Title: Perceptual errors support the notion of masking by object substitution

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**Abstract**

Two experiments examined the effect of Object Substitution Masking (OSM) on the perceptual errors in reporting the orientation of a target. In Experiment 1 a four-dot trailing mask was compared with a simultaneous-noise mask. In Experiment 2, the four-dot and noise masks were factorially-varied. Responses were modelled using a mixture regression-model and Bayesian-inference to deduce whether the relative impacts of OSM on guessing and precision were the same as those of a noise mask, and thus whether the mechanism underpinning OSM is based on increasing noise rather than a substitution process. Across both experiments, OSM was associated with an increased guessing-rate when the mask trailed target offset, and a reduction in the precision of the target representation (although the latter was less reliable across the two experiments). Importantly, the noise mask also influenced both guessing and precision, but in a different manner, suggesting that OSM is not simply caused by increasing noise. In Experiment 2 the effects of OSM and simultaneous-noise interacted, suggesting the two manipulations involve common mechanisms. Overall results suggest that OSM is often a consequence of a substitution process, but there is evidence that the mask increases noise levels on trials where substitution doesn’t occur.

**Abstract word count**: 198

"Perceptual errors support the notion of masking by object substitution"

Object substitution masking (OSM) is a form of backwards masking in which the perceptibility of a briefly presented target is diminished by the presence of a surround mask which onsets simultaneously with the target but trails it at offset (Di Lollo, Enns & Rensink, 2000). The most characteristic attribute of OSM is the fact that the surround mask need not contain any significant contour for the phenomenon to occur. Indeed, a mask composed of just four surrounding dots is sufficient to produce a substantial masking effect (Enns & Di Lollo, 1997; Di Lollo et al. 2000). The distance between the dots is largely unimportant in the production of the effect (Di Lollo et al. 2000), though the spatial overlap between the surround mask and target is important (Kahan & Mathis, 2002; Guest, Gellatly, & Pilling, 2011), as are factors associated with the status of the target as a perceptual object within the scene (Lleras & Moore, 2003; Moore & Lleras, 2005, Pilling & Gellatly, 2011; Tata, 2002). Because of the properties of OSM, most theories assume that the phenomenon largely represents the outcome of object-level interactions (Di Lollo et al., 2000; Moore & Llearas, 2005; Enns, Lleras & Moore, 2009; Goodhew, 2017), and not the sorts of low-level spatiotemporal interactions which have been argued to occur in conventional forms of masking (Breitmeyer & Ganz, 1976). Consequently, OSM is of particular interest for researchers understanding the process by which object representations are formed in early vision (Goodhew, Edwards, Boal, & Bell, 2015; Camp, Pilling & Gellatly, 2017; Enns, Lleras & Moore, 2010).

Theories of OSM

OSM has been seen as something of a test case for comprehending the functional architecture of the visual system (Bridgeman, 2006; Di Lollo et al., 2000; DiLollo, Enns & Rensink, 2002; Enns, & Di Lollo, 2000; Francis & Hermens, 2002; Francis & Cho, 2007; Macknik & Martinez-

Conde, 2007; Di Lollo, 2013, Põder, 2013). The characteristics of OSM are not easily accounted for by standard models of masking (e.g. Breitmeyer & Ganz, 1976). Because of this it has been argued that a new theoretical orientation is necessary, one which assumes a re-entrant brain architecture (Di Lollo et al. 2000; Enns, & Di Lollo, 2000; Di Lollo, 2013). However, others have claimed that standard feedforward models of visual processing can be adapted to account for OSM (Frances & Hermans, 2002; Põder, 2013).

