

Consciousness is not necessary for visual feature binding

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Published online: 19 August 2014
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Abstract When visual information enters the brain, it is relayed to different specialized regions, processing features such as shape, color, or motion. And yet, in our conscious experience of a colored, moving shape, all the different features seem to be integrated into one unified percept. Therefore, it has been hypothesized that consciousness and feature binding share an intimate relationship. To study this relationship, we used a paradigm in which the behavioral effects of feature binding can be measured. Using masks, we investigated whether spontaneous binding between the orientation and location of a Gabor patch takes place when the Gabor patch is processed consciously or unconsciously. The results of our study suggest that orientation and location of a visually presented object are automatically integrated, even when subjects are unaware of that object. We conclude that binding and consciousness share a less intimate relationship than previously hypothesized, since consciousness is not a necessary condition for binding to occur.

Keywords Feature binding · Integration · Awareness · Consciousness

Introduction

One of the most intriguing problems that scientific studies of the human mind face today is how the brain creates conscious

experiences. One salient feature of consciousness is that it is *unified*; when we perceive the face of a loved one, say, the different features belonging to that face, his/her tint, shape, movement, and so forth are integrated into one coherent percept. The fact that consciousness seems unified is remarkable, since the brain consists of a large number of specialized modules (coding, e.g., for faces, Kanwisher, McDermott, & Chun, 1997; color, Zeki et al., 1991; or motion, Zeki, 1980). This modular representation seems to call for a binding mechanism that integrates the information represented in spatially segregated brain areas in a fast and flexible manner.

Research focusing on this so-called *binding problem* (Treisman & Gelade, 1980) has shown that binding can occur between arbitrary feature conjunctions, even when this is irrelevant to the current task: Spontaneous binding has been demonstrated within the visual modality (Kahneman, Treisman, & Gibbs, 1992), but also across different modalities, such as between visual features and auditory features (Zmigrod & Hommel, 2009) and between visual features and action features (Hommel, 1998).

There is currently much debate about the relationship between binding and the unity of consciousness (e.g., Revonsuo, 1999), which boils down to two opposing hypotheses. The first hypothesis states that binding processes are independent from consciousness. Unified conscious experiences may depend on the product of binding processes, but these binding processes can in themselves proceed unconsciously. This would also raise the possibility that the “product” of binding processes does not necessarily have to be conscious.

The second hypothesis states that binding and consciousness share an intimate relationship. In this view, the contents of consciousness are always unified because, in order for the features of an object to be integrated, there needs to be a conscious representation of that object. It may turn out that whenever features are bound together, this automatically results in a phenomenological experience of that unified

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representation (Crick & Koch, 1990; Engel, Fries, Konig, Brecht, & Singer, 1999), or vice versa; Whenever individual features enter consciousness, they are automatically bound. The latter could also imply that binding is the function of consciousness (Desmedt & Tomberg, 1994).

The hypothesis that is tested in the present study is whether binding two features of a visual stimulus (location and orientation) is possible even though the stimulus is masked to prevent conscious report. We used a paradigm with which it is possible to assess the behavioral effects of spontaneous binding between the visual features of an object (Hommel, 1998). This paradigm was combined with effective and ineffective masking.

In the effective masking condition (as opposed to the ineffective masking condition), subjects were unable to report whether a Gabor patch was presented or not, and we assume that the Gabor patch is processed unconsciously in that condition. Our predictions were clear-cut: If consciousness is necessary for the binding between the location and orientation of the Gabor patch, the behavioral effects of this binding should be absent when Gabor patches are effectively masked, but if consciousness plays no functional role in the binding between the location and orientation of the Gabor patch, the behavioral effects should be equal for effectively and ineffectively masked Gabor patches.

Method

Participants

Forty-one right-handed volunteers (13 male; mean age: 22.4 years) participated in the experiment for course credits or a fee. Informed consent was obtained before the start of the experiment.

