whether a target numeral is smaller or larger than 5 by pressing a left or right response key. The target is preceded by

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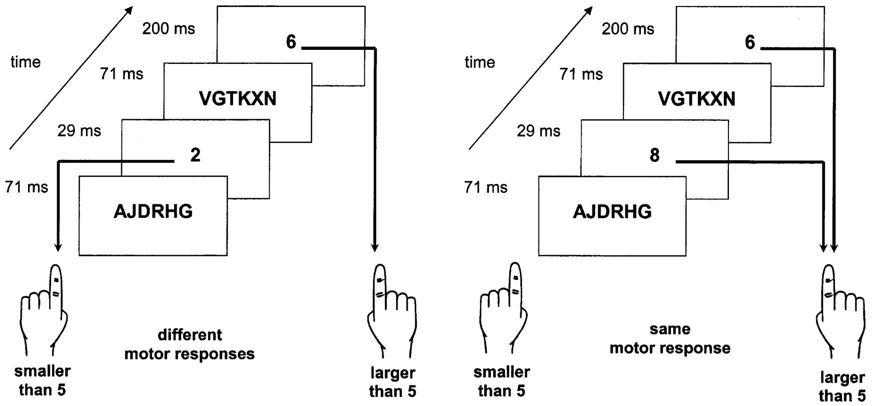

Fig. 1. Experimental task. In the example the participant was to give a left-hand response when the target was smaller than 5 and a right-hand response when it was larger than 5. The target was preceded by a brief prime, presented too briefly to be discriminable. The left side shows an incongruent trial, in which the prime would afford a different response than the target, thereby producing a covert response conflict. The right side shows a congruent trial in which the prime would afford the same response as the target (adopted from Dehaene et al., 1998).

a prime numeral, presented too briefly to be identified consciously. Nevertheless, responses are faster when prime and target fall on the same side of the 5, and thus call for the same response (congruent trial), than when they fall on opposite sides, and thus call for different responses (incongruent trial) (Dehaene et al., 1998; Koechlin, Nacchache, Block, & Dehaene, 1999; Naccache & Dehaene, 2001). Brain imaging has shown that such subliminal primes evoke their corresponding manual responses up to a measurable activity of motor areas, which produces a covert motor conflict and an increase of reaction times when this response differs from the one subsequently required by the target (Dehaene et al., 1998).

From demonstrations like these it is commonly accepted that stimuli can influence behaviour unconsciously. What is disputed, however, is the nature of mechanisms that mediate these influences. Basically, two competing positions can be identified.[1]

The ‘elaborate processing’ hypothesis, on the one hand, holds that subliminal stimuli are unconsciously processed up to a semantic level, in principle not different from conscious cognition (Dehaene et al., 1998; Dell’Acqua & Grainger, 1999; Koechlin et al., 1999; Naccache & Dehaene, 2001). Following this view, task-defined cognitive operations become unselectively applied to any suitable stimulus, be it consciously perceivable or not. Participants thus “unconsciously apply the task instructions to the prime, would therefore categorize it as smaller or larger than 5, and would even prepare a motor response appropriate to the prime” (Dehaene et al., 1998, p. 598). The elaborate processing hypothesis is corroborated by three observations (cf. Dehaene et al., 1998; Koechlin et al., 1999; Naccache & Dehaene, 2001). First, priming extends beyond cases in which the

[1] In a sense, these positions reflect extreme poles on a continuum regarding the ‘smartness’ of unconscious cognition, ranging from very ‘smart’ to very ‘dull’. More moderate positions will be treated in Section 7.

target is merely a replication of the prime (e.g. prime: 4 → target: 4). It is thus not simply a repetition effect, but covers stimuli from the entire task-defined category (i.e. all primes smaller or larger than 5). Second, priming effects generalize over notation format, that is they occur even when primes are Arabic numerals and targets are numeral words and vice versa. Thus, the primes' impact appears to depend on their semantics rather than on their superficial physical appearance. Third, with a congruent prime, responding is faster with a small numerical difference between prime and target (e.g. prime: 3 → target: 4), than with a large difference (e.g. prime: 1 → target: 4), which requires that the magnitude meaning of the primes is accessed. It is often claimed, or implied, that "nonconscious perceptual processes automatically redescribe sensory data into every representational form and to the highest levels of description available to the organism" (Marcel, 1983, p. 238). This is assumed to be particularly true for numerical stimuli, like Arabic numbers, number words, or manageable amounts of objects, where the processing of quantity meaning "cannot be prevented even in situations where it is totally irrelevant" (Naccache & Dehaene, 2001, p. 235).

The 'evolving automaticity' hypothesis, on the other hand, denies the possibility of elaborate processing without awareness (Abrams & Greenwald, 2000; Damian, 2001; Logan, 1988; Neumann & Klotz, 1994). Instead, it attributes unconscious priming effects to "acquired mappings between targets and response keys that are also applied to subliminally presented primes" (Damian, 2001, p. 158). In other words consciously perceived stimuli (targets) that afford a certain response can acquire the power to activate the same response some time later when presented as subliminal primes via a persisting memory trace of this stimulus-response (S-R) episode. The 'evolving automaticity' hypothesis also gains support from three observations. First, subliminal stimuli produce congruency effects primarily when they serve as supraliminal targets for the same participants in the same experimental epoch (i.e. when primes are part of the target set). Thus, a stimulus appears to have the power to activate a response unconsciously only when a corresponding conscious S-R memory trace already exists (Abrams & Greenwald, 2000; Damian, 2001). Second, primes not used as targets evoke responses only to the degree they physically resemble seen targets (Abrams & Greenwald, 2000). Third, subliminal stimuli do not have response-activating power immediately, but acquire it with practice, that is with increasing strength of residing S-R memory traces (Damian, 2001).