A highly influential model of OSM, one which makes the case for a new theoretical orientation is the *Object Substitution Theory of Masking* (OSTM; Di Lollo et al., 2000; Di Lollo et al. 2002; Di Lollo, 2013). The OSTM is cast in terms of object-level processes. Masking is explained within a re-entrant model of perceptual processing. In this conscious perception of a stimulus occurs as a consequence of repeated iterative cycles of information exchange between different levels of the visual system. It is argued that in perception the initial feedforward-sweep of information through the visual system –from the retina through to an iconic representation in V1 and onto higher visual areas– is not itself sufficient to produce awareness. Instead this initial feedforward activity serves to allow the generation of perceptual hypotheses in the higher visual areas regarding the nature of the input signal. This hypothesis is then fed-back via re-entrant pathways and tested against the iconic representation in V1. It is only when a confirmatory match is found between the re-entrant hypothesis and V1 that conscious perception occurs; where a match is not found the iterative exchanges between V1 and higher visual regions continue until a stable match is found. In this model it is suggested that, even for a brief target stimulus, the perceptual processes will often result in a successful re-entrant match. However, it may be that the target has offset from screen before an appropriate perceptual hypothesis is formed. In this case, although the target's representation in V1 is no longer sustained by retinal input, a fading trace will still be present based on residual activity; this trace can then still form a basis on for a successful match with the descending hypothesis because the correlation between the two signals will still be relatively high. The difficulty for perception comes when a brief target is trailed by a delayed-offset mask. Here the icon representation will consist of a fading trace of the target and a robust representation of the mask sustained by current input. The perceptual hypothesis based on earlier activity is likely to be rejected because of the low correlation between the two signals. When this occurs a new hypothesis is likely to be instigated and later confirmed based on the stable iconic representation of the mask alone. Thus according to the OSTM, it is the instability in the visual input generated by the mask combined with the inherent latency of the re-entrant response which leads to masking of the form seen in OSM. The masking process can be said to be one of *substitution* of the target by the mask object: the presence of the trailing mask obstructs the formation of a stable percept involving the target, and instead promotes the formation of a percept containing of the mask alone.[1]

The *object updating theory of masking* (OUTM; Lleras & Moore, 2003) can be thought of as a reformulation of the OSTM, rather than a rival theoretical account. The OUTM accepts many of the tenets of the original OSTM. The OUTM, like the OSTM considers masking to be a process which occurs at the level of object representations, however, the OUTM views the competition between target and mask to occur within a single object representation, rather than two separate representations. Masking, it is argued, occurs when the visual system fails to *individuate* the target and mask as separate perceptual elements. The consequences of this are that the two elements become part of the same 'object token' representation. It is argued that the standard masking paradigm is one where the visual system is particularly likely to represent the target and mask as the same perceptual object because of the spatiotemporal overlap of the target and mask elements. The OUTM argues that when target and mask are both represented by the same token then the target features become vulnerable to being overwritten when the mask lingers after the target offset. The OUTM predicts that masking is dependent on whether the target and mask are presented in ways which promote the perception of the two as the same or different perceptual objects. Several lines

[1] Indeed the name OSM explicitly assumes a substitution process. Others have described OSM using, more theoretically neutral terms, such *as four-dot masking* or *common-onset masking*. These terms are also problematic in describing the OSM phenomenon since the OSM effect can occur when the mask is composed of something other than four-dots and when the mask does not have a common-onset with the target.

of evidence have supported this claim (Lleras & Moore, 2003; Moore & Lleras, 2005; Pilling & Gellatly, 2011; Gellatly, Pilling & Guest, 2010; Guest, Gellatly & Pilling, 2012).

A key prediction of the OSTM model is that it presumes masking to be an all-or-none process: Either the target representation emerges as the focus of perception or it is obliterated by the mask. The OUTM is arguably more neutral on the question of whether or not the masking process is total or partial in nature.

A proposed alternative to the OSTM (and its reformulation as the OUTM) is the *Attentional Gating Model* (AGM, Põder, 2013)[2]. The AGM model argues that OSM reflects a limit of temporal attentional selection. In the model masking occurs when in selecting the target, the mask, by virtue of being in in close temporal proximity, is also inadvertently selected. The consequence for this is that the target representation becomes degraded leading to reduced accuracy in target report. Thus in the AGM the masking effect on perception considered to be a matter of degree rather than a discrete all-or-none process. The attentional gating model has the clear appeal over the OSTM in its parsimony. It explains OSM as a consequence of a single stage process which is entirely feedforward in nature and thus makes no appeal to any re-entrant architecture.