Task 1: Mask configuration

In the mask configuration task (see Fig. 1a), subjects were instructed to discriminate between the absence and presence of a target (Gabor patch, white lines on a black background; 4° diameter; spatial frequency: 12 cycles/°), by responding with a left or right buttonpress (counterbalanced across subjects). The target could occur either above or below the fixation cross (distance to center Gabor patch: 4°) and had either a horizontal or a vertical orientation. On 50% of the trials, a target was present. The target screen lasted 17 ms and was preceded and followed by a screen lasting 100 ms, which contained two masks. These masks consisted of a two overlapping Gabor patches (horizontal+vertical orientation, black lines on a light background) and appeared above and below the fixation cross. After a response interval lasting between 1,000 and 1,200 ms, feedback was presented (“correct,” “incorrect,” or “respond faster”) for 300 ms.

The strength of the masks was varied by changing the maximum luminosity values of the Gabor patch and the corresponding luminosity values of its surroundings (see Fig. 1a). The luminosity was adjusted according to a staircase procedure. On trials where a target was present, the luminosity of either the top or the bottom mask was raised when subjects detected the target and lowered when they missed the target (in 1% steps), depending on the location of the target. The task consisted of 200 trials. Using this procedure, subjects were driven to perform at chance level, indicating that they were no longer able to discriminate between the absence or presence of a target.

Task 2: Binding

The binding task (see Fig. 1b) was a modified version of the task developed by Hommel (1998). A trial started with a dimming of the fixation cross to indicate the start of a new trial. Two Gabor patches (identical to the Gabor patch used in the first task) were presented in sequential order. The first (S1) and second (S2) Gabor patches were preceded and followed by masks. The strength of the masks was equal to the average strength of the last 10 trials of the mask configuration task, increased with 10%. On 50% of the trials, the masks that preceded and followed S1 were separated from S1 by blank screens, lasting 100 ms. In other words, half of the trials contained an S1 that was effectively masked, while on the other half of the trials, S1 was ineffectively masked. Between the second mask screen (following S1) and the third mask screen (preceding S2), a blank interval was presented. This screen had a duration of 500 ms on the effectively masked trials. On the ineffectively masked trials, this screen lasted 400 ms in order to ensure that the interval between S1 and S2 was identical on both the effectively and ineffectively masked trials. Subjects were instructed to respond with a left or right buttonpress (counterbalanced across subjects) to the orientation of S2. The masks that preceded and followed S2 were separated from S2 by blank screens, lasting 100 ms, rendering S2 visible for the orientation discrimination task. The task consisted of 384 trials, with an equal number of trials per condition.

Task 3: Mask evaluation

The mask evaluation task was similar to the mask configuration task in the sense that subjects again had to discriminate between the absence and presence of a target. However, in the mask evaluation task, mask strength was identical to the mask strength used in binding task and remained the same throughout the task. Subjects did not receive feedback about their responses.

The goal of this task was to test whether subjects’ performance was still at chance level after completing the binding

