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Research report

Semantic processing of neglected numbers

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ABSTRACT

While neglected stimuli can still be processed, few studies have directly addressed the issue of the unconscious access to semantics. In order to clarify this issue, we engaged four patients with unilateral left spatial neglect in a number comparison task. Each target number was preceded by a lateralized number prime, either in the intact or neglected hemifield (HF). Both group analyses and the intensive study of a single patient show that left (neglected) as well as right (consciously perceived) number primes affect performance: primes representing quantities that fall on the same side of the reference as the target lead to faster categorization. This congruency effect is highly suggestive of numerical semantic processing of neglected stimuli. Absence of conscious perception of neglected primes was evaluated using a combination of subjective and objective measures of performance in forced-choice tasks.

1. Introduction

The notion of unconscious cognitive representations (Kihlstrom, 1987) is now uncontroversial. However, the level of processing up to which unconscious representations may proceed is still a matter of debate. The claim that unconscious stimuli can undergo semantic processing was put forth in seminal papers by Marcel (1983a, 1983b), sparking off intense controversies (Holender, 1986; Marcel, 1986; Merikle, 1992). It was, however, shown that unperceived stimuli could be processed all the way up to motor representations (Dehaene et al., 1998). The controversy then shifted to the issue of whether a ‘‘direct motor specification’’ (DMS) (Neumann and Klotz, 1994), without semantic mediation, might explain this motor priming effect (Abrams and Greenwald, 2000; Damian, 2001). According to DMS theory, when subjects consciously process targets, they establish stimulus–response chains that once created can be elicited unconsciously by masked

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stimuli. Far from demonstrating unconscious access to semantic representations, most masked priming results could be explained in terms of low-level direct stimulus–response associations. In many priming paradigms rote stimulus–response learning is possible because a small set of stimuli is used repeatedly. However, recent evidence shows that genuine semantic processing of unconscious representations is indeed possible (Devlin et al., 2004; Dijksterhuis and Aarts, 2003; Naccache and Dehaene, 2001b; Naccache et al., 2005; Winkielman and Berridge, 2004) even though it is highly dependent on contextual effects and conscious goals (Greenwald et al., 2003; Kunde et al., 2003).

In this paper we investigate how deeply unconscious representations can be processed under conditions of invisibility associated with spatial hemineglect. We address the question of whether unconscious neglected numerical symbols are amenable to semantic processing. This seems plausible because the lesions that cause neglect most often spare the ventral visual route, which subtends the abstract identification of words and symbols and their access to semantic-level representations in the temporal and frontal lobes. Therefore, stimuli unperceived because of a deficit in spatial attention might nevertheless be processed up to a high level of abstraction.

It is well-known that neglected stimuli are not simply ignored. The performance of neglect patients in simple tasks such as line bisection shows that they have some access to the neglected part of the line, since the rightward bias is a proportion of the total line extent. Similarly, in neglect dyslexia, Kinsbourne and Warrington (1962) observed that paralexic substitutions generally preserve the total length of the target word. More recently, Làdavas et al. (1997a, 1997b) showed that the semantic route for reading is relatively preserved in neglect dyslexia, which implies some processing of the neglected part of the words. Using a different approach, Vuilleumier (2000) and Vuilleumier et al. (2001) showed that faces are preattentively processed in the extinguished or neglected field. However, the claim that a stimulus presented in the left hemifield (HF) of a neglect patient can be semantically manipulated is stronger, because it implies that abstract dimensions of the stimulus can be accessed without awareness. Volpe et al. (1979) showed that unidentified neglected stimuli could nevertheless yield better than chance same/different judgements. This opened the question of the representational level at which this performance was obtained (Karnath and Hartje, 1987; Marshall and Halligan, 1988, 1995; Berti and Rizzolatti, 1992; Berti et al., 1992, 1994; Làdavas et al., 1993; see also Peru et al., 1996, 1997; Bisiach and Rusconi, 1990). Significant evidence supporting semantic processing in hemineglect patients was demonstrated by McGlinchey-Berroth et al. (1993) using a lexical decision task on centrally presented strings of letters preceded by picture primes, presented laterally, either in the right or left visual HF. With this experimental set-up, the authors found a facilitatory effect of semantically related images on decision times, even when the picture prime was in the left, neglected field. This result suggests that neglected pictures may activate semantic representations.

