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# Unconscious information integration: A replication and the role of spatial window in masking experiments

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ABSTRACT

Consciousness and high-level information integration have commonly been closely related to each other (Baars, 2002; Dehaene & Naccache, 2001; Tononi, 2004). Different results, however, have challenged this assumption by showing that information integration can occur for stimuli presented outside of conscious awareness. More recently, a re-examination of some of the data and different replication attempts questioned these results thereby again suggesting a close link between consciousness and information integration. The current study aimed at (i) replicating another piece of evidence for unconscious information integration and (ii) investigating if the size of the spatial window in which the information to be integrated is presented could explain why unconscious information integration sometimes fails. Results showed a reliable replication so providing further evidence for unconscious information integration in a subliminal priming paradigm. Furthermore, our results revealed that unconscious integration depends on the size of the spatial window in which the information is presented.

## 1. Introduction

Prominent theories in the field of consciousness research have emphasized the relation between consciousness and the integration of information (see Mudrik, Faivre and Koch, 2014). Especially high-level semantic integration has been held to be unique for conscious (as opposed to unconscious) processing (Baars, 2002; Dehaene & Naccache, 2001; Tononi, 2004). High-level semantic integration has been operationalized in many ways but overall indicates the ability to generate a novel semantic representation by combining distinct semantic stimuli. For example, when presented with the three stimuli 5, ×, and 4, these can be integrated to form the novel representation 20. Other examples of high-level semantic integration are the combination of words into sentences (Schuberth & Eimas, 1977) or judging the semantic similarity of stimuli (Van Opstal & Verguts, 2011).

The relation between conscious processing and high-level semantic integration has been extensively tested during the last decade. Initially, this resulted in a significant number of studies showing that integration also occurs for unconsciously presented stimuli. For example, using a continuous flash suppression (CFS) paradigm, it was shown that participants can subtract three numbers or understand sentences without being aware of the presentation of the distinct stimuli (Sklar et al., 2012). Unconscious information integration was also observed with CFS when processing visual scenes. Participants were faster to become aware of visual scenes that included incongruent objects (Mudrik, Breska, Lamy, & Deouell, 2011). This result was also found in a masking experiment in which subliminally presented (in)congruent scenes primed the response to conscious (in)congruent scenes (Mudrik & Koch, 2013). Other evidence from subliminal masking experiments include unconscious addition (Ric & Muller, 2012; Van Opstal, de Lange, & Dehaene, 2011), and multiplication of Arabic digits (Garcia-Orza, Damas-Lopez, Matas, & Rodriguez, 2009), or integrating negations in word pairs (Armstrong & Dienes, 2013).

Recently, however, a critical re-analyses of the data supporting unconscious information integration put some of the reported effects into question. Moors and colleagues re-examined the data on unconscious subtraction in CFS using Bayesian statistics and found no support for the original claims (Moors & Hesselmann, 2018). Recent replication studies also casted doubt on the work investigating the role of awareness in object-scene integration. A direct replication of the finding that in CFS participants become faster aware of scenes with incongruent objects failed to find the same results as the original study (Moors, Boelens, van Overwalle, & Wagemans, 2016). Also in subliminal masking, no compelling evidence was found in a replication study that investigated the unconscious processing of object-scene congruency (Biderman & Mudrik, 2018).

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Although for CFS the current consensus seems to be directed towards no unconscious information integration, for subliminal masking the evidence is still mixed. One piece of evidence that still supports unconscious information integration is our work showing that the semantic similarity of subliminally presented stimuli can be processed (Van Opstal Filip, Calderon, Gevers, & Verguts, 2011; Van Opstal, Gevers, Osman, & Verguts, 2010). In these studies, two prime letters were presented unconsciously followed by two target numbers. The task of the participants was to judge if the two target stimuli were the same or different. What we found in a series of experiments is that the same/different relation of the primes influenced the response to the targets: Reaction times (RTs) were smaller when the relation between the two prime letters was the same as the relation between the two targets (i.e., a congruency effect). Interestingly, this task could not be solved by low-level processing because the similarity of the primes was based on their meaning rather than on their visual appearance (i.e., the prime letters 'a D' are different because they are visually dissimilar but also because they denote a different letter. The prime letters 'a A' are visually equally dissimilar but denote the same letter; they are only the same on a higher-level, semantic dimension). Because other work on unconscious information integration failed to replicate, a first aim of the current study is to replicate our earlier findings and establish their reliability.