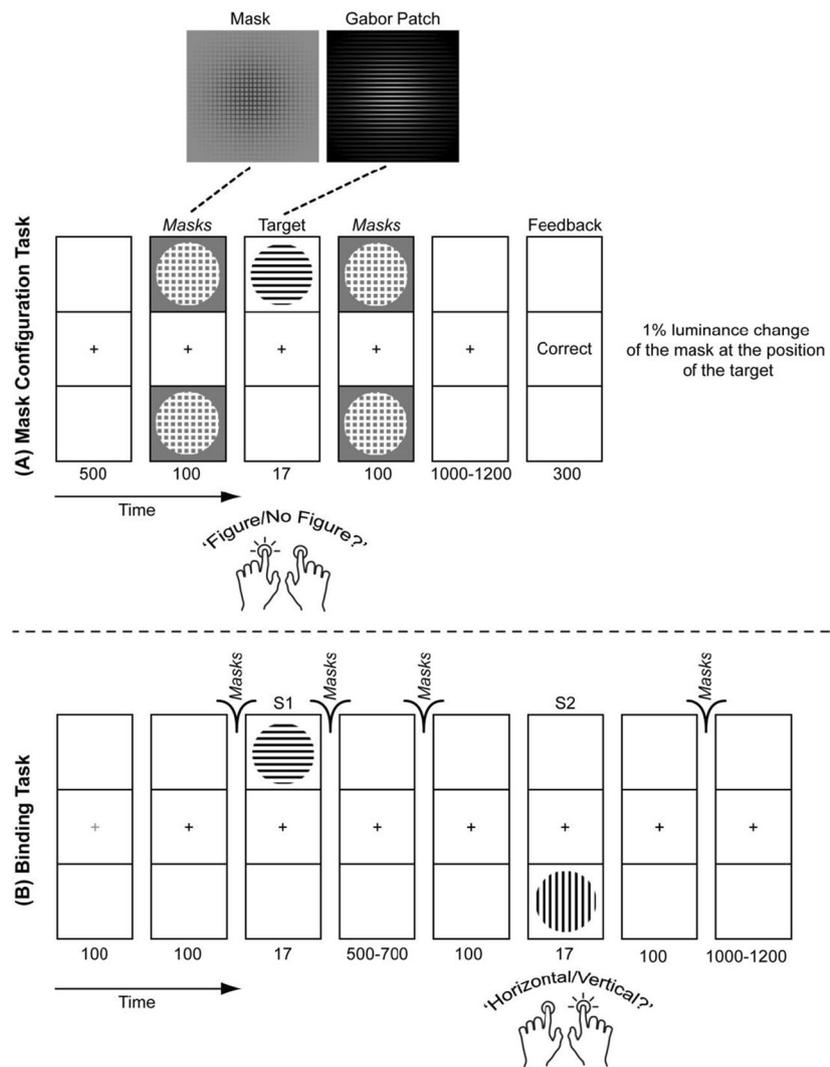


Fig. 1 Time sequence of an example trial in the **a** mask configuration task and **b** binding task

task, which may have led to some form of perceptual learning of the Gabor patch.

Results

Performance on the mask evaluation task served as a selection criterion for the inclusion of subjects in the statistical analysis of the binding task. In order to minimize the risk of false positives due to multiple comparisons, two binominal tests were performed on each subject. The first binominal test was done on half of the trials of all subjects (odd/even split). The results showed that 5 subjects deviated significantly from chance performance ($ps < .05$, two-sided). The second binominal test was performed on the remaining half of the trials of these 5 subjects. Two of these 5 subjects showed significant above-chance performance on the second

binominal test ($ps < .005$, two-sided), which indicates that the masked Gabor patches may not have been fully masked in the preceding binding task for these subjects. Therefore, these subjects were excluded from further analyses. Reaction times below 200 ms and above 1,000 ms were considered as outliers and were discarded. For the analyses of the reaction times, only correct responses were included. Using these criteria, subjects were included in the analyses only if no more than 40% of the trials were discarded. This resulted in the exclusion of 10 subjects. These subjects seemed to be unable to execute the task at an acceptable level of performance (mean accuracy = 60%, $SE = 3.7$; mean RT outliers = 15%, $SE = 3.1$). Including these subjects in the analyses rendered the binding costs in reaction times reported below nonsignificant, when S1 was both effectively and ineffectively masked, ($ps > .08$).

The behavioral results of the binding task are summarized in Table 1. To assess the binding costs for trials on which S1 was effectively versus ineffectively masked, we performed a

Table 1 Behavioral data as a function of S1-masking (effective/ineffective), orientation (repetition/alternation), and location (repetition/alternation)

	Mean RTs (ms)	SE	Accuracy (% correct)	SE
S1-masking = ineffective				
Orientation repetition/location repetition	638	14.1	91	1.1
Orientation repetition/location alternation	640	14.3	92	0.9
Orientation alternation/location repetition	653	15.3	86	2.0
Orientation alternation/location alternation	637	17.1	88	1.8
S1-masking = effective				
Orientation repetition/location repetition	674	16.0	90	1.3
Orientation repetition/location alternation	682	15.4	89	1.3
Orientation alternation/location repetition	675	15.9	93	1.1
Orientation alternation/location alternation	673	14.7	91	1.1

repeated measures ANOVA, with S1 masking (effective/ineffective), orientation (repetition/alternation), and location (repetition/alternation) as two-level factors.