In a more recent study Rusconi et al. (2006) showed that arithmetic problems presented in the neglected HF may nevertheless be associated with the correct solutions, again suggesting semantic processing. The authors engaged one patient in a parity judgement task on foveally presented Arabic digits, with primes consisting of pairs of Arabic digits presented on the right or left of fixation. On some trials, primes were factors of the target (for instance primes 2 and 5 for target 10), while on other trials they were unrelated to the target. Interestingly, the authors found a dissociation of performance, whereby related prime–target pairs were associated with faster reaction times (RTs) in the left (neglected) HF and slower RTs in the right, intact, HF. This dissociation was not found in normals, where related prime–target pairs were always associated with slower RTs. The authors therefore argued that this dissociation reveals an automatic computation of the product of the two digits, followed by inhibition only when the stimuli are conscious.

Numbers are particularly well suited for the study of unconscious semantics for at least three reasons: first, the basic semantic property of numbers, numerosity, follows a unidimensional metric which is highly similar across individuals. Thus, we can detect unconscious numerical semantic effects with a strong sensitivity. Second, numerals are among the most frequent words and therefore access to their meaning is quite automatic. Finally there are two symbolic formats for numerals, the Arabic notation and the spelled-out verbal notation. This permits a simple control of the low-level visual features of the stimuli.

Therefore, even without resorting to arithmetic calculations, it seems that numbers provide one of the most direct means of testing the claim that semantic processing is possible in the neglected HF, due to their exceptionally simple semantics. Processing of the semantic dimensions of the stimuli manifests itself through well-known and quantitative effects as the distance and congruity effects in number comparisons. We therefore designed a simple number comparison task adapted from Dehaene et al. (1998) where subjects had to decide whether single-digit numerals were larger than the memorized reference 5. Each target was preceded by a prime presented laterally in the neglected or in the intact HF. This task was intended to probe the activation of semantic representations by neglected prime stimuli. From number comparison experiments with masked primes in normal subjects (Dehaene et al., 1998), we know that unconscious numerical symbols can bias RTs: primes that fall on the same side of the reference as the subsequent numerical target (congruent primes) have a facilitating effect, whereas when the prime and the target are on the opposite sides of the reference (incongruent primes) the effect is inhibitory (slower RTs and more errors). There is now reliable evidence that these effects are mediated by the semantics of the primes (Greenwald et al., 2003; Naccache and Dehaene, 2001a, 2001b; Reynvoet et al., 2002, 2005). We examined whether such semantic-level processing occurs for number symbols presented in the left HF of hemineglect patients, and which they strongly denied seeing.

Left number primes' visibility was assessed through three measures. First, at the end of the main experiment we asked every patient if she/he perceived stimuli on the left side of the fixation cross. Then, we engaged the patients in post-tests designed to provide an objective measure of prime discriminability. This enabled us to have a measure of the effect of neglect

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on the awareness of left primes in the very context of our experiment, in addition to the clinical assessment of the deficit.

2. Methods

2.1. Participants

2.1.1. Patients

Four right-handed female patients (40–56 years old) suffering from left unilateral neglect secondary to right hemispheric strokes were tested (see Table 1 for a summary of neglect etiology and clinical details). Experimental testing was performed 6–12 months from stroke onset. For each patient, neglect was assessed by non-standardized neuropsychological testing (including cancellation, line bisection, clock and copy drawing tests). All patients had clear left visual neglect on these tests. Only patient AM received a standardized battery of paper-and-pencil tests (Azouvi et al., 2002). She scored 56/97 on this standardized battery (star cancellation: 43/54, 11 left stars were omitted; figure copying: 2/3, impairment on cube drawing; form copying: 1/1; free drawing: 2/3, left wing of the butterfly was omitted; line cancellation: 8/36, all left line segments were omitted).

The presence of extinction was also tested clinically by wiggling fingers for 2 sec in one or both visual fields while central gaze fixation was controlled by the examiner (JS or LN) as described in Azouvi et al. (2002). Six trials were given including four unilateral trials (two on each side), and two simultaneous bilateral trials. Extinction was considered as present when a patient failed at least once to report a contra-lesional stimulus during bilateral simultaneous presentation, while accurately detecting unilateral stimuli. Left visual extinction was observed for each of the four patients. Additionally, our experimental methodology included direct subjective measures and objective tests, which indicated the absence of conscious perception of left presented numbers during the main experiment.

2.1.2. Normals

Fourteen neurologically normal, right-handed, subjects (six females, nine males, age ranging from 19 to 32) were tested on the main experiment. An additional group of four neurologically normal age-matched control subjects (three female, one male, age ranging from 41 to 56) was separately tested on the main experiment.

Behavioral experiments were approved by the local ethical committee for biomedical research, and both patients and controls gave their informed consent. All subjects had normal or corrected-to-normal vision.