A second aim of the current study is to investigate why unconscious integration would work in our same-different task but not in other experimental tasks. According to one suggestion, the spatial window in which information can be integrated (i.e, the spatial integration window; SIW) is smaller for unconscious compared to conscious stimuli (Hirschhorn, Kahane, Gur-Arie, Faivre, & Mudrik, 2021; Mudrik, Faivre and Koch, 2014). In our same-different task, the stimuli were presented at a close distance to each other, spanning a spatial window of 1.53°. In contrast, the study that used subliminal object-scenes used stimuli that were larger in size, subtending to 6.51° in width and 9.07° in height (Mudrik & Koch, 2013), or 7.27° in height and 5.20° in width (Biderman & Mudrik, 2018). According to the SIW hypothesis, the failure to integrate information for the object-scene stimuli could be caused by the size of the stimuli used in the experiment. To test this hypothesis, the stimuli to be integrated in the current experiment were presented in different SIWs: A small SIW of 1.53° (as in Van Opstal et al., 2010), a large SIW of 6.51° (as in Mudrik & Koch, 2013), and a medium sized SIW of 4.02°.

In sum, the current study aims to replicate the results of Van Opstal et al. (2010) and investigate the effect of the SIW on unconscious information integration. It is expected that a congruency effect for masked primes will only be found in a small SIW. In contrast, when the primes are not masked, a congruency effect is expected independent of the size of the SIW.

## 2. Experiment

### 2.1. Methods

#### 2.1.1. Participants

The sample size was calculated based on an unpublished experiment ($n = 40$) identical to the one presented here with the only difference that the size of the stimuli were not scaled to the size of the spatial window in which they were presented[1]. The effect size of the critical 3-way interaction of that experiment ($\eta_p^2 = 0.067$) was used to calculate the required sample size for the current experiment. The G*Power tool (Faul, Erdfelder, Lang, & Buchner, 2007) was used to estimate the sample size to reach 98% power with $\alpha = 0.05$. We assumed only a small correlation among the repeated measures (0.1) rather than the default value (i.e., 0.5) to not overestimate the obtained power. This resulted in an sample size of 56 participants. Anticipating the possibility of minor data loss, we decided to test 64 participants in total.

One participant failed to show up for the experiment and one participant experienced a technical problem. The remaining 62 participants (15 males, mean age 23.6 years) participated in this experiment for course credits or a small amount of money (8 Euros). Prior to the experiment all participants gave their informed consent and were debriefed afterwards. The study was approved by the Ethics Committee of the Faculty of Social and Behavioral Sciences at the University of Amsterdam. All participants had normal or corrected-to-normal vision.

#### 2.1.2. Apparatus and stimuli

Apparatus and stimuli were taken from Experiment 3 of Van Opstal et al. (2010). Stimuli were presented on a 60 Hz monitor. Stimulus presentation was synchronized with the vertical refresh rate (16.67 ms) and programmed in MATLAB 2017a (Mathworks Inc.) with a Psychtoolbox extension (Brainard, 1997; Pelli, 1997). Prime stimuli were upper and lower case letters. Two different sets of letters were used between participants (ADEG and LMQR). Primes consisted of one upper case and one lower case letter. The physical similarity between the letters was minimized using Boles and Clifford's similarity rating (Boles & Clifford, 1989). Targets were the numbers 1, 3, 5 and 7. The lay-out of a trial was similar to that of Experiment 3 in Van Opstal et al. (2011) with the only differences being that the SIW varied between blocks and that the primes were unmasked for half of the participants (see Fig. 1). The SIW was identical for the prime and target and was equal to 1.53°, 4.02°, or 6.51°. The size of the stimuli was scaled with the size of the SIW according to Strasburger, Rentschler, and Juttner (2011).

$$S = S_0\left(1 + \frac{E}{E_2}\right)$$

With S being the stimulus size at eccentricity E, $S_0$ the threshold size in the center of the fovea (i.e., $E = 0$), and $E_2$ a constant (here $E_2 = 2.6$ according to Drasdo (1991). The sizes of the stimuli are listed in Table 1.