In the present study we argue that both positions draw an inadequate, or at least incomplete, picture of unconscious response priming. Basically, this is because both positions bear on an inappropriate but still prominent dogma of cognitive science which regards the stimulus as the ultimate origin of action (Donders, 1868/1969; Sanders, 1980; Sternberg, 1969). In contrast we propose that the impact of subliminal stimuli is crucially determined by the actor's pre-stimulus intentions. The basic suggestion is that actors categorize existing cognitive representations of external events into appropriate release preconditions for task-defined response alternatives.[2] If an external event sufficiently matches one of these conditions the corresponding action is prepared and possibly initiated instantaneously before (or without) the actor becomes aware of the action-triggering event

[2] These need not necessarily be particular motor commands, but might well be more abstract response codes (cf. Abrams, Klinger, & Greenwald, 2002).

itself. Subliminal stimuli thus bias responses to the degree they match pre-specified action-trigger conditions – a position in the following referred to as the 'action-trigger' hypothesis.

Even at this admittedly coarse level of description the action-trigger hypothesis allows for predictions that challenge the two above mentioned positions. First, in contrast to the 'elaborate processing' hypothesis, it denies that briefly presented stimuli (primes) are always subjected to conceptual categorization procedures if only these stimuli qualify as appropriate input. We suggest that semantic codes primarily operate in advance of task performance to segment potential stimulus events into appropriate and inappropriate action triggers. In a typical experiment this proceeds when task requirements become apparent, that is during task instructions or initial practice trials, and thus often long before the first experimental response is recorded. The subsequent analysis of experimental stimuli is then limited to a degree that suffices to detect the stimulus' match (or mismatch) with one of these triggers. For example, the instruction to respond left to Arabic numerals smaller than 5 might induce the recollection of codes of individual objects that fit this semantic criterion (the numerals 1, 2, 3, and 4). Thus, although action triggers may initially be recollected from memory by means of a semantic criterion, a perceptual match with these recollected triggers may then suffice for subliminal response activation. Second, in contrast to the 'evolving automaticity' hypothesis, we assume that subliminal response priming does not require repetitions of conscious S-R episodes, but takes place instantaneously, and can occur even for a stimulus never consciously perceived in a given task context, providing this stimulus sufficiently matches a pre-specified trigger code.

This basic idea is not new. It has emerged in behavioural sciences in one form or the other several times. For example, Narziß Ach (1905) termed the action-trigger conditions he claimed to have identified in his experimental subjects 'Bezugsvorstellungen' (referential propositions). In modern cognitive psychology, terms like 'conditional automaticity' (Bargh, 1989) and 'prepared reflex' (Hommel, 2000) have been coined to describe that stimuli can evoke actions in an immediate fashion given that corresponding action release codes have been set up (cf. also Tzelgov, Henik, & Leiser, 1990). Even in research on unconscious priming it has been observed that only those stimuli evoke responses subliminally that subjects are prepared to attend to, and to respond to, which again is pointing to the relevance of action-trigger conditions (Ansorge, Heumann, & Scharlau, 2002; Eimer & Schlaghecken, 1998; Naccache, Blandin, & Dehaene, 2002; Neumann & Klotz, 1994). Nevertheless, these observations have not yet prompted a systematic investigation of the existence and the nature of these conjectured trigger conditions, which is particularly true for the domain of unconscious numerical cognition. The purpose of the present study was to provide a first step in this direction.

2. Overview of the experiments

We report four experiments that provide converging evidence for the existence of unconsciously operating action triggers, but at the same time disprove crucial predictions of the two traditional hypotheses outlined above. Basically – to use Ach's original term – we varied the content of our participants' 'Bezugsvorstellungen' (i.e. trigger conditions), and demonstrate that the response-activating impact of subliminal stimuli crucially depends on whether these stimuli meet the content of these trigger conditions or not, irrespective of their fit to semantic response categories (thereby refuting a crucial aspect of the 'elaborate processing' hypothesis) or their contribution to conscious S-R episodes (thereby refuting a crucial aspect of the 'evolving automaticity' hypothesis). We will demonstrate this by means of the standard smaller/larger than 5 task described in Section 1, although we do not consider our basic reasoning to be confined to it. Rather numerical stimuli allow us to easily vary the (numerical) content of participants' action-trigger conditions, and, moreover, to compare our findings with existing studies on subliminal priming that extensively used this particular task (Dehaene et al., 1998; Koechlin et al., 1999; Naccache & Dehaene, 2001).

Experiment 1 will replicate two observations against the evolving automaticity hypothesis and in favour of the elaborate processing hypothesis: (i) the extension of priming to novel, unseen primes; and (ii) the format independency of priming. We then suggest that priming extends to novel stimuli not because of their genuine semantic analysis, but because of their incidental inclusion in initially assembled action-trigger sets. This suggestion is substantiated by the observations that unseen numbers exert no priming when not falling into participants' numerical action-trigger range (Experiment 2) or when action triggers are recruited by means of non-numerical criteria (Experiment 3). Finally, we show that notation independent priming occurs only when format is varied within subjects, but not (or much less) when it is varied between subjects, and thus stimuli in an unseen format can be identified as inadequate action triggers by means of simple format features (Experiment 4).

3. Experiment 1

A strong argument against the evolving automaticity hypothesis and at the same time for the elaborate processing hypothesis is that priming can extend to novel unseen stimuli. For example, Naccache and Dehaene (2001) showed that in a smaller/larger than 5 task, where only the targets 1, 4, 6, and 9 were used, priming spread to the numbers 2, 3, 7, and 8, although these numbers were never consciously responded to themselves (cf. also Greenwald, Abrams, Naccache, & Dehaene, in press). Additionally, priming generalized over notation format, i.e. occurred when primes were Arabic numerals and targets were number words or vice versa. Both observations suggest that priming is based on semantic prime codes rather than on learned responses to specific stimuli. As a first step Experiment 1 intended to replicate these observations, to ensure that crucial variations of the basic data pattern in subsequent experiments were not caused by some more or less minor aspect of our specific experimental set up.