2.2. Experimental procedure

2.2.1. Priming experiment

Stimuli (see Fig. 1a) were presented on a standard cathode ray tube (CRT) monitor using Expe6 software (Pallier et al., 1997) running on an IBM compatible computer. Stimulus sequence (see Fig. 1a) consisted of a fixation cross (500 msec); a screen with a numerical prime on one side and a distractor stimulus on the other (200 msec); and finally the target stayed on the screen until a response was made. This timing was the same for all participants and did not change during the experiments. The duration of the prime was chosen so as to ensure that participants would not saccade on the prime stimulus. It has been shown that a proportion of saccade latencies in healthy individuals is below 200 msec threshold (‘‘express’’ and ‘‘fast regular’’ saccades, Gezeck et al., 1997). In hemineglect, however, it is known that saccade latencies towards left stimuli are much slower (Girotti et al., 1983; Natale et al., 2007) and systematically above 200 msec threshold. Furthermore, patients often fail to initiate saccades to the left (Girotti et al., 1983), reinforcing the notion that the 200 msec duration for the presentation of the prime would still not yield conscious perception of the prime as a consequence of fast saccades. Prime and target were randomly selected among the set of four numbers 1, 4, 6, 9, presented equally often in Arabic notation or in verbal notation (‘‘UN’’, ‘‘QUATRE’’, ‘‘SIX,

Table 1 – Description of the four neglect patients

Patient	Gender	Laterality	Age	Neglect onset – testing delay (months)	Additional signs	Neglect etiology
SA	F	Right	44	9	Left hemiparesis, dysexecutive syndrome	Right MCA and right ACA strokes (superficial territories) secondary to arterial spasm after aneurysm rupture (supra-clinoid portion of right ICA)
SU	F	Right	40	12	Left hemiparesis	Right MCA stroke (superficial territory)
LE	F	Right	53	7	Left hemiparesis, and left hypoesthesia	Right and left paramedian ACA strokes secondary to arterial spasms after aneurysm rupture (left pericallosal bleeding complicated by acute subarachnoid hematoma and post-embolization lesions)
AM	F	Right	56	6	Left hemiparesis	Right MCA stroke (superficial and deep territory)

ACA = anterior cerebral artery.
MCA = middle cerebral artery.
ICA = internal carotid artery.

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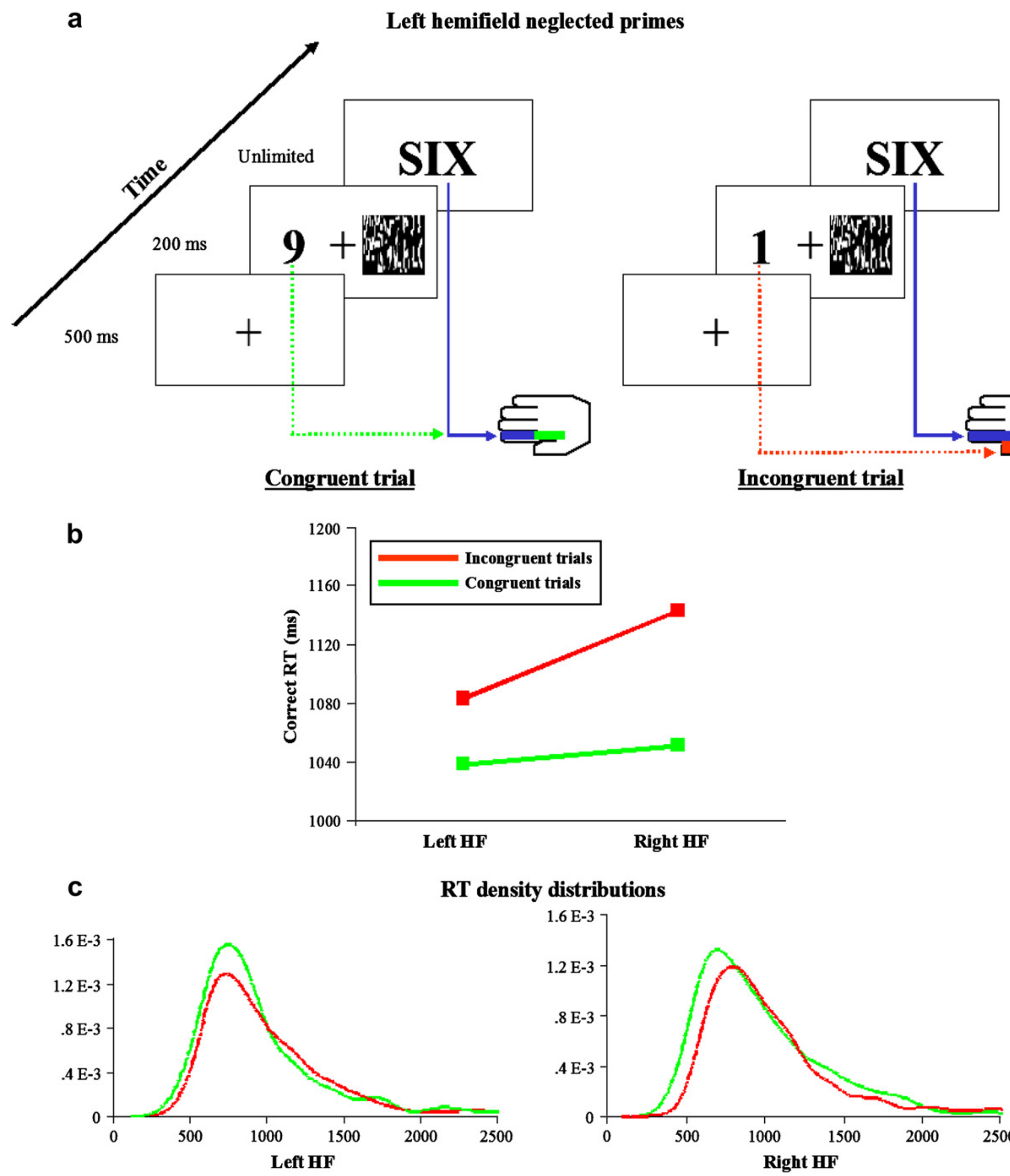