For reaction times, a significant main effect of S1 masking, $F(1, 27) = 22.1, p < .0001$, indicated that responses were faster with an ineffectively masked ($M = 642$ ms, $SE = 15$) than with an effectively masked ($M = 675$ ms, $SE = 15$) S1. Second, and a prerequisite for answering the question posed here, there was also a significant interaction between the repetition and alternation of orientation and location, $F(1, 27) = 10.8, p < .005$ (see Fig. 2a, b). This is a replication of earlier findings illustrating the behavioral effects of binding between the features presented on S1 (Hommel, 2004). Repeating the location resulted in faster responses when the orientation was repeated versus alternated ($M = 656$ ms, $SE = 14$ vs. $M = 664$ ms, $SE = 15$), while alternating the location resulted in slower responses when the orientation was repeated versus alternated ($M = 661$ ms, $SE = 14$ vs. $M = 655$ ms, $SE = 15$).

Most important, and directly addressing the question about the presence or absence of unconscious binding, there was no sign of any three-way interaction between S1 masking, orientation, and location, $F(1, 27) = 0.25, p > .6$. This indicates that binding costs were not significantly different when S1 was effectively or ineffectively masked. Planned comparisons showed that the binding costs were significant when S1 was ineffectively masked (8.6 ms), $t(27) = 2.3, p = .02$, (one-tailed) and when it was effectively masked (5.8 ms), $t(27) = 1.8, p = .04$, (one-tailed) (see Fig. 2c).

For the accuracy data, a significant main effect of S1 masking, $F(1, 27) = 4.6, p < .05$, indicated that accuracy was slightly lower for ineffectively masked than for effectively masked S1 ($M = 89.1\%$, $SE = 1.2$ vs. $M = 90.6\%$, $SE = 1.0$). S1 masking interacted with location, $F(1, 27) = 8.8, p < .01$, and with orientation, $F(1, 27) = 18.9, p < .005$. Repeating versus alternating the location resulted in lower accuracy if S1 was ineffectively masked ($M = 88.3\%$, $SE = 1.3$ vs. $M =$

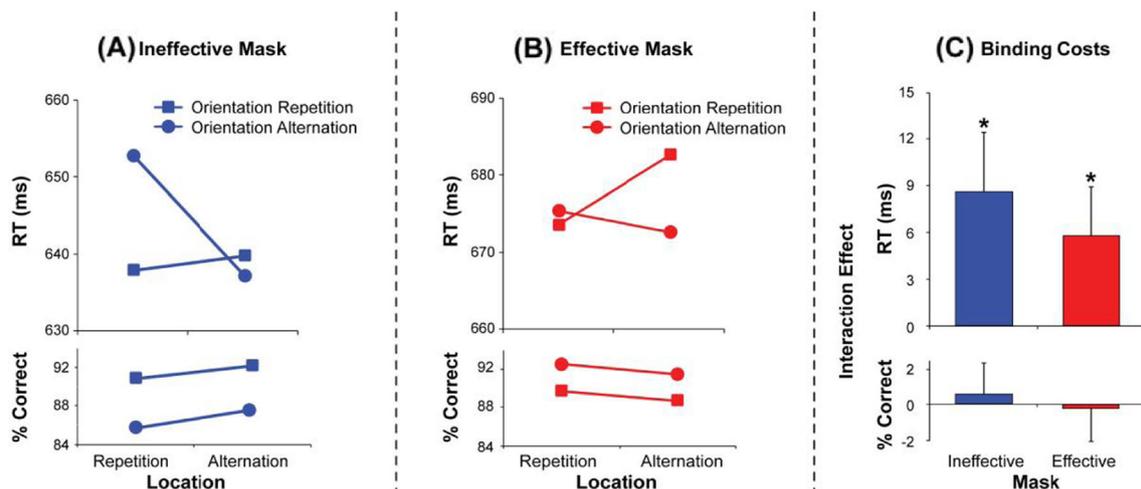


Fig. 2 a Behavioral data (reaction times and accuracy) of the binding task as a function of S1 (effective/ineffective), orientation (repetition/alternation), and location (repetition/alternation). b Binding costs were

highly comparable when S1 was either consciously or unconsciously processed. Error bars represent standard errors; asterisks indicate significance level of $p < .05$

89.9%, $SE = 1.2$) than if it was effectively masked ($M = 91.1\%$, $SE = 1.0$ vs. $M = 90.0\%$, $SE = 1.0$). Repeating versus alternating the orientation resulted in the opposite effect; Accuracy was higher if S1 was ineffectively masked ($M = 91.5\%$, $SE = 0.9$ vs. $M = 86.7\%$, $SE = 1.8$) than if it was effectively masked ($M = 89.2\%$, $SE = 1.1$ vs. $M = 92.0\%$, $SE = 0.9$).