3.1. Method

3.1.1. Participants

Twelve volunteers (aged 20–32 years) took part in an individual session of approximately 90 min either in fulfilment of course requirements or in exchange for pay. All reported having normal or corrected-to-normal vision, and were not familiar with the purpose of the experiment.

3.1.2. Apparatus and stimuli

An IBM-compatible computer with a 17 inch VGA-Display was used for stimulus presentation and response sampling. Stimulus presentation was synchronized with the vertical retraces of a 70 Hz monitor, resulting in a vertical refresh rate of approximately 14.5 ms. Responses were executed with the index fingers of both hands and collected with an external keyboard with three response keys (1.7 cm width, distance 0.2 cm); the middle response key was not used.

Eight primes (numbers 1–9 excluding 5), a neutral prime (the symbol '&') and four targets (numbers 1, 4, 6, and 9) were used as stimuli. The primes were presented for three refresh cycles of the display, i.e. 43 ms. They were preceded and followed by a random letter mask consisting of six letters with a duration of 72 ms. The target was presented for 200 ms immediately after the post mask. All characters were presented in Triplexfont in white on a dark-grey background; a character extended approximately 1 cm in height and 0.8 cm in width.

The stimulus set consisted of 128 pairs of primes and targets either in Arabic or spelled-out format. These 128 combinations were presented three times per block in addition to 128 trials with a neutral prime (with each target and format combination for a total of 16 times).

In a post-experimental detection task another 64 trials were presented consisting of 32 trials with each prime–target combination and 32 trials with the neutral prime. In the detection task half of the primes and targets were presented in Arabic or spelled-out format.

3.1.3. Procedure

After being familiarized with the stimulus set by means of 24 practice trials participants performed three blocks of 512 trials. Half of the participants were asked to press a left button with the left index finger when the target was smaller than 5 and a right button with the right index finger when the target was larger than 5 as fast and as accurately as possible. For the other half of the participants the response mapping was reversed. Errors were indicated by a beep sound and excluded from reaction time analysis.

After the experiment participants performed a detection task to test whether they were able to consciously perceive the primes. Participants were fully informed about the precise structure of the prime stimuli and were then presented with 64 trials identical to the experimental trials. Thirty-two trials contained a neutral prime. Participants were to discriminate between neutral and non-neutral primes. When they indicated to have seen a non-neutral prime they were asked to identify it.

3.2. Results

3.2.1. Response priming

Responses with RTs above 1500 ms were discarded (0.1% of the data). Mean RTs from correct responses were then submitted to an analysis of variance (ANOVA) with the

Table 1
Experiment 1: response times (in milliseconds) and error rates (in percent) as a function of congruency, prime-type, and prime–target notation match[a]

	Prime–target notation							
	Same				Different			
	Congruent		Incongruent		Congruent		Incongruent	
Prime-type	RT	PE	RT	PE	RT	PE	RT	PE
From target set	462	4.9	470	6.6	456	4.5	473	5.4
Not from target set	461	4.1	472	5.2	456	5.5	464	5.7

[a] RT, response times in milliseconds; PE, percentage of errors.

variables of Congruency (congruent or incongruent[3]), Prime-type (from the target set vs. not from the target set), and Prime–Target notation match (prime and target used the same or different format). The mean RTs and error rates from the factorial combination of these variables are listed in Table 1.

Responses were faster with congruent than with incongruent primes ($F(1, 11) = 25.17$, $P < 0.001$). The congruency effect did not interact with prime-type ($F < 1$, for the congruency × prime-type interaction), and it was significant for primes from the target set ($F(1, 11) = 24.55$, $P < 0.001$), as well as for primes not from the target set ($F(1, 11) = 12.47$, $P < 0.01$). The congruency effect did also not depend on a prime–target notation match ($F < 1$ for the congruency × notation match interaction), and it was significant when prime and target format were the same ($F(1, 11) = 7.36$, $P < 0.05$) as well as when they were different ($F(1, 11) = 27.56$, $P < 0.001$). Additionally, responses were on average slightly slower with a notation repetition than with a notation change ($F(1, 11) = 7.15$, $P < 0.05$). This presumably reflects larger forward masking by the prime, when it exactly matched the subsequent target regarding physical length. Finally, the congruency effect was slightly reduced when primes from the target set preceded targets in the same notation, or primes not from the target set preceded targets in a different notation ($F(1, 11) = 5.25$, $P < 0.05$, for the congruency × prime-type × notation interaction). At this point we have no straightforward explanation for this. At least the former effect might reflect slightly stronger backward masking of the prime by the subsequent target when using the same format. Importantly, however, the congruency effect was significant in all conditions (all $P < 0.05$).

The same ANOVA performed on error rates revealed the interaction between prime-type and notation change to be significant ($F(1, 11) = 7.40$, $P < 0.05$). Error rates were on average relatively high when primes from the target set preceded targets in the same notation, which was primarily due to the increased error rates for incongruent primes from this condition. No traces of a speed–accuracy trade off were found.

[3] With a neutral prime mean RTs amounted to 461 ms and mean error rate to 5.7%. Because the same neutral symbol (‘&’) was used under all conditions, the data with a neutral prime could not be included as an orthogonal factor in this analysis.