To ensure that the SIWs would be stable and identical for all participants, they were asked to place their heads on a chin rest located 60 cm from the screen. The SIW varied between blocks in a random order. Each SIW block contained 160 trials. The main experiment thus consisted of 480 trials in total. Every 80 trials, participants were offered a short break and presented with their mean RT and accuracy. The different set of letters (ADEG and LMQR), and the masking condition (hash masks or no masks; see Fig. 1) were between-subjects variables and counterbalanced across participants.

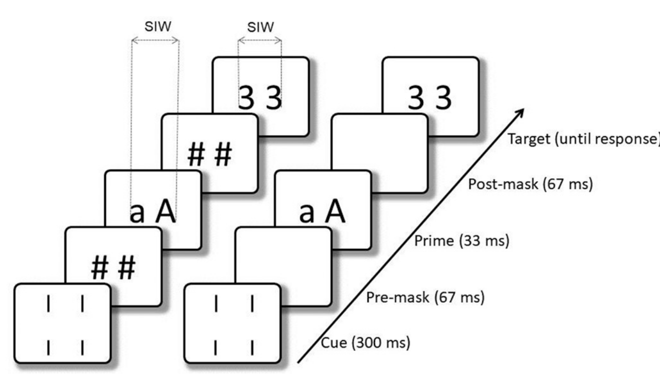


**Fig. 1.** Lay-out of a trial. Each trial started with the presentation of a cue for 300 ms. This was followed by the presentation of a pre-mask for 67 ms, the primes (33 ms), and a post-mask (67 ms). Then the targets appeared until a response was given. The masks were hash marks in the mask condition (shown on the left); nothing was presented in the no-mask condition (shown on the right). The spatial integration window in which the stimuli were presented (i.e., the SIW) varied between blocks and was equal to 1.53°, 4.02°, or 6.51°.

[1] The full experiment is reported in the Supplementary Materials

**Table 1**
The size of the stimuli was scaled with the size of the spatial window to compensate for peripheral vision. All sizes are in visual degrees.

| Spatial window | Width | Height |
|---|---|---|
| Small | 0.34 | 0.51 |
| Medium | 0.54 | 0.79 |
| Large | 0.68 | 1.02 |

## 2.2. Procedure

Participants were told that they were going to see a series of flashes ending with two simultaneously presented numbers. They were instructed to indicate on every trial if these numbers were the same or different by pressing the corresponding keys on the keyboard. Participants pressed the 'd' key to indicate a 'same' response, and 'l' to indicate a 'different' response. Prior to the experiment, participants performed five exercise trials in which feedback about their accuracy was given after every trial. After this short exercise block, the main experiment started.

After the main experiment, a prime visibility task was performed that was identical to the main experiment, but participants were now instructed to respond to the primes rather than the targets. Participants were fully informed about the lay-out of a trial before the start of this part of the experiment.