More important for present purposes, however, was the absence of any hint to a three-way interaction between S1 masking, orientation, and location, $F(1, 27) = 0.13$, $p > .7$. In other words, the interaction between orientation and location was in no way influenced by the way S1 was masked (effectively or ineffectively).

It can be argued that the presence of a binding effect in the ineffective mask condition has limited generalizability, since almost a quarter of our subjects needed to be excluded from the analyses because of their poor performance of the task. We therefore reran the analyses without the response time exclusion criteria (>200 ms and <1000 ms in the previous analyses). Except for this adjustment the second data analyses procedures were identical to the first data analyses procedures.

Results 2

The results of the second data analyses procedure are highly similar to the results of the first data analyses procedures. Again, performance on the mask evaluation task served as a selection criterion for the inclusion of subjects in the statistical analysis of the binding task, resulting in the exclusion of 2 subjects. For the analyses of the reaction times, only correct responses were included. Using these criteria, subjects were included in the analyses only if no more than 40% of the trials were discarded. This resulted in the exclusion of 4 subjects. These subjects seemed to be unable to execute the task at an acceptable level of performance (more than 60% discarded trials). Including these subjects in the analyses resulted in highly similar binding costs and binding costs \times mask condition in reaction times.

The behavioral results of the binding task are summarized in Table 2. To assess the binding costs for trials on which S1 was effectively versus ineffectively masked, we performed a repeated measures ANOVA, with S1 masking (effective/ineffective), orientation (repetition/alternation), and location (repetition/alternation) as two-level factors.

The main effects were very similar to those of the first analyses. Again, for reaction times, there was significant main effect of S1-masking, $F(1, 33) = 27.2$, $p < .00005$, indicating that responses were faster with an ineffectively masked ($M = 674$ ms, $SE = 16$) than with an effectively masked ($M = 728$ ms, $SE = 19$) S1. Second, there was also a significant interaction between the repetition and alternation of orientation and location, $F(1, 33) = 4.7$, $p < .05$ (see Fig. 3a, b). Repeating the location resulted in faster responses

when the orientation was repeated versus alternated ($M = 696$ ms, $SE = 17$ vs. $M = 700$ ms, $SE = 18$), while alternating the location resulted in slower responses when the orientation was repeated versus alternated ($M = 701$ ms, $SE = 16$ vs. $M = 707$, $SE = 17$). Figure 3c shows the binding costs for both mask conditions.

Most important, and directly addressing the question about the presence or absence of unconscious binding, there was no sign of any three-way interaction between S1 masking, orientation, and location, $F(1, 33) = 0.31$, $p > .55$. This indicates that binding costs were not significantly different when S1 was effectively or ineffectively masked. Planned comparisons did not show significant binding costs for the ineffectively masked or the effectively masked condition (see Fig. 3c).

For the accuracy data, a significant main effect of S1 masking, $F(1, 33) = 5.1$, $p < .05$, indicated that accuracy was slightly lower for ineffectively masked than for effectively masked S1 ($M = 85.8\%$, $SE = 1.6$ vs. $M = 88.0\%$, $SE = 1.3$). S1 masking interacted with location, $F(1, 33) = 8.8$, $p < .01$, and with orientation, $F(1, 27) = 16.9$, $p < .0005$.

More important for present purposes, however, was the absence of any hint to a three-way interaction between S1 masking, orientation, and location, $F(1, 33) = 0.33$, $p > .5$. In other words, the interaction between orientation and location was in no way influenced by the way S1 was masked (effectively or ineffectively).