A further ANOVA analyzed the RTs from congruent primes as a function of numerical prime–target distance. No distance effect was found, independent of whether prime and target notation matched or not ($F < 1$ for the distance effect and its interaction with prime–target notation). Mean RTs (error rates in parentheses) with a prime–target distance of 1, 2, and 3 amounted to 459 ms (5.2%), 459 ms (4.4%), and 462 ms (5.1%).

3.2.2. Prime visibility

Participants' discrimination performance for neutral vs. non-neutral primes was $d' = 0.29$ (the mean hit rate was 31.5%, false alarm rate 21.1%) and deviated from zero ($t(11) = 2.23$, $P < 0.05$). However, the non-zero detection rate was mainly due to the participants' ability to indicate correctly the presentation of the neutral prime. The identification rate for the prime numbers was 2.2% (the chance level is 6.25% as each prime is presented four times in the 64 test trials). Thus, the primes were indeed unidentifiable, as is usually found under the experimental conditions that we adopted (Damian, 2001; Dehaene et al., 1998; Koechlin et al., 1999; Naccache & Dehaene, 2001).

3.3. Discussion

Experiment 1 successfully replicated two findings from the literature on unconscious response priming. Priming extended to novel unseen primes and it survived a notation change between prime and target. Both observations are hard to be reconciled with rote S-R learning. Instead these observations appear to suggest a more or less automatic extraction of quantity meaning from subliminal stimuli.

However, one aspect of the data casts doubt on a semantic level of priming: response latencies for congruent trials were unaffected by the numerical prime–target distance, which suggests that the primes were not processed up to a level that implies their localization in cognitive magnitude space.

But how then might priming extend to unseen numbers, if not assuming that primes were processed up to a semantic level? To understand this it is essential to realize that numbers are mentally represented in a highly interrelated manner, often described as a quasi-spatial mental number line (e.g. Galton, 1880; Göbel, Walsh, & Rushworth, 2001). The activation of certain elements of this integrated representation is thus likely to spread over to tightly associated adjacent elements. When instructions suggest a magnitude judgement, the recruitment of action triggers will rely on the mental number line. We conjecture that the initial picking-up of action triggers from this integrated representation for task preparation makes it very hard to prevent numerically enclosed numerals from entering the same trigger set. In other words, the spread of priming to unseen numbers may reflect the incidental inclusion of these numbers in participants' action-trigger sets, which for convenience is allowed as long as task instructions do not explicitly forbid it. Later on, subliminal stimuli may well activate an action simply by matching an existing action trigger without being necessarily located on the number line themselves.

The next experiments intend to further this conjecture. Experiment 2 will show that priming barely extends to unseen numbers that are less adjacent to (i.e. not enclosed by) to-be-recruited target triggers on the number line, and hence an accidental inclusion of additional numbers in the trigger set is less likely. Experiment 3 will show that a spread of

Targetsets in	smaller than 5				larger than 5			
Exp. 2 (narrow range)	-	-	3	4	6	7	-	-
Exp. 1, 4 (wide range)	1	-	-	4	6	-	-	9

Fig. 2. The targets used in Experiments 1, 2 and 4. The shaded area illustrates the presumed content of the participants' action-trigger conditions induced by these target sets.

priming to unseen numbers can indeed be fully abolished when participants are explicitly encouraged to confine their action triggers to individual elements rather than to numerical ranges on the number line.

4. Experiment 2

According to the action-trigger account a spread of priming to unseen stimuli should not occur when these stimuli are not included in participants' action-trigger sets. To test this conjecture we again employed a subset of available numbers as targets, but these targets were now from a limited magnitude range between 3 and 7 (i.e. the numbers 3, 4, 6, and 7, cf. Fig. 2). We predicted that unseen numbers would now enter the same trigger set incidentally much less easily because these numbers were now well outside (rather than inside) the range of to-be-recruited target triggers in magnitude space.

The elaborate processing hypothesis, in contrast, attributes the spread of priming to unseen stimuli to the automatic semantic categorization of all unconscious stimuli. It thus predicts that priming should clearly extend to all numbers that fall into the task-defined semantic response categories. "This should result in an interference effect for all primes, whether new or old." (Naccache & Dehaene, 2001, p. 225).

For this experiment we used Arabic numerals exclusively because we wanted to optimize the conditions for a spread of priming to unseen numbers, which is reasonably more likely the smaller the set of novel stimuli. Admittedly, the unseen numbers in this experiment (1, 2, 8, and 9) although not enclosed by, were still adjacent to the conjectured action-trigger range. The probability of unseen numbers entering the trigger set is thus presumably not zero, and they may therefore still exert some residual priming. But this effect should be clearly smaller than the one for primes from the trigger set. Note that we predict this although the unseen numbers were *further* away from the neutral reference 5 than the seen numbers, which typically produces *larger* rather than smaller priming effects (Koechlin et al., 1999).

4.1. Method

4.1.1. Participants

Twelve participants (aged 19–32 years) took part in an individual session of approximately 60 min either in fulfilment of course requirement or in exchange for pay. They reported having normal or corrected-to-normal vision and were naive about the hypothesis of the experiment.

4.1.2. Apparatus and stimuli

The apparatus and stimuli were the same as in Experiment 1 with the following exceptions. Targets were the numbers 3–7 excluding 5. Primes and targets were presented as Arabics. As Arabics are perceived faster than letter strings the prime duration was reduced to 29 ms.

The stimulus set consisted of 32 pairs of primes (Arabic numbers 1–9 excluding 5) and targets (Arabic numbers 3, 4, 6, and 7) which were presented three times per block in addition to a pairing of each target with a neutral prime (the symbol '&') presented eight times per block, resulting in 128 trials per block.

4.1.3. Procedure

The procedure of the experiment and the detection task were similar to Experiment 1. Now participants performed six blocks of 128 trials.