Fig. 1 – (a) Paradigm used in the main priming experiment. Examples of a congruent trial (prime and target on the same side of five) and an incongruent trial (prime and target on opposite sides) are represented, with left HF primes' presentations. Primes appeared equally often in the right HF, with the distractor on the other side. (b) Main experimental result for the group of four patients: correct RTs for congruent (green) and incongruent (red) trials within the left HF and the right HF. The interaction was not statistically significant (see text). (c) RT distributions for the same group of four patients, in the right and left HFs; green line: congruent trials, red line: incongruent trials.

"NEUF"). All stimuli were presented in a Courier font 1 cm in height; width varied from 7 mm for the digits to 4.4 cm for the longest word. The distractor was a meaningless pattern obtained from scrambling the letters of the word "QUATRE". Primes and distractor were placed symmetrically on either side of the fixation cross; the center of the prime and distractor were at 2.7 cm off fixation, which yielded, at approximately 80 cm viewing distance, a visual angle of 2°. The target was presented at fixation until patients responded. The inter-trial interval was 1 sec.

All subjects responded with the thumb and index of their right-hand, on a response pad (Electrical Geodesics Inc.). The thumb key was assigned to the "smaller than five" response and the index key to "larger than five". The response pad was aligned with the patient's mid-sagittal plane such that the "smaller than five" button was closest to the patient's body. Instructions were given verbally by the experimenter. Patients were instructed to fixate the cross and to compare to five the target that appeared at fixation. They were told that other stimuli sometimes appeared before the target on the screen, but that they should not pay attention to them.

The experiment comprised 512 random trials, following a fully crossed factorial design with the following factors: prime value (1, 4, 6, 9), target value (1, 4, 6, 9), prime notation (Arabic or verbal), target notation (Arabic of verbal), and prime side (left or right). Thus, there were four repetitions of each trial type in this priming experiment. A pause was introduced every 64 trials.

2.2.2. *Post-tests: assessment of prime awareness*

We designed two forced-choice post-tests in order to assess the extent to which left stimuli were neglected or extinguished in the main experiment.

2.2.2.1. Post-test A: forced-choice judgement of prime presence. The stimulus sequence in the first post-test was identical to the one in the main experiment, except that the prime display could either comprise the prime alone (on the left or right of fixation), the distractor alone (on the left or right), or both the prime and the distractor (prime on the left or right). Patients had to say whether they saw one or two numbers (the prime if present, and the target). Patients were informed about the different types of trials, and were encouraged to guess if they were not sure about their response. The post-test contained 64 trials, randomly selected.

2.2.2.2. Post-test B: forced-choice comparison. The second post-test, used only for one patient, had exactly the same stimulus sequence as the main experiment, except that the target was replaced by the neutral number five (stimulus "5" or "CINQ"). The patient's task was to categorize the primes as smaller or larger than five. Patients were instructed to respond quickly and were encouraged to guess whenever they had not seen the prime. In essence this post-test required the patient to perform the same task as in the main experiment, but now treating the primes as the targets of the comparison (Naccache and Dehaene, 2001b). This post-test also contained 64 randomly selected trials.