OSM and the role of attention

Initial studies of OSM seemingly indicated that the phenomenon was restricted to circumstances where attention could not be rapidly focussed on the target location. For instance, OSM seemed to be restricted to circumstances where the target was presented in a display of multiple distractor items (Di Lollo et al, 2000; Kotsoni, Csibra, Mareschal & Johnson, 2007), or in

[2] Põder (2013) describes the AGM in terms of a reinterpretation of the OSTM not as a rival account. However, the reinterpretation focuses on Di Lollo et al.'s CMOS the computational model of object substitution. For the purposes of this paper we treat the attentional gating as a rival account and one which assumes the operation of different cognitive mechanism and which makes differing predictions about the consequences of masking.

conditions where the target occurs in a temporal stream of distractors (Dux, Visser, Goodhew & Lisp, 2010). Furthermore, initial work suggested that attentional cueing tended to modulate the extent to which OSM occurs (Di Lollo et al. 2000; Enns, 2004; Luiga & Bachmann, 2010). However later work has strongly challenged the claim that attention and OSM interact. Many early studies of OSM were confounded by the fact that performance was at ceiling in some conditions. The earlier reported interactions between display set size and OSM were accounted for either by this confound (Argyropoulos, Gellatly, Pilling & Carter, 2013; Filmer, Mattingley & Dux, 2014), by other processes such as visual crowding (Camp, Pilling, Argyropoulos, Gellatly, 2015; Camp, Pilling & Gellatly, 2017). Experiments which control for ceiling effects have generally found no influence of attentional variables, either in its spatial or temporal manifestation, on masking (Pilling, Gellatly, Argyropoulos, & Skarratt, 2014; Agaoglu, Breitmeyer & Öğmen, 2016; Filmer, Wells-Peris & Dux, 2017).

Such findings have been problematic for some of the previously discussed theories of masking. These theories have largely formulated on the basis of the assumption that OSM and attention interact. The OSTM in particular made strong appeal to the assumed role of attention in its initial formulation (Di Lollo et al., 2000). More recent formulations of the OSTM, however, have removed attention as a factor while retaining the emphasis on re-entrant processing and substitution (Di Lollo, 2014; Jannati, Spalek & Di Lollo, 2014). The role of attention is perhaps more fundamental to the AGM. According to the AGM masking occurs when attention is deployed towards a target location but finds the target representation to be both decayed by the target signal and degraded by visual noise, resulting in selection of a target signal with a lower signal-noise ratio (Põder, 2013; Di Lollo, 2014. However, the AGM is arguably underspecified in terms of the exact role attention plays, and, while predicting an overall role for attention, the model is ambiguous with respect to the effects of attentional manipulations on masking itself (Di Lollo, 2014; *c.f*. Põder, 2014).

OSM and perceptual errors

It seems that the relationship between attention and OSM is not something which is unambiguous in deciding between models. The models are either too underspecified, or too flexible with regards to their implementation of attention, for this factor to be useful in falsifying the models.

How then do we test between the OSTM and AGM accounts which present OSM in terms of radically different visual architectures? Another approach is to explore the patterns of errors in target perception resulting from masking. Analysis of these errors could be revealing in teasing between the models. The OSTM implies that OSM is an all-or-nothing phenomenon. Either the putative re-entrant process results in a successful match regarding the target or it does not, meaning that the target is substituted. The presence of the trailing mask is deemed to reduce the probability of a successful match occurring on any trial, the probability decreasing as a function of target duration. However, on trials in which a match is found the target percept is deemed to be intact. Thus in a perceptual discrimination task the effect of masking should be only to increase the number of trials in which a *guessing response* is made (i.e. one in which the response is selected from all possible options purely at random). The AGM makes different predictions. It argues that the masking process is not a consequence of substitution but of increased noise generated by the mask associated with the target. Therefore, the masking effect is one in which the target percept becomes degraded due to the *additional noise* generated by the incorporation of the mask into the target stimulus, the amount of noise increasing as a function of the trailing mask. Thus the AGM predicts that the effect of OSM is one of increasing noise associated with the target. This increased noise should therefore be reflected in a loss of precision in reporting about the target rather than just an increase in pure random guessing.[3]

We explore this possibility in two experiments. In both experiments the target stimulus is a Landolt C. After being presented with the masked stimulus participants adjust a rotating stimulus to match the orientation to the previously seen target. This basic approach is similar to one recently reported by (Harrison, Rajsic & Wilson, 2015) which, to our knowledge, was the first study to report using this approach within the OSM field, although it is well established in other perceptual tasks as a way of measuring the precision and character of visual representations of viewed stimuli (e.g., Agaoglu et al., 2015; Peich, Hussain & Bays, 2013; Guest, Howard, Brown, & Gleeson, 2015).