4.2. Results

4.2.1. Response priming

Responses with RTs above 1500 ms were excluded (0.1% of the data). Mean RTs were submitted to an ANOVA with the repeated measures of Congruency (incongruent or congruent[4]) and Prime-type (from the target set or not from the target set). The mean RTs and error rates from the factorial combination of these variables are listed in Table 2. Responses were faster with congruent than with incongruent primes ($F(1, 11) = 15.24$, $P < 0.01$). This was true, however, only for primes from the target set, which produced a significant interaction of congruency and prime-type ($F(1, 11) = 8.03$, $P < 0.05$). Single comparisons revealed a significant congruency effect for primes from the target set ($F(1, 11) = 15.38$, $P < 0.01$), but no reliable effect for primes not from the target set ($P > 0.12$).

The interaction of congruency and prime-type was also significant in error rates ($F(1, 11) = 7.74$, $P < 0.05$), again indicating a significant congruency effect for primes from the target set ($F(1, 11) = 6.35$, $P < 0.05$), but a non-significantly reversed congruency effect for primes not from the target set ($F < 1$).[5]

4.2.2. Prime visibility

Participants' discrimination performance for neutral vs. non-neutral primes was $d' = 0.33$ (the mean hit rate was 58.9%, false alarm rate 47.1%) and deviated from zero ($t(11) = 4.09$, $P < 0.01$). Again the non-zero detection rate was mainly due to partici-

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[4] With a neutral prime mean RT was 422 ms and mean error rate was 3.7%.

[5] Due to the particular subset of targets, the numerical prime–target distance was confounded with prime-type (i.e. from the target set or not). For example, a numerical distance of 3 included only primes not from the target set (the numbers 1 and 9), whereas a distance of 1 also included primes from the target set (e.g. the numbers 3 and 7). Because the factor prime-type significantly altered the congruency effect, an analysis of the distance effect could not be unambiguously interpreted, and was thus not computed.

pants' ability to indicate correctly the presentation of the neutral prime. The identification rate for the prime numbers was 5.6%, which was below the chance level of 6.25%.

4.3. Discussion

In Experiment 2 the incidental consideration of unseen numbers as action triggers was rendered unlikely because these numbers were now outside the numerical target range. No extension of priming to unseen numbers was observed, even though these numbers could be unambiguously classified as smaller/larger than 5. Thus, minimal changes in the task were sufficient to remove priming effects even for the very same prime–target pairs as in Experiment 1 (e.g. $2 \rightarrow 4$, $8 \rightarrow 6$). This is a devastating finding for automatic spreading activation theory (e.g. Neely, 1991) but in line with other studies pointing to attentional and intentional constraints of subliminal response priming (Dagenbach, Carr, & Wilhelmsen, 1989; Naccache et al., 2002).

The observed restriction of priming to seen numbers might seem like a reanimation of the evolving automaticity hypothesis, which we had already rejected because of its inability to explain the extension of priming to novel stimuli in Experiment 1 (a finding replicated in Experiment 4). Yet, a closer look at the data casts doubt as to whether this hypothesis does a better job in explaining the results. It turned out that the priming effect for primes from the target set was present from the outset even in the first experimental block (22 ms, $P < 0.05$), and it was not systematically affected by practice (in the six blocks the congruency effect in RTs (error rates in parentheses) amounted to 22 ms (2.1%), 8 ms (3.1%), 21 ms (4.2%), 30 ms (6.9%), 14 ms (2.1%), and 24 ms (4.5%), respectively). This is hardly to be reconciled with evolving S-R automaticity which predicts that priming "should clearly build up across the experiment" (Damian, 2001, p. 158).

Altogether, Experiments 1 and 2 stress the importance of the type of mental representation action-trigger codes are initially recruited from. Apparently priming extends to unseen stimuli if the mental representation of collected action triggers promotes the co-activation of codes of unseen stimuli, but it does not when this co-activation is unlikely. Experiment 3 furthered this conjecture.

Table 2
Experiment 2: response times (in milliseconds) and error rates (in percent) as a function of congruency and prime-type[a]

	Congruency			
	Congruent		Incongruent	
Prime-type	RT	PE	RT	PE
From target set	415	2.3	435	6.1
Not from target set	422	3.5	426	3.4

[a] RT, response times in milliseconds; PE, percentage of errors.

5. Experiment 3

We attribute the extension of priming to unseen numerical primes to the integrated representation of numbers from which action triggers are recruited (the mental number line). This allows for a straightforward prediction. No extension of priming should occur when participants refrain from specifying action triggers according to this mental representation.

We tested this by varying instructions. Experiment 3 was essentially a replication of Experiment 1 with the exception that participants were not told to classify numbers as smaller/larger than 5 any more, but to press a left button with a digit 1 or 4 and a right button with a digit 6 or 9. We expected that action triggers would no more be recruited by means of ordinal but perceptual features of the individual stimuli. To promote an exemplar-based stimulus interpretation, a brief classification task with numerically unrelated symbols (e.g. #, +, ~, *) preceded the experimental trials. If participants successfully disregarded ordinal aspects of the numbers when setting up their action triggers, numbers numerically enclosed by the targets should not tend any more to enter the trigger sets.

Note that a lack of priming to numerically enclosed primes would not be a trivial finding from the perspective of the elaborate processing view which bears on the assumption that "access to the quantity meaning of numbers is a highly automated process that cannot be prevented even in situations where it is totally irrelevant" (Naccache & Dehaene, 2001, p. 235). If this were the case, activation should spread to a certain degree to numerically close numbers irrespective of task context. For example, because the primes 2 and 3 are numerically closer to the 'left-response' targets (1, 4) than to the 'right-response' targets (6, 9), the primes 2 and 3 should activate left-response stimulus codes more than right-response stimulus codes. Thus, some facilitatory influence by numerical prime–target adjacency can reasonably be expected under these conditions, provided magnitude meaning is actually accessed.