Testing sessions lasted less than 1 h. However, no patient processed 512 trials of the main experiment in one session. Three patients were tested during one session for both the priming experiment and the post-test A, while one patient (SA) was tested in two sessions, each of which comprised the main priming experiment. For this patient, post-test A concluded the first session and post-test B the second session. As a result, patient SA processed 601 trials while the minimum number of trials of the main priming experiment processed was 384 (patient AM).

2.3. *Data analysis*

Guided by RT distributions (see Fig. 1c), we excluded trials with responses under 250 msec and above 3000 msec. This resulted in the rejection of 3.7% of the trials. Error rates were low (maximum 8.4%, minimum 2.2%), showing that patients had no difficulty performing the task. Total rejection rates (outliers + errors) varied from 16.6% to 3.1%.

For RT analyses on normal controls, we excluded errors and RTs with responses under 250 msec and above 1000 msec (3.8% of the trials).

Statistical analyses were performed using ANOVAs and χ^2-tests.

3. Results

3.1. *Normal subjects*

3.1.1. *Target processing*

We ran a 2×2 repeated measures ANOVA on mean correct RTs with factors of absolute target distance (stimuli with numerical values 1 and 9 were *far* targets, 4 and 6 were *close* targets) and target notation. The two main effects were significant: *close* trials were slower than *far* trials (509 msec vs. 470 msec, $F(1,13) = 60.14$, $p < .00001$), which replicates the standard distance effect in number comparison; *verbal* trials were slower than *Arabic* trials (499 msec vs. 479 msec, $F(1,13) = 32.55$, $p < .00001$). The interaction was not significant ($p > .38$), which is also a standard result in number comparison. A similar ANOVA on error rates revealed only an effect of target distance (*close* 5.3% errors, *far* 1.9%, $p < .001$), while no other effect or interaction approached significance (all *ps* $> .29$). Thus, there was no speed–accuracy trade-off in the task.

3.1.2. *Prime processing*

We then ran a $2 \times 2 \times 2$ repeated measures ANOVA on correct RTs with factors of prime HF (*left* vs. *right*), prime–target congruity (trials where prime and target are on the same side of five are *congruent* vs. *incongruent* otherwise) and prime–target notation identity (*same* vs. *different*). The main effects of notation identity and congruity were found significant (*same* trials 486 msec vs. 493 msec for *different* trials, $F(1,13) = 18.14$, $p < .001$; *congruent* trials 486 msec; *incongruent* trials 499 msec, $F(1,13) = 31.6$, $p < .0001$). The similar ANOVA on error rates did not yield any significant effects (all *ps* $> .3$). Thus, the prime has clear effects on the processing of the target, but these effects do not depend on the HF of presentation.

Notice that congruent trials include trials with a physically identical prime and target (same quantity, same notation), trials with distinct physical stimuli representing the same quantity (same quantity, different notations), and trials in which both the numerical quantity and the physical appearance differed. Therefore, part of the congruency effect might be explained by a low-level visual repetition effect. In order to assess the weight of such a mechanism, we ran a 2×2 ANOVA restricted to congruent trials with factors of prime–target numerical identity (same vs. different numerical values for the prime and target) and notation identity (same vs. different). The two main effects were significant (repeated trials 34 msec faster than non-repeated $F(1,13) = 23.8$, $p < .001$); same notation trials were 9.8 msec faster than different notation trials ($F(1,13) = 15.6$, $p < .01$), but the interaction with the notation effect was not ($p > .18$). Within congruent trials there is therefore an effect of abstract numerical repetition on one hand and an effect of notation repetition on the other. The influence of numerical repetition is thus not limited to same notation trials. It seems therefore that at least part of the congruency effect cannot be explained by a simple visual repetition priming.

3.1.3. Assessment of prime awareness

All normals spontaneously noticed the presence of numerical primes, which they judged highly visible. Therefore, we did not find it useful to administer the post-tests.

3.2. Age-matched controls

The group of four age-matched control subjects replicated these findings. Two of these age-matched control contributed too few errors (less than 2%) precluding any analysis based on error rates.

3.2.1. Target processing

The 2×2 ANOVA on correct RTs with factors of target notation and target distance yielded two significant main effects. *Close* (6 and 4) targets were slower than *far* (1 and 9) targets (552 msec vs. 523 msec, $F(1,3) = 16.177$, $p < .02761$). For the target notation factor, *verbal* targets were slower than *Arabic* targets (551 msec vs. 524 msec, $F(1,3) = 10.435$, $p < .0482$). The interaction was not significant ($p > .41$).