Discussion

Replicating earlier findings (Hommel, 2004), the results of our experiment showed a significant increase of reaction times when the features of the first presentation of a Gabor patch (S1) were partially repeated on the second presentation of a Gabor patch (S2). These “binding costs” can be attributed to the integration of the features of S1 and the automatic retrieval of this association when a feature is repeated on S2 (Keizer et al., 2008). Importantly, the present experiment showed that this effect was present not only when S1 was consciously processed, but also when it was unconsciously processed. Therefore, it can be concluded that consciousness is not necessary for visual feature binding between the location and the orientation of a visual stimulus. Interestingly, in order for binding costs to occur in the present paradigm, not only did the visual features need to be integrated on S1, but also this association had to be implicitly stored for a short duration (500 ms) and automatically retrieved on S2. Apparently, all these binding-related processes were unaffected by the absence of awareness of S1. This is remarkable, since the effects of unconsciously processed stimuli tend to be rather short-lived (e.g., Fazio, 2001; Greenwald, Draine, & Abrams, 1996).

Previous research has shown that feature binding can occur without attention (Mordkoff & Halterman, 2008). In short,

Table 2 Behavioral data as a function of S1-masking (effective/ineffective), orientation (repetition/alternation), and location (repetition/alternation)

	Mean RTs (ms)	SE	Accuracy (% correct)	SE
S1-masking = ineffective				
Orientation repetition/location repetition	667	15.6	89	1.4
Orientation repetition/location alternation	668	15.6	90	1.3
Orientation alternation/location repetition	687	17.1	82	2.5
Orientation alternation/location alternation	674	18.4	83	2.7
S1-masking = effective				
Orientation repetition/location repetition	725	19.7	87	1.6
Orientation repetition/location alternation	734	18.3	87	1.3
Orientation alternation/location repetition	726	18.3	90	1.5
Orientation alternation/location alternation	727	19.6	89	1.5

Mordkoff and Halterman showed that irrelevant visual feature combinations can be conditioned to be associated with a particular response, which may then affect the response times of the relevant target stimulus. It is important to realize that the irrelevant visual feature combinations that were used in the study of Mordkoff and Halterman were presented for a duration that was long enough for the subjects to have a conscious experience of the visual feature combinations. Thus, the conclusions of Mordkoff and Halterman are limited to attention and cannot be generalized to conscious versus unconscious processing. Even though consciousness and attention may have often been used interchangeably in the literature, they reflect different cognitive and neurobiological processes (e.g., Lamme, 2003).

It is also known that rather complex stimuli can be processed unconsciously, such as faces (e.g., Morris, Pelphrey, & McCarthy, 2007) and words (e.g., Dehaene et al., 1998). Although these stimuli consist of specific configurations of more low-level visual features, it is not clear whether

processing them requires the binding of these features. The brain has specialized areas for processing complex stimuli and for acquiring representations of complex configurations, which may rely more on hierarchical feed-forward processing than on flexible feature binding. Indeed, binding studies have provided evidence for two parallel and largely independent pathways—one binding features according to purely bottom-up criteria and another, more interactive pathway that is informed by previous learning of complex configurations (Colzato, Raffone, & Hommel, 2006; Hommel & Colzato, 2009). In our study, the combinations of location and orientation of the Gabor patch were completely random for each trial, which seems to require a more flexible integration process than the processing of complex stimuli for which the combination of features is less random.

Our findings raise a number of interesting questions. First, since the products of feature-binding processes can be represented unconsciously, unified conscious experiences must require more than (the creation of) unison alone. Thus, in