5.1. Method

5.1.1. Participants

Twelve volunteers (aged 18–28 years) took part in an individual session of approximately 30 min either in fulfilment of course requirements or in exchange for pay. All reported having normal or corrected-to-normal vision, and were not familiar with the purpose of the experiment.

5.1.2. Apparatus and stimuli

In the practice trials the symbols #, +, ~, and * were used as targets. During the experimental session the targets were the Arabics 1, 4, 6, and 9. The stimulus set consisted of 32 pairs of primes (Arabic numbers 1–9 excluding 5) and targets which were presented three times per block in addition to a pairing of each target with a neutral prime (the symbol '&') presented eight times per block, resulting in 128 trials per block. Prime duration was 29 ms.

5.1.3. Procedure

Participants performed 24 practice trials in which they were instructed to press a left button when the symbol # or + was presented and a right button for ~ or *. Then they were informed that the targets changed to the Arabics 1, 4, 6, and 9. Half of the participants were asked to press a left button with the left index finger when the target was 1 or 4 and a right button with the right index finger when the target was 6 or 9 as fast and as accurately as possible. For the other half of the participants the response mapping was reversed. Attention was paid to never use the term smaller or larger than 5. Participants performed three blocks with 128 trials and a similar detection task as in Experiment 1.

5.2. Results

5.2.1. Response priming

No response exceeded the outlier criterion of 1500 ms. Mean RTs were submitted to an ANOVA with the repeated measures of Congruency (congruent or incongruent[6]) and Prime-type (from the target set or not from the target set). The mean RTs and error rates from the factorial combination of these variables are listed in Table 3. Only the interaction of these factors was significant ($F(1, 11) = 31.28$, $P < 0.001$). This was due to a significant congruency effect for primes from the target set ($F(1, 11) = 21.67$, $P < 0.001$), but a significantly reversed congruency effect for primes not in the target set ($F(1, 11) = 6.58$, $P < 0.05$). The analysis of error rates revealed no reliable effects (all $Ps > 0.16$).

5.2.2. Prime visibility

Participants' discrimination performance for neutral vs. non-neutral primes was at chance level ($d' = -0.11$) as the hit rate did not exceed the false alarm rate (30.5% and 34.4%). The prime identification rate was 2.9% and did not exceed the chance level of 6.25%.

5.3. Discussion

In Experiment 3 task instruction encouraged an exemplar-based interpretation of the target numbers. No spread of priming to numbers numerically encompassed by targets was found. Indeed the priming effect for numbers not from the target set was even significantly *reversed*. Debriefing participants clarified why this was the case. Some of them reported constructing action triggers in the following manner: respond left with straight-lined stimuli (1 and 4) and right with curved stimuli (6 and 9). As a consequence the curved primes 2 and 3 presumably activated a right rather than a left response, and at least the straight-lined number 7 activated a left rather than a right response, which explains the overall reversed priming effect for unseen stimuli.

Even if one accepts that the spread of priming to novel stimuli might result from the off-line inclusion of these stimuli into action-trigger sets, rather than from their on-line semantic analysis, still one finding deserves explanation: does the format independency

[6] With a neutral prime RTs amounted to 404 ms and error rate was 2.8%. As in Experiment 2 prime-type affected the congruency effect, disallowing a reasonable analysis of the prime–target distance effect.

of priming in Experiment 1 not imply that the stimulus' meaning is actually extracted upon prime presentation? From the perspective of an action-trigger account an alternative explanation offers itself. Experiment 1 (like other format manipulation in the literature) varied the target format *within* participants. Thus, subjects consciously perceived stimuli in both formats, which allows for the possibility that notation independency is based on the setting up of triggers in both experienced formats, rather than on the genuine extraction of prime meaning. Therefore, Experiment 4 sought to provide a more powerful test of the semantic basis of notation independency.

6. Experiment 4

For this experiment, the target format was varied *between* participants. That is, one group of subjects was exclusively presented with target digits, whereas the other group was exclusively presented with target words. Both formats were used as primes for all subjects. If priming is based on genuine semantic codes, as proposed by the 'elaborate processing' hypothesis, it should clearly survive a notation change even with this between-subjects variation. If, however, the creation of action triggers follows acknowledged task demands, stimuli in a never experienced format should be disregarded as action triggers (e.g. by means of differences in physical width between Arabic numerals and number words).

Basically we thus expected priming to be confined to stimuli in a seen format. Again, this might appear as an attempt to save the evolving automaticity hypothesis. To clarify that this is not the case, we employed a numerically wide-spread set of targets (1, 4, 6, and 9), and the standard smaller/larger than 5 instruction again. As the instruction stresses numerical stimulus features, we expected that numerical aspects might well contribute to the task-preparing recruitment of action-trigger codes, rendering the inclusion of numerically enclosed stimuli into the trigger set possible. This should produce priming by numerically enclosed, but nominally unseen numbers (2, 3, 7, and 8) at least when presented in the expected format – a finding that again could barely be reconciled with rote S-R learning.

Table 3
Experiment 3: response times (in milliseconds) and error rates (in percent) as a function of congruency and prime-type[a]

	Congruency			
	Congruent		Incongruent	
Prime-type	RT	PE	RT	PE
From target set	394	3.7	416	5.4
Not from target set	409	3.9	400	3.4

[a] RT, response times in milliseconds; PE, percentage of errors.

6.1. Method

6.1.1. Participants

Twenty-four participants (aged 18–36 years) took part in an individual session of approximately 35 min either in fulfilment of course requirement or in exchange for pay. They reported having normal or corrected-to-normal vision and were naive about the hypothesis of the experiment.