3.2.2. Prime processing

The $2 \times 2 \times 2$ repeated measures ANOVA on correct RTs with factors of prime HF (*left* vs. *right*), prime–target congruity (trials where prime and target are on the same side of five are *congruent* vs. *incongruent* otherwise) and prime–target notation identity (*same* vs. *different*) yielded only a marginally significant main effect which was the congruity effect (*congruent* trials 547 msec; *incongruent* trials 527 msec, $F(1,3) = 7.1278$, $p < .07$). We also ran the 2×2 ANOVA within congruent trials with factors of notation identity and numerical value identity, in order to assess whether the congruency effect was due to physical repetition of the stimuli – in which case there should be an interaction between the two factors. However, no effect (main or higher order) was found significant (all *p*s $> .34$).

3.2.3. Assessment of prime awareness

These subjects were aware of the presence of the primes, thus we did not consider it useful to administer the post-tests. However, at the end of the experiment they could not spontaneously report the complete set of prime stimuli. This seems to show that for this group high level processing of the parafoveal primes is found in the absence of attentionally controlled processing.

3.3. Patients group

3.3.1. Target processing

The same ANOVA as in control subjects showed an effect of target distance (*close* trials 1149 msec; *far* 1014 msec, $F(1,3) = 368.9$, $p = .0003$), with no effect of target notation and no interaction. A similar ANOVA on error rates revealed only a marginal effect of target distance (*close* 6.8% errors; *far* 2.8%, $p = .09$). These results indicate that patients performed the comparison task correctly with few errors and no speed–accuracy trade-off.

3.3.2. Prime processing

A $2 \times 2 \times 2$ ANOVA on correct RTs with factors of prime HF, prime–target congruity, and notation identity showed that all three main effects were significant: left prime trials were responded to 36 msec faster than right primes (($F(1,3) = 12.12$, $p < .05$), *congruent* trials were 68 msec faster than *incongruent* trials ($F(1,3) = 11.2$, $p < .05$), and a marginal notation identity effect was observed ($F(1,3) = 6.9$, $p = .07$). *Same* notation trials were responded to 34 msec faster than *different* notation trials. None of the interactions between these factors reached significance, and crucially the congruity $\times$ prime HF interaction was not significant ($p > .25$), although the effect seems to be stronger in the right HF (see Fig. 1b). The analogous ANOVA performed on error rates did not reveal any significant effects (all *p*s $> .16$).

These results are demonstrative of significant cognitive processing of left neglected numerical primes. Indeed, the absence of interaction of prime–target congruity effect with the notation identity factor clearly indicates that prime processing was not restricted to a low-level visual repetition effect.

In order to better disentangle representational levels of neglected primes, we ran an additional analysis on correct RTs restricted to congruent trials, with factors of prime HF, notation identity, and numerical identity. Only a marginal effect of numerical identity was observed, with same numerical value trials being responded to 65 msec faster than different prime–target values ($F(1,3) = 7.33$, $p < .07$). There was no main effect of notation identity, and no numerical identity $\times$ prime HF interaction. More importantly, there was no numerical identity $\times$ notation identity interaction. This means that, within congruent trials, the abstract numerical repetition tends to have an effect as opposed to the mere physical repetition of the stimulus. Since the only marginally significant difference within congruent trials occurs between same and different numerical value trials, on the left as well as on the right, it seems that we are entitled to conclude that the congruency effect cannot be explained by low-level visual mechanisms.

In addition, we ran a 2×2 ANOVA on correct RTs with factors prime HF (*left* vs. *right*) and congruency (*congruent* vs. *incongruent*), restricted to the first 32 trials of the experiment. We found that both main effects were significant (*left* trials 170 msec faster than *right* trials, $p = .064$; *congruent* trials 104 msec faster than *incongruent* trials, $p = .028$), while once again the interaction was not ($p > .15$). Thus, it seems that the congruency effect that we observe is present from the outset, which indicates that it does not depend on learning stimulus–response association during the course of the experiment.

3.3.3. Assessment of prime awareness

3.3.3.1. Post-tests. To evaluate the extent to which stimuli presented on the left were neglected we used a combination of subjective and objective measures. Subjectively, none of the subject reported seeing any number primes in the left HF, after the experimental session. In order to obtain an objective measure, we ran post-test A for each patient in the group (see Table 2). We calculated a d' measure of signal detection theory, and its associated chi-2 probability, with "hits" defined as a response "2 numbers" when the prime was present and "misses" as a response "1 number" when the prime was present. Clearly, performance in the left HF was above chance, but nevertheless showed a decrement compared to performance in the right HF. This is somewhat paradoxical considering the absence of any spontaneous report of the left primes. Further below, we discuss why we believe that such a performance can be attained without awareness of the neglected stimuli, and the results of the second post-test that was administered only to patient SA.