## 2.3. Results

All analyses were done with JASP 0.14.1 (JASP Team. 2020.). A 2 (Mask: Masked or Unmasked) × 2 (Congruency: Congruent or Incongruent) × 3 (SIW: Small, Medium or Large) repeated measures (rm) ANOVA with Mask as a between-participants variable was performed on the median reaction times of the correct trials. Mauchly's test indicated that the assumption of sphericity had been violated, therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity. This showed a main effect of SIW, $F(1.83, 109.65) = 5.62$, $p = .006$, $\eta^2 = 0.011$, with RTs of 467, 479 and 472 ms for the small, medium and large SIW respectively. There was also a significant main effect of Congruency, $F(1, 60) = 40.96$, $p < .001$, $\eta^2 = 0.012$, with faster RTs to congruent (468 ms) compared to incongruent trials (478 ms), and a significant interaction between Mask and Congruency, $F(1, 60) = 11.62$, $p < .001$, $\eta^2 = 0.003$. Most importantly, the critical 3-way interaction between Mask, SIW and Congruency was also significant, $F(1.88, 112.60) = 4.20$, $p = .019$, $\eta^2 = 0.001$. To further analyze this 3-way interaction, a 2 (Congruency) × 3 (SIW) rmANOVA on the median RTs for the masked condition revealed main effects of SIW, $F(1.88, 56.27) = 3.90$, $p = .028$, $\eta^2 = 0.087$, and congruency, $F(1,30) = 4.71$, $p = .038$, $\eta^2 = 0.015$. Crucially, also the interaction between the two factors was significant, $F(1.93, 57.84) = 6.75$, $p < .005$, $\eta^2 = 0.025$. Planned comparisons with Holm corrections revealed a significant difference between congruent and incongruent trials for the small SIW, $t(30) = 4.17$, $p_{holm} < 0.001$. No difference were observed for the medium and large SIWs (both $t$'s $< 1$). The same analysis for the unmasked condition only showed a significant effect of congruency, $F(1, 30) = 45.78$, $p < .001$, $\eta^2 = 0.149$, but no significant interaction was observed ($F < 1$). These results are summarized in Fig. 2.

The same analysis on the mean error rates was performed. The results were corrected using Greenhouse-Geisser estimates of sphericity and revealed a significant main effect of Congruency, $F(1, 60) = 29.70$, $p < .001$, $\eta^2 = 0.026$, with a higher error rate on incongruent trials (6.44%) compared to congruent trials (4.89%). The interaction between SIW and Congruency was also significant, $F(1.97, 117.94) = 5.89$, $p = .004$, $\eta^2 = 0.009$. Post-hoc tests revealed that significantly more errors were made on incongruent trials compared to congruent trials when the SIW was small, $t(60) = 5.94$, $p_{holm} < 0.001$, but not when the SIW was medium or large.

## 2.4. Prime visibility

Because of technical error, the data of one participant from the unmasked condition was not recorded properly. The following analysis were thus performed on 61 participants only. Visibility of the primes was investigated by calculating a $d'$ for the different widths for both masked and unmasked conditions. A 3 (SIW: Small, Medium or Large) × 2 (Mask: Masked or Unmasked) rmANOVA on the average $d'$ with Mask as a between subjects factor was performed. Results only showed a main effect of Mask, $F(1, 59) = 17.82$, $p < .001$, $\eta^2 = 0.204$, with a higher $d'$ for unmasked compared to masked trials. Given that testing visibility depends on testing the null, both student's and Bayesian one sample $t$-test were performed on $d'$ and are summarized in Table 2. While the Bayes Factors (BFs) for the $d'$s in the unmasked conditions provided very strong evidence in favor of a difference from 0, the BF for the small and medium SIW in the masked condition gave substantial evidence in favor of the null. For the large SIW in the masked condition, the BF gave no reliable evidence in favor or against 0.

# 3. Discussion

The results of this experiment showed a clear congruency effect when the stimuli were unmasked, independent of the SIW size. In contrast, in the masked condition a congruency effect was found in the small and medium sized SIW only; no effect was found for the largest SIW. These results replicate our earlier work (Van Opstal et al., 2010)