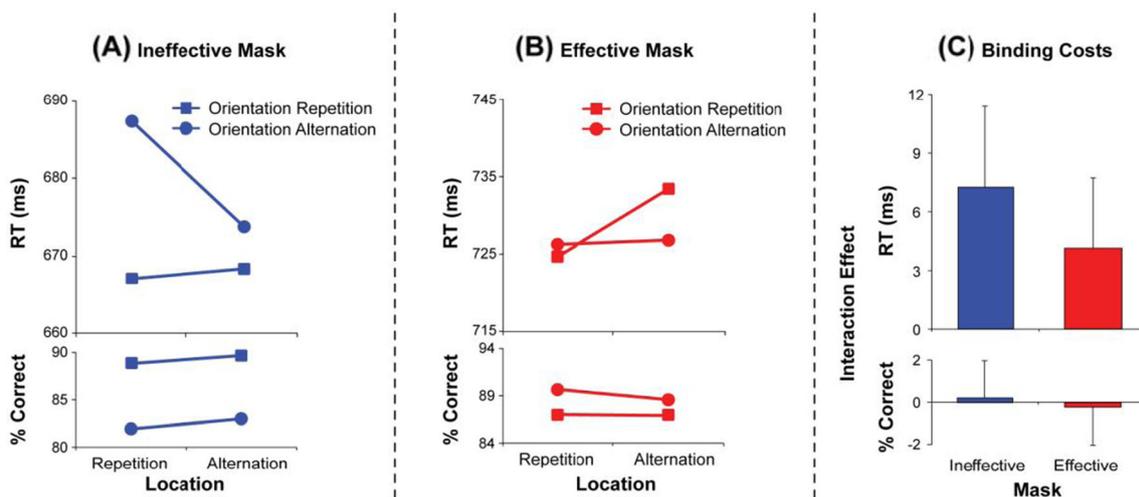


Fig. 3 a, b Behavioral data (reaction times and accuracy) of the binding task as a function of S1 (effective/ineffective), orientation (repetition/alternation), and location (repetition/alternation). c Binding costs were

not significantly different when S1 was either consciously or unconsciously processed. Error bars represent standard errors

contrast with influential theories that do suggest that binding results in consciousness (Crick & Koch, 1990; Engel et al., 1999), there seem to be additional processes necessary for conscious experiences. The question that future research needs to address is what these processes are.

Second, why are our conscious experiences always unified? In other words, why is binding necessary for consciousness? One explanation could be that visual processing is hierarchically organized in such a way that the products of binding processes provide the building blocks for conscious experiences, but a conscious experience does not automatically need to follow after binding processes are completed.

Third, in the present study, we have shown that consciousness is not necessary for binding between the location and orientation of a Gabor patch. However, this does not rule out the possibility that consciousness is required for binding between other visual features. It has been proposed that there may be two forms of feature binding (Roelfsema, 2006). One type of binding may be performed by dedicated neurons that code for combinations of simple visual features such as orientation and color or location and motion direction. This so-called *base-grouping* can occur in a rapid but inflexible manner, since it relies on feedforward connections. However, feature combinations that cannot be represented by single neurons require a more flexible mechanism, which relies on horizontal and feedback connections. It is conceivable that the former base-grouping can occur unconsciously, while the later, so-called *incremental grouping* does require consciousness. Other examples of such base groupings would be the fully automatic recognition of words versus nonwords, where it has been shown that the assembly of letters into words occurs in a feedforward sequence of processing steps located in the occipito-temporal pathway (Dehaene et al., 2004). This progression from letter to letter-combination to word coding does not depend on consciousness, since it occurs also for fully masked and invisible words. It is hypothesized that these “base-groupings” depend on highly dedicated pathways and, hence, occur only for highly relevant or overtrained stimuli (words, faces, etc.). Related to this issue is the demonstration that different visual features may lead to different sequential effects in priming experiments independently of their task relevance (Kristjánson, 2006, 2009). It should therefore be made clear that our study demonstrates a proof of principle: It is possible that unconsciously perceived visual features are integrated. Whether this effect can be generalized to other feature combinations should be determined by future research.

Finally, we note that there has been ample debate concerning the methodology of studying consciousness in psychophysiological experiments (e.g., Crick, 1996; Kim & Blake, 2005; Lamme, 2010). There are many methods besides masking that are used in the study of consciousness, such as inattention blindness, change blindness, attentional blink, or binocular rivalry. All these methods assume that if a subject is

not able to report the presence of a stimulus, the subject is not conscious of that stimulus. This is an assumption that has been questioned in the literature (e.g., Lamme, 2010). Therefore, a fruitful approach would be to use different methodologies for testing hypotheses on consciousness that either do or do not depend on the subject’s behavior. Accordingly, it will be important to provide converging evidence in support of our conclusions by using different methodologies as well.

To conclude, even though research on visual feature binding (and its neural correlates) has often been deemed relevant for the scientific study of consciousness, the present findings suggest that this belief is unjustified. In our view, the problem of how the brain produces unified conscious experiences should be split up into two independent problems, the problem of how the brain produces unison and the problem of how the brain produces conscious experiences.

Acknowledgments Victor A. F. Lamme is supported by an advanced investigator grant from the European Research Council. We would like to thank Simon van Gaal for his comments on the design of the experiment.

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