3.4. *Patient SA*

We now focus on a single patient (SA) whom we were able to test more extensively than the three other patients (601 trials in the main priming experiment and two post-tests).

3.4.1. *Target processing*

The ANOVA on correct RTs with factors of target distance and target notation revealed two significant main effects with no interaction (*far* targets 826 msec vs. *close* targets 966 msec, $F(1,600) = 32.22$, $p < .001$; Arabic numerals faster by 77 msec than verbal ones $F(1,600) = 10.97$, $p < .001$). The similar ANOVA calculated on error rates did not reveal any significant effects (all $ps > .17$).

3.4.2. *Prime processing*

The $2 \times 2 \times 2$ ANOVA on correct RTs with factors of prime HF, congruency and notation identity yielded a significant main effect of congruency (*congruent* primes trials 80 msec faster than *incongruent*, $F(1,600) = 8.37$, $p < .004$), while no other main effect or interaction reached significance (all $ps > .7$); crucially the congruency $\times$ prime HF interaction was not significant. In order to assess the semantic dimension in the congruency effect, we ran a $2 \times 2 \times 2$ ANOVA on correct RTs, restricted to congruent trials, with factors of prime HF, notation identity and numerical identity. We found a main effect of numerical identity (repeated trials 135 msec faster than non-repeated, $F(1,286) = 17.53$, $p < .001$), while no other main effect or interactions were significant (all $ps > .2$). Once again this suggests that the processing of the primes has some semantic aspects in both HFs since within congruent trials, the abstract numerical value of the prime is relevant, not its physical repetition. We refined this analysis by comparing within congruent left primes trials with different notations for the prime and target (for instance left prime "2", target "QUATRE" or "DEUX"), those where prime and target had the same numerical value, and those where it was different. We found a significant difference (repeated trials 122 msec faster, $F(1,155) = 3.77$, $p < .054$). This shows that the numerical value of left congruent primes had a significant effect on RTs, even for trials where primes and targets were always physically different. We ran a χ^2 test on error rates with factors of prime side (left or right) and congruity. There was no significant effect ($p > .31$), suggesting that the effect on RTs that we found with this patient was not the result of a speed–accuracy trade-off.

3.4.3. *Assessment of prime awareness*

3.4.3.1. Post-tests. Patient SA spontaneously said that she sometimes saw non-numerical words on the right of the fixation cross before the target appeared. These words appeared to be superimposed on the distractor.

Patient SA passed the two different post-tests. In the first one, her performance was very similar to the group (see Table 2): performance in the left HF was worse than in the right, but still significantly different from chance. However, there are reasons to think that this level of performance is achievable without being aware of the left stimuli. This is vindicated by the patient's performance in the second post-test, where she exhibited a nearly perfect performance in the right HF together with chance performance in the left (Table 2).

4. Discussion

We obtained significant priming effects in a number comparison task with primes presented in the left neglected HF of four patients. Our results demonstrate extensive processing of neglected primes. The absence of interaction between the priming effect and the prime HF suggests that primes were processed in a very similar fashion in both HFs. This result is related to the findings of McGlinchey-Berroth et al. (1993), who observed similar priming in neglect patients and in controls in a lexical decision task, with no interaction with visual HF. Furthermore, the congruency effect was not restricted to same notation prime–target pairs, demonstrating that unconscious processing goes beyond low-level visual features. Indeed, with neglected numbers, the patients' performance show that they unconsciously recognize, for instance, that ONE and 1 represent the same number, and that ONE and 4 fall on the same side of 5. Therefore, it seems

Table 2 – Discrimination d' values of both the patients group, and single patient SA

	Left HF				Right HF			
	Post-test A		Post-test B		Post-test A		Post-test B	
	d'	$p(\chi^2)$	d'	$p(\chi^2)$	d'	$p(\chi^2)$	d'	$p(\chi^2)$
Group of four patients	1.12	<.0001	–	–	2.36	<.00001	–	–
Patient SA	1.4	<.001	**0**	**1**	>3	<.00001	**2.3**	**0.001**

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probable that left primes enter a chain of processing that includes extraction of an abstract semantic code.