This approach, known as the method of adjustment, yields much more informative data than a simple correct/incorrect judgement as it allows participants to report more exactly on their perceptions. A further benefit is that the data generated allows use of a mixture model to determine the source of an error (Bays, Catalao, & Husain, 2009; Zhang & Luck, 2008). On a proportion of trials participants may have a representation of the target in which case their responses will be derived from a circular Gaussian distribution centred on the target. The standard deviation of this circular Gaussian distribution indicates the degree of variability of the representation and thus is an estimate of precision. On other trials participants may simply guess in which case their response will come from a uniform distribution.  The mixture model can therefore be used to estimate how masking influences the degree of precision and the amount of guessing.

Harrison, Rajsic and Wilson, (2015) used this approach in an attempt to establish whether OSM is the result of elimination, or merely the degradation, of the target percept. In their experiments they varied set size (number of display items) and the duration of the trailing mask

[3] Põder's original description of the model (Põder, 2013) seems to implicitly consider masking noise to be perceptual in character. In a later elaborated account the model is presented as one in which the noise could be either perceptual or decisional in nature (Põder, 2014). However, the predicted pattern of responses would be the same irrespective of the locus of this noise interference.

(Exp. 1) or the inter-stimulus interval of the trailing mask (Exp. 2). Their results indicated that masking resulted in a degradation in precision, a finding which is inconsistent with the notion that OSM involves a purely substitution process. Importantly, Harrison et al.'s data did show evidence that masking also increased guessing responses. This suggests that part of the masking effect was caused by elimination of the target percept a finding which is consistent with the substitution account of OSM. However, the data in Harrison et al. are arguably not definitive in distinguishing between feedforward (e.g. AGM), and re-entrant (OSTM) accounts because it is possible that an OSM mask might decrease precision and that this decrease in precision alone might lead to guessing. For example, there might be a threshold beyond which representations are degraded enough that a participant simply guesses rather than use the limited representational information available.

In order to assess this question, the current studies compare the effects of an OSM (i.e. four-dot) surround mask that trailed the target with that of a noise mask. The noise mask was an overlay of white noise on top of the target and appeared and offset simultaneously with the target (Lu & Dosher, 2008; Pelli & Farrell, 1999; Allard, Faubert & Pelli, 2015). As the noise mask did not trail the target it should not produce any substitution and should simply add noise to the target. This should lead primarily to a loss of precision in target report and may also result in an increase in guessing if the stimuli are degraded enough that participant simply switch to a guessing strategy. The important question is how the effect of the OSM type mask compares with that of the noise mask. If they behaved similarly and both had their effect primarily through influencing precision, then this would suggest a common determinant of the masking effect (supporting the AGM). In contrast, if the OSM mask resulted in object substitution, then we would expect that it would behave differently to the noise mask, such that it would primarily increase the rate of guessing.

Importantly we modelled the data using a mixture regression model and Bayesian inference (details below). Several aspects of this approach are worth noting. First the model was hierarchical-multilevel in that it fits individual and group level data simultaneously (see Gelman 2015; Gelman &

Hill, 2007). This approach enabled us to generate parameters for the group as a whole whilst still modelling individual level data. Bayesian inference enabled us to calculate high posterior density (HPD) intervals around the parameter estimates to reflect the uncertainty of these estimates. Lastly, although we used the standard mixture model, the relative weights of the parameters reflecting guessing and precision were regression functions of the mask duration and the noise level which were treated as ordinal variables. In other words, we assumed a generalised linear model relating the guessing and precision parameters across mask duration levels and noise levels. This is the first time such a modelling approach has been used in the field of OSM.

## Experiment 1

### Method

*Participants*. There were 14 participants, comprising undergraduate Psychology students recruited from Nottingham Trent University and one of the authors. All had normal or corrected-to-normal vision. Participants were either given course credit for participation or paid £5.