6.1.2. Apparatus and stimuli

The stimulus set consisted of 64 pairs of primes (numbers 1–9 excluding 5) in Arabic or spelled-out format and targets (numbers 1, 4, 6, and 9) that were presented for half of the participants in Arabic or spelled-out format. No neutral prime was used during the experimental session. During the detection task again the symbol '&' served as a neutral prime and was presented in half of the trials. As numeral words are perceived more slowly than digits, the prime duration was set to 43 ms.

6.1.3. Procedure

The procedure was the same as in Experiment 1, however half of the participants were presented with targets as Arabics only and the other half with targets in spelled-out format only. Participants performed ten blocks with 64 trials and the detection task.

6.2. Results

6.2.1. Response priming

Responses with RTs above 1500 ms were excluded (0.2% of the data). Mean RTs were submitted to an ANOVA with the variables of Congruency (congruent or incongruent[7]), Prime-type (whether the prime was also used as a target or not), and Prime–Target format match (whether the prime and target format matched or not) as repeated measures. The mean RTs and error rates from the factorial combination of these variables are listed in Table 4. Responses were faster with congruent than with incongruent primes ($F(1,23) = 43.20$, $P < 0.001$). The congruency effect interacted with Prime–Target format match ($F(1,23) = 6.39$, $P < 0.02$). There was a congruency effect when prime and target format matched ($F(1,23) = 23.27$, $P < 0.001$), but not when they did not match ($P > 0.20$). With prime–target notation match the congruency was significant for primes from the target set ($F(1,23) = 16.04$, $P < 0.001$), as well as for primes not from the target set ($F(1,23) = 7.27$, $P < 0.02$). Finally, the increased RTs with incongruent format-matching primes produced overall slightly slower RTs with a notation match ($F(1,23) = 5.21$, $P < 0.05$).

Error rates mirrored RTs. Responses were more accurate with congruent than with incongruent primes ($F(1,23) = 9.17$, $P < 0.01$), which was confined to a prime–target match ($F(1,23) = 11.17$, $P < 0.01$) for the interaction of congruency and notation match.

An additional ANOVA, confined to congruent primes, with the repeated measures of notation match and numerical prime–target distance produced no reliable effects (all

[7] No neutral prime was used in this experiment.

$F < 1$). The mean RTs (error rates in parentheses) with a prime–target distance of 1, 2, and 3 amounted to 464 ms (2.9%), 463 ms (2.7%), and 464 ms (2.7%). Thus, there was no sign of a numerical prime–target distance effect, neither with notation match nor mismatch.

6.2.2. Prime visibility

Participants' discrimination performance for neutral vs. non-neutral primes was $d' = 0.22$ (the mean hit rate was 45.6%, false alarm rate 37.6%) and deviated from zero ($t(23) = 2.67$, $P < 0.05$). Again the non-zero detection rate was mainly due to participants' ability to indicate correctly the presentation of the neutral prime. The identification rate for the prime numbers was 4.0% and did not exceed the chance level of 6.25%.

6.3. Discussion

Response priming in Experiment 4 did not generalize to stimuli of a format not consciously perceived. Thus, priming did not bear on a format independent, semantic prime code as predicted by the elaborate processing view – a conclusion again corroborated by the absence of a semantic prime–target distance effect. In contrast, primes affected the motor system only when they were matching the targets regarding their perceptual format. This accords well with an action-trigger account which holds that semantic categorization procedures may mediate the initial recruitment of triggers, which can then be bypassed by a simpler match with pre-semantic (presumably sensory) trigger features.

Response priming generalized, however, to stimuli that fell numerically into the target range, but were not consciously perceived themselves. This contradicts rote S-R learning as a basis for the present response priming effect. Rather participants relied on ordinal aspects of the targets when forming action-trigger sets, promoting the inclusion of numbers in the expected format when numerically encompassed by conscious targets.

Table 4
Experiment 4: response times (in milliseconds) and error rates (in percent) as a function of congruency, prime-type and prime–target notation[a]

	Prime–target notation							
	Same				Different			
	Congruent		Incongruent		Congruent		Incongruent	
Prime-type	RT	PE	RT	PE	RT	PE	RT	PE
From target set	462	2.1	483	4.6	464	3.0	467	3.3
Not from target set	463	2.5	472	3.9	463	3.1	467	3.5

[a] RT, response times in milliseconds; PE, percentage of errors.

7. General discussion

Two concurring hypotheses have dominated the debate on response priming by unconscious stimuli. The elaborate processing hypothesis, on one hand, holds that unconscious primes activate responses because of their automatic assignment to semantic response categories. The evolving automaticity hypothesis holds that unconscious primes activate responses because of acquired associations between responses and consciously perceived prime exemplars. We suggested a third alternative, the action-trigger hypothesis, which holds that unconscious primes activate responses to the degree they match pre-stimulus action-trigger sets.

In a sense this view combines the two former positions. Both types of processing, a semantic categorization, as well as direct response activation are assumed to take place but at different points in time. A semantic analysis is assumed to categorize memory codes of potential stimuli into adequate and inadequate action triggers, when task demands become apparent, either explicitly by instruction and/or implicitly by initial practice. Response activation via S-R associations is assumed to take place whenever stimuli match these triggers, which is presumably the 'normal' way of response generation in practised task performance after action triggers have been set up.