Our demonstration is limited by the fact that the set of left primes is exactly the same as the set of targets. Therefore, there is a possibility that patients set-up a "DMS" on visible primes, which could then be transferred to unseen primes (Neumann and Klotz, 1994). High level semantic processing during conscious trials may thus serve as a basis for the setting up of lower level sensory motor associations that are active during unconscious trials, yielding the unconscious congruity effect. However, the fact that the congruency effect is already present in the first 32 trials, is a fair indication that at least this effect does not depend on an extensive learning, as should be expected if the effect was due to a DMS. The presence of a congruency effect with minimal learning, as well as its independence from notational effects, is suggestive of semantic-level cognitive processing rather than the learning of a direct motor chain. Indeed, in normal subjects, the contribution of a DMS to subliminal priming has been disproved through experiments in which novel primes were used, which never appeared as targets in the experiments, and thus could not be easily associated with a motor response (Naccache and Dehaene, 2001b). In future work, a similar manipulation could be used with neglect patients to strengthen the evidence for semantic processing of neglected stimuli.

The priming effects that we observed in patients are very similar to those that are found in normals. Congruent primes have a facilitating effect on target processing compared to incongruent primes, and this effect is even stronger for repeated prime–target pairs. This has been repeatedly found in normal subjects with conscious primes (Koechlin et al., 1999) as well as unconscious primes (Dehaene et al., 1998), and there is now some strong evidence that these effects have a semantic origin (Greenwald et al., 2003; Naccache and Dehaene, 2001b).

4.1. *Were the patients truly unaware of the neglected primes?*

There is a discrepancy between the robust clinical neglect exhibited by our patients, accompanied by a strong denial of seeing the primes, and their better than chance performance in the first post-test used to assess their awareness of the primes. However, this discrepancy does not necessarily imply that they consciously perceived the neglected primes (see discussion in Naccache and Dehaene, 2001b). Rather, above chance performance could be due to unconscious processing. This is typically the case in blindsight studies (Weiskrantz, 1997), where patients achieve nearly perfect performance in some conditions, while at the same time denying any visual awareness in their scotoma. In the present case, there are reasons to think that the particular task that we rely on in our first post-test is in fact amenable to automatic processing. Vuilleumier and Rafal (1999) have shown that neglect patients have better performance in enumeration tasks than in localization tasks, which is in fact what we find in our experiment: in post-test A, patients were indeed asked to detect whether the sequence of visual events contained two digits (the prime and the target) or only one (the target). But this is precisely the situation where Vuilleumier and Rafal (1999) found that neglect patients could perform well above chance, although they were unable to identify and localize the stimuli on the left. Thus, post-test A may well have probed unconscious performance: patients may be able to perform above chance in the enumeration task of this post-test, while they still subjectively failed to see the left component of the stimuli.

Post-test B, with a more demanding task of direct comparison of the primes, appeared more appropriate to reveal the extent of neglect. Now, patient SA had the same performance pattern as the group in post-test A, but was unable to perform better than chance with left primes in post-test B. This suggests that even with the group, it is more plausible to attribute the non-random performance in post-test A to unconscious processing rather than to awareness of the primes. This echoes previous reports showing that a more adequate post-test consisted in having patients performing on masked primes the very same task they performed on consciously perceived targets (Naccache and Dehaene, 2001b; Naccache et al., 2002).

Furthermore, we may note the fact that left prime trials were faster than right prime trials is also very suggestive of left neglect. One interpretation of this finding is in terms of an effect of a central mechanism for the monitoring of possible response conflicts. It has indeed been shown that the amount of control, responsible for slower responses and lower error rates, is modulated online by the monitoring of *possible* conflicts rather than by *actual* conflict (Botvinick et al., 2001; Carter et al., 1998). According to this interpretation, right primes, being consciously perceived, induce an increase of cognitive control to cope with the possibility of conflict. By contrast, left primes are not perceived because of neglect, and therefore they cannot trigger an increase of control. This might explain the faster RTs. Thus, the HF effect is readily interpretable as a sign of neglect. But in addition, if this is correct, we expect to find important sequential modulation (Gratton et al., 1992; Kunde, 2003), in that trials following a right (visible) prime trial should display a reduction of the HF effect, due to a more controlled mode of processing triggered by the previous trial. This is exactly what we find: the difference between *left* and *right* trials is 85 msec when preceded by a *left* trial, but only 14 msec when preceded by a *right* trial, and this interaction is significant ($F(1,3) = 16.12$, $p < .05$). This finding of an influence of prime HF on the next trial performance, exclusively for right (consciously perceived) primes, is a supplementary cue for the absence of conscious perception of left primes. While both right and left numerical primes are semantically processed, only right (consciously perceived) primes cause an increase of cognitive control.

Our main finding is that neglected, unperceived primes induce an abstract congruity effect, based only on their numerical values, when they precede an explicitly processed target. Taken together, our results therefore strongly suggest that the semantic dimension of neglected stimuli can be extracted and processed in the absence of conscious perception.

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