*Design.* There were seven mask conditions: A baseline condition in which no white noise was overlaid on the target (0% noise) and the target was surrounded by a four-dot mask which did not outlast the stimulus (0 ms four-dot mask), three simultaneous noise mask conditions in which the target was overlaid with a 25%, 50% and 75% white noise mask which onset and offset simultaneously with the target and three trailing four-dot mask conditions in which the mask offset trailed the target offset by 80 ms, 160 ms or 320 ms.

*Stimuli*. Stimuli were presented on an ASUS 3D 27inch LCD monitor (resolution= 1280 x1024 ; refresh rate=100 Hz) which was viewed at a distance of 52cm. The monitor was controlled by a standard PC. The PC was running software purpose written and compiled in the BlitzMax programming language (BlitzMax v.1.50; Blitz Research Ltd., Auckland: New Zealand). This software controlled all aspects of the experiment including stimulus generation and randomisation. The target consisted of a standard Landolt C stimulus. The diameter of the stimulus subtended a visual angle of 2.5 degrees. The thickness of the stimulus was 0.5 degrees and the gap size was 0.5 degrees. The target was presented in an array with seven distractors. These distractors were also Landolt Cs. All stimuli were black on a white background. The gap position of each stimulus was determined randomly in any one of 360 degree positions on each trial. The target stimulus was defined in the array by a radial cue which onset with the stimulus array and by virtue of the four surrounding dots. On trials in which there was a simultaneous noise mask this was present at the target location. The simultaneous noise mask was created by taking the region inside the four dots containing the target stimulus. From this region a proportion of pixels, depending on the simultaneous mask condition were randomly selected. Each of these randomly selected pixels were then randomly set to either black or white, overwriting the luminance values of the pixels that were otherwise present there. Thus for the 25%, 50% and 75% noise conditions, these refer to the number of pixels within this area that were randomly set to black or white. All eight stimuli in the array were positioned at regular positions on a virtual circle in the centre of which was the fixation cross. The diameter of this virtual circle was 8 degrees.

*Procedure*. All trials started with the onset of the fixation cross which remained on-screen until the presentation of the test stimulus. The stimulus array onset 350 ms after the onset of the fixation cross and remained on-screen for 50 ms. On trials in which there was a simultaneous noise mask the noise was present at the target location for the duration of the stimulus array. On trials in which the trailing OSM mask was greater than 0 ms the four surrounding dots lingered on screen for the appropriate duration. The seven mask conditions were given with equal frequency in a random order across the trials. After the offset of the mask a variable blank interval was given in which only the fixation cross was present. The test stimulus followed the offset of the mask after a blank interval (0-320 ms). The duration of this blank interval varied to keep the time constant between the offset of the target and the onset of the test stimulus. Thus, with a 0 ms mask a 320 ms blank interval was given, with a 320 ms mask a 0 ms blank interval was given. The test stimulus was also a Landolt C of the same dimensions as those in the stimulus array. The gap was initially always set to the upright position. The participant’s task was to rotate the test stimulus to try to match the gap position to that of the previously seen target. They did this by pressing the up and down keys on the computer keyboard which respectively rotated the test stimulus anticlockwise and clockwise when held. The participants also had the option to press the left and right arrow keys to nudge the test stimulus one degree at a time in a respectively anticlockwise and clockwise direction. No time limit was given for the adjustment; the participant then pressed the Enter key to select the adjusted gap position. This then recorded the adjustment position and began a new trial after a 600 ms inter-trial interval. There were 560 trials in the experiment. A demonstration and practice were given before commencing the experiment.

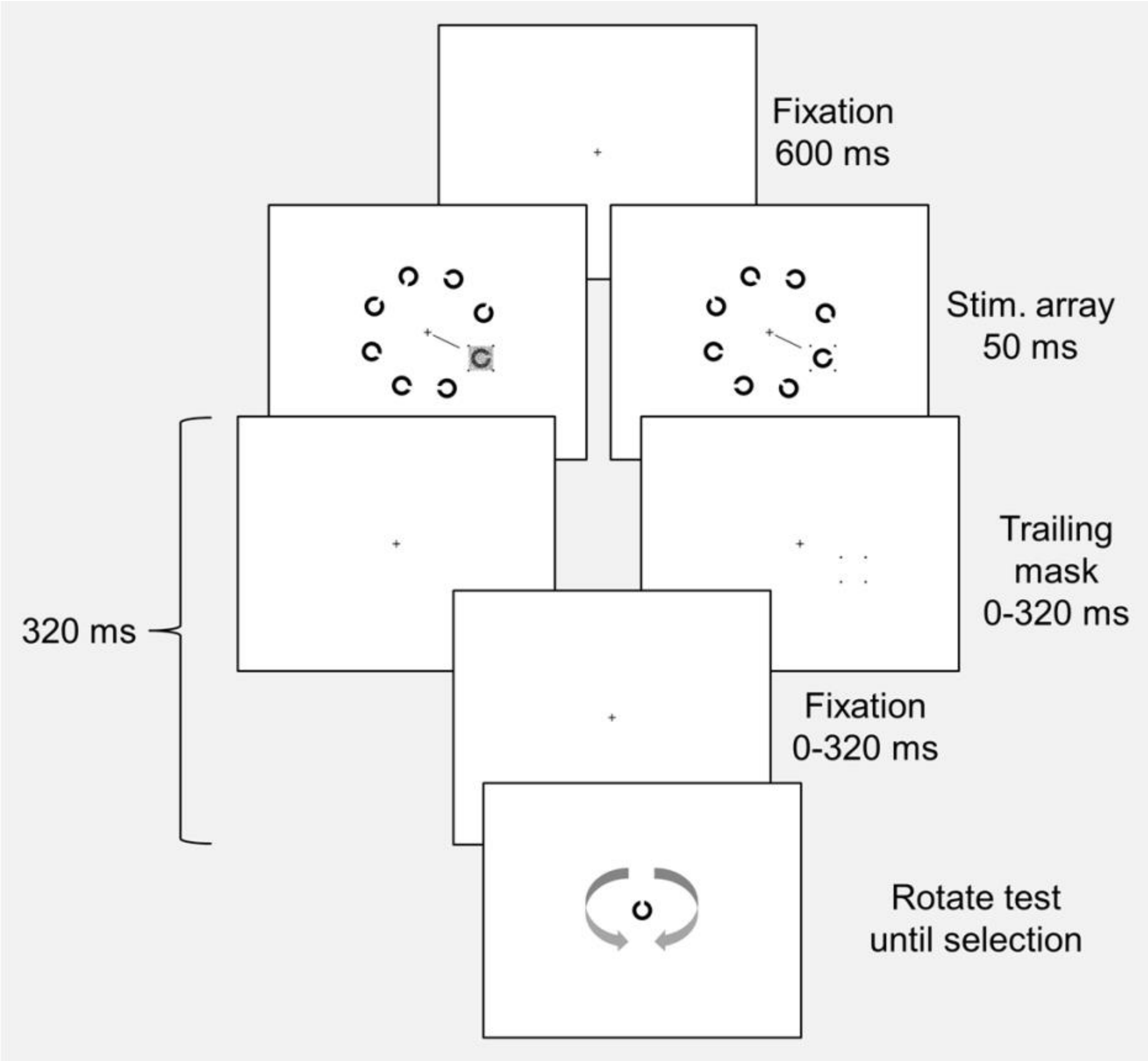



Figure 1. A schematic depiction of the trial sequence in Experiment 1. Note that the arrows in the last frame are schematic and not present in the presented image.

## Results

Mean error for each condition is given in Figure 2. For the OSM mask there was a clear effect of trailing mask duration. However, the effect was a consequence of a difference between the simultaneous offset (0ms) mask condition and the trailing mask conditions (80ms, 160ms, 320ms) which did not differ from each other. A one way repeated measures ANOVA with trailing mask duration (0 ms, 80 ms, 160 ms, 320 ms) as a factor yielded a significant effect of mask duration, *F*(3,

39) = 9.12*, p* =.002, $\eta_p^2$ =.41 (all ANOVAs in this paper use the Greenhouse Geisser correction). Polynomial contrasts showed significant linear (*p*<.001) and quadratic trends (*p*=.001), indicating no clear linear effect of noise. Post hoc Bonferroni comparisons showed that the 80 ms, 160 ms and 320 ms all significantly differed or showed a marginally significant difference from the 0 ms condition (*p* =.016, *p* =.007, *p* =.054 respectively).

For the simultaneous noise mask, the noise density had a clear effect. Mean error for the 25% mask did not differ from the 0% baseline condition, however subsequent increases to 50% and 75% worsened performance, A one way repeated measures ANOVA with percentage of white noise as a factor (0%, 25%, 50%, 75%) yielded a significant effect of mask duration *F*(3, 39) = 28.29*, p* <.001, $\eta_p^2$ =.69. Polynomial contrasts showed significant linear (*p*=.01) and quadratic trends (*p*=.002), indicating no clear linear effect of noise. Post hoc Bonferroni comparisons showed that all conditions differed significantly from each other (all *p* <.006) except for the 0% and 25% noise conditions which did not significantly differ (*p* =1.00). Of course, underlying these different levels of performance are the precision of the target representation and the rate of guessing. We now describe the modelling process to derive these estimates.

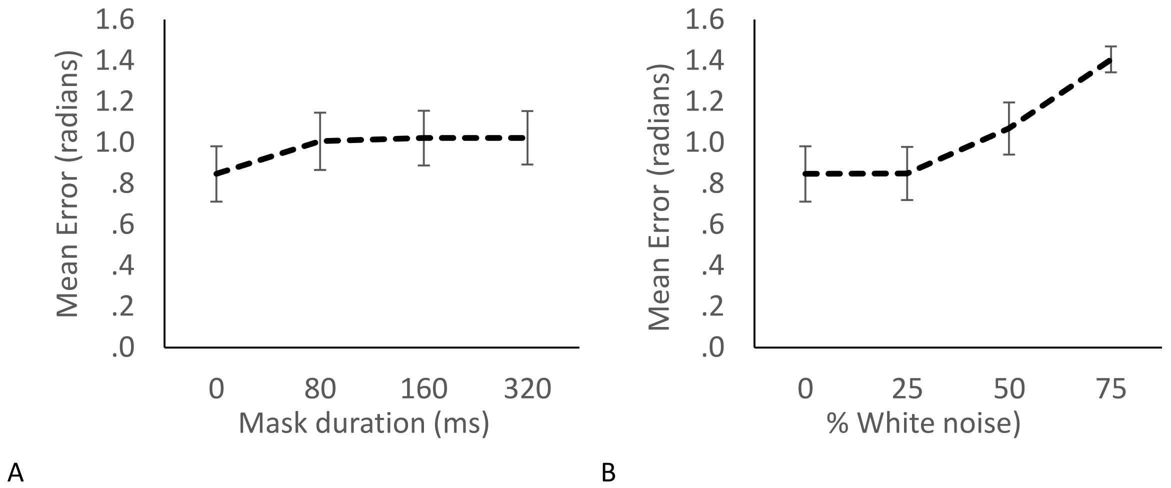



Figure 2. Mean error (in radians) as a function of A) increasing duration (0ms, 80ms, 160 ms, 320 ms) of the four-dot mask and B) increasing percentage of white noise (0%, 25%, 50%, 75%). Error bars denote +/- 1 standard error.

<u>Modelling</u>

We model the behavioural data using a probabilistic mixture regression model. Specifically, on trial *i,* denoting the angle chosen by the subject by $\theta_i$, and the correct or true angle of the stimulus by $\hat{\theta}_i$, we assume that $\theta_i$ is distributed according to the following mixture model:

$$\theta_i|\gamma_i, \kappa_i \sim \gamma_i \phi_{\kappa_i}(\theta_i - \hat{\theta}_i) + (1 - \gamma_i)\frac{1}{2\pi} \qquad 1$$

Where $\phi_{\kappa_i(}\theta_i - \hat{\theta}_i)$ signifies a Von Mises distribution with location parameter $\hat{\theta}_i$and concentration parameter (reciprocal of the dispersion parameter) $\kappa_i$. A Von Mises distribution is essentially a normal distribution defined on a circle rather than the real line. As such, as $\kappa_i$ increases the Von Mises distribution becomes more precise and, in the case of this model, the difference between the chosen angle $\theta_i$ and the true angle on that trial $\hat{\theta}_i$becomes less. On the other hand, the variable $\gamma_i$ which takes values in the range (0; 1), indicates the mixing proportion of the mixture model. Specifically, the probability that on trial *i* the subject responds with a guess at random is given by $1 - \gamma_i$. The probability that they do not guess at random but choose an angle that is distributed as a noisy function of the true angle is given by $\gamma_i$. Our general aim in modelling is to determine how $\kappa_i$ and $\gamma_i$ vary as a function of the mask duration and the noise level.

For the analysis of Experiment 1, we analyse how $\kappa_i$ and $\gamma_i$ vary as an ordinal regression function of the mask duration and the noise level. To do so, we code the noise level on trial *i* using the ordinal variable $x_{1_i}$ that indicates the rank of the noise level, and we code the mask duration level on trial *i* by $x_{2_i}$ that indicates the mask duration. Specifically, we have $x_{1_i} \in \{0, 1 ,2, 3\}$ that indicates the rank of the noise level, from lowest to highest percentages, i.e. 0; 25; 50; 75. Likewise, we have $x_{2_i} \in \{0, 1 ,2, 3\}$ that indicates the mask duration, from shortest duration to longest, i.e., 0; 80; 160; 320. We then model the log odds of $\gamma_i$ and the log of $\kappa_i$ as the following linear functions of the ordinal variables $x_1$ and $x_2$.

$$\log\left(\frac{\gamma_i}{1-\gamma_i}\right) = b_0 \sum_{k=0}^{x_{1_i}} b_k^1 + \sum_{k=0}^{x_{2_i}} b_k^2$$

$$\log(\kappa_i) = a_0 \sum_{k=0}^{x_{1_i}} a_k^1 + \sum_{k=0}^{x_{2_i}} a_k^2$$

All $b_k^1$, $b_k^2$, $a_k^1$, $a_k^2$ for $k \in \{1 ,2, 3\}$ have Normal priors, i.e. N(0; 100:0), i.e. a variance of 100.0. The coefficients $b_0^1$, $b_0^2$, $a_0^1$, $a_0^2$ are set to 0.0. As such, the effect when the noise and mask duration are both 0.0 is captured by the value of $b_0$ and $a_0$. The coefficients $b_1^1$ $b_2^1$, $b_3^1$ and $a_1^1$, $a_2^1$ , $a_3^1$ provide the coefficients for the ordinal regression that correspond to the three non-zero levels of the noise predictor. The coefficients $b_1^2$ $b_2^2$, $b_3^2$ and $a_1^2$, $a_2^2$ , $a_3^2$ provide the coefficients for the ordinal regression that correspond to the three non-zero levels of the mask duration predictor. From these coefficients, estimates of the contribution of guessing and the variability of the target representation can be estimated for the white noise mask conditions and the trailing mask conditions.

Table 1 shows the estimated coefficients from the ordinal regression model. For the effects of the noise and mask on $\gamma$ we see that $b_1^1$ is near to zero and has 0.95 HPDs (highest posterior density intervals) either side of 0, that is to say there is no reliable effect on guessing as noise increases to 25%. However, both $b_2^1$ and $b_3^1$ are negative and have 0.95 HPDs that are either all negative ($b_2^1$) or close to all negative ($b_3^1$) indicating that as noise increases to 50% and then again to 75% guessing increases. For the mask duration predictor $b_1^2$ has a negative mean and all zero 0.95 HPDs indicating that moving from a 0 ms trailing mask to an 80 ms trailing mask results in an increase in guessing. However, $b_2^2$ and $b_3^2$ have close to zero and HPDs cantered around zero, indicating that increasing mask duration beyond 80 ms has no effect on guessing, In other words it looks like there is a categorical effect on guessing for masks that trail the target.

For the effects of the noise and mask on $\kappa$ the results are less clear. For increases in white noise in the case of $a_1^1$ the mean is negative, as is the entire HPD indicating a decrease in precision as noise increases from 0% to 25%. However, for $a_2^1$ the mean is close to zero with HPDs centred around zero, indicating no real change in precision from 25-50% noise. For $a_3^1$ the mean is roughly the same size as $a_1^1$ but its .95 HPD is very different, with a large range which crosses zero. Looking further the .50 HPD, not shown in the table, is -.25; -.03, providing some indication that the increase in noise from 50% to 75% may have led to