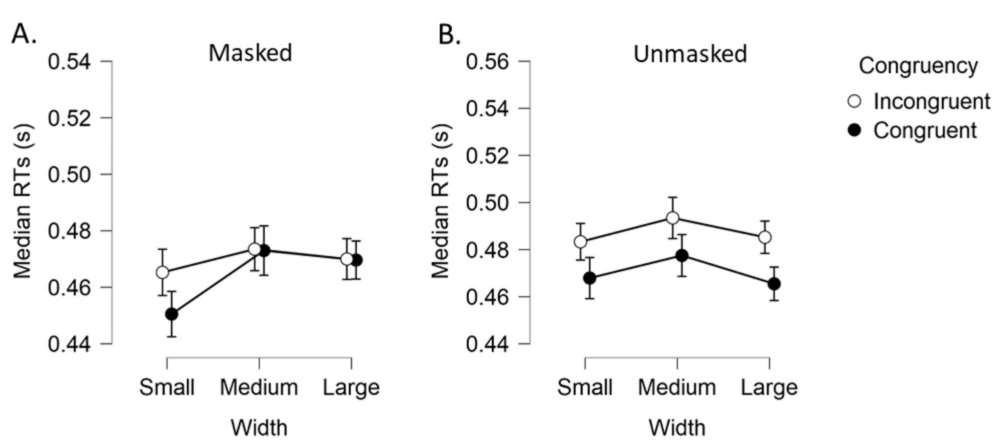


**Fig. 2.** Median RTs on incongruent and congruent trials for the different SIWs used in the experiment for the (A) masked and (B) unmasked condition. Error bars denote the standard 95% confidence intervals.

**Table 2**
$d$'s for all different conditions. $BF_{10}$ = Bayes Factor for the alternative versus the null hypothesis.

| | SIW | $d'$ | % Correct (range) | Student's t | $BF_{10}$ |
|---|---|---|---|---|---|
| No mask | Small | 0.36 | 59 (43–88) | $t(30) = 4.13, p < .001$ | 106.3 |
| | Medium | 0.36 | 59 (44–84) | $t(30) = 4.56, p < .001$ | 310.4 |
| | Large | 0.34 | 59 (46–86) | $t(30) = 4.50, p < .001$ | 304.9 |
| Hash mask | Small | 0.009 | 50 (42–59) | $t(29) = 0.42, p = .680$ | 0.211 |
| | Medium | 0.06 | 51 (44–56) | $t(29) = 1.11, p = .278$ | 0.339 |
| | Large | 0.06 | 51 (43–58) | $t(29) = 2.00, p = .055$ | 1.111 |

and support the hypothesis that the SIW is smaller for masked compared to unmasked stimuli.

The effect of SIW for masked stimuli offers a potential explanation for the absence of unconscious information integration in previous work, e.g. in object-scene integration (Biderman & Mudrik, 2018; Moors et al., 2016). Because of the size of the object-scene stimuli, the incongruence between the scene and the object could have taken place outside the scope of the SIW. Furthermore, object-scene stimuli are more complex than the letter stimuli used in this study and might therefore even be subject to a smaller SIW than those that allowed unconscious information integration in the present study (Mudrik et al., 2014). Similarly, the large SIW needed to integrate multiple words into a sentence could be one of the contributing factors for the failure to find unconscious sentence processing (Rabagliati, Robertson, & Carmel, 2018). Earlier work already showed that barely visible words presented a few visual degrees from fixation are not semantically processed (Duscherer & Holender, 2002; Paap & Newsome, 1981), further suggesting that a string of perceptually degraded letters in a larger SIW cannot be integrated to form a meaningful word. It should, however, be noted that the results of the current experiment might only apply for subliminal masking experiments. To extrapolate our findings to other research paradigms (e.g., CFS), future research should test this explicitly.

The results from our visibility experiment showed that $d'$ in the masked conditions was not significantly different from 0. Furthermore, in the condition that showed an unconscious congruency effect (i.e., the small window), also the Bayes Factor provided substantial evidence in favor of the null hypothesis. In medium and large condition, where the Bayes Factor supported the null nor the alternative hypotheses, no congruency priming was observed. The results of this study can therefore not be explained by the visibility of the masked primes. Although the use of a post-experimental objective visibility test certainly has its limits, and an alternative such as trial-by-trial subjective measurements would be more suitable, the choice of measuring visibility like this was primarily based on the fact that we wanted to replicate our initial findings (Van Opstal et al., 2010), and that other subjective measures might be too liberal (e.g., Stein & Peelen, 2021, for a recent demonstration and overview of the objective/subjective debate).

In sum, contrary to recent replication studies, this study provides further support for unconscious information integration in subliminal masking experiments. However, further research is needed to investigate if this only holds when stimuli are easy to segregate and fall within a small spatial window.

## CRediT authorship contribution statement

**Filip Van Opstal:** Conceptualization, Methodology, Software, Formal analysis, Visualization, Supervision. **Molly Rooyakkers:** Investigation, Methodology.

## Declaration of Competing Interest

None.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2022.105113.

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