The present study revealed several results that accord with the proposed action-trigger hypothesis but at the same time challenge the two traditional views. Experiment 1 showed that primes bias responses when they match a certain action-trigger range, although they were not consciously responded to. This casts doubts on the role of rote S-R learning proposed by the evolving automaticity hypothesis. We attributed the extension of priming to the incidental inclusion of unseen numbers when task instructions favour a magnitude-based selection of action triggers. Experiment 2 revealed primes to be inefficient when not matching the numerical range of targets, although unambiguously belonging to a certain semantic response category. This casts doubts on the automatic extraction of quantity meaning at least from unconscious numbers. We attributed the lack of priming to numbers outside the target range to the low likelihood of being incidentally incorporated in the set of action triggers. Experiment 3 showed that the quantity meaning of unconscious prime numbers has no impact on the processing of target numbers, when numerical features are disregarded in assembling action-trigger sets, which again casts doubts on an inevitable extraction of quantity meaning of numbers. This experiment provided preliminary hints for the use of sensory features in the selection of action-trigger codes. Finally, Experiment 4 showed that even when valence information is nominally response-defining, stimuli carrying the *same* valence information produce no response activation at all when presented in an unexpected format. Again this questions whether priming is based on genuine semantic codes, but points to the relevance of sensory codes in the setting up of adequate action-trigger sets. In the remainder we want to discuss if and how the traditional positions can be modified to explain the present experimental findings.

7.1. Modifications of the elaborate processing view

The present study did not address the still debated issue of whether or not a semantic analysis of subliminal information *in principle* is possible. We question, however, whether unconscious semantic codes bias behaviour as generally and automatically as often implied (e.g. Marcel, 1983; Neely, 1991) – a conjecture well in line with the observation that masked priming affords attention (Naccache et al., 2002). To save the elaborate processing view one might suggest that priming in the present experiments is still based on semantic codes which were accessed, however, only for those primes that were efficient (e.g. primes in the target range in Experiment 1, or in the seen format in Experiment 4). Indeed, such modifications of the elaborate processing view have been advocated. For example, Dagenbach et al. (Carr & Dagenbach, 1990; Dagenbach et al., 1989) suggested that encoding strategies can be intentionally applied to masked stimuli, thereby determining which type of information is extracted from unconscious stimulation. Likewise, Dehaene and Naccache (2001) in a more theoretical prospect suggested that conscious instructions and task contexts determine the processing routes taken by subliminal information. This modified elaborate processing approach offers a different interpretation, particularly of the present Experiment 4. From this perspective subjects would (i) attentionally amplify the processing of stimuli in the seen format (Arabic or written), whereby (ii) only stimuli in the seen format were processed up to a semantic level, and (iii) biased responses according to their relation to 5. Thus, this interpretation would still imply a semantic prime coding, whereas the action-trigger view suggests that this semantic coding might be bypassed in task performance by a simpler pre-semantic trigger match.

We cannot rule out this alternative account, but we hesitate to favour it over our action-trigger hypothesis for the simple reason that we could not find unequivocal indications of semantic prime coding. Most notably, in no experiment (where the computation was possible) did we find a prime–target distance effect which is the commonly accepted indicator for the extraction of magnitude meaning (increasing RTs with increasing target distance to congruent primes[8]). By contrast several observations point to the relevance of sensory prime codes (e.g. the inefficiency of primes in the unseen format in Experiment 4, the impact of curvedness in Experiment 3). Since semantic rather than perceptual processing of masked primes is the (still) debated issue, we find it both more conservative and more parsimonious to assume only a single mode of prime processing (priming depends on the match with perceptual triggers) rather than two modes (primes bias responses by semantic codes but are filtered out when not meeting certain perceptual criteria).

However, as noted above, we do not want to exclude that, given appropriate conditions, primes are processed to a semantic level. At the present stage we can only warrant future research to clarify the conditions that give masked stimuli access to semantic memory codes or – in terms of the trigger account – allow a trigger match on a semantic level. For example, the probability of creating unconscious prime codes might increase the larger the set of individual response-affording targets (cf. Dell'Acqua & Grainger, 1999). Also, subtle variations of exposure duration may determine whether this creation takes place or not (Greenwald & Abrams, 2002).

[8] One indicator for the magnitude-based coding of *targets*, the target-distance effect (decreasing RTs with increasing target distance to 5), was present (increasing the distance from 1 to 4 decreased RTs by 24, 24 and 26 ms in Experiments 1, 3 and 4 and increasing the distance from 1 to 2 decreased RTs by 13 ms in Experiment 2). Thus, according to this indicator semantic codes were created for the consciously perceived targets. However, the distance effect for *unmasked* targets is non-diagnostic for the processing level of *masked* primes.

To summarize, even if one wants to maintain that priming is based on semantic codes one has to admit that either (i) stimuli are not automatically coded on this semantic level, or that (ii) codes on this level are not automatically transmitted to the motor system (Naccache et al., 2002; Naccache & Dehaene, 2001).

7.2. Modification of the evolving automaticity view

There is little doubt that subliminal stimuli are capable of activating already learned S-R associations. However, we found priming effects for primes never responded to (cf. Experiments 1 and 4), which were present from the outset and did not increase with practice. The evolving automaticity view may account for these findings by the additional assumptions that (i) responses can be linked to codes of stimuli never consciously seen in a given task context and that (ii) these links can be intentionally created without (repeated) execution (i.e. need not be formed as a result of practice).

Of course these modifications are possible in principle. But they appear to us as an uncomfortable stretch of the original concepts. At present we therefore favour explaining our findings by referring to the old, but still not widely acknowledged, idea of cognitive action triggers. A fascinating aspect of this idea is that by intentionally setting up action triggers we gain control over the impact of stimuli we cannot perceive consciously. Whereas the creation of such triggers is probably consciousness-mediated (and possibly consciousness-requiring) the covert response activation by an appropriate trigger stimulus is definitely not. Thus, such action triggers guarantee fast and effortless execution of appropriate actions whenever plausible predictions about upcoming stimulus events are possible. Evolution would therefore have been well advised to promote the capability of creating and using such triggers. For us this seems a rather convincing argument for why their further investigation is a worthwhile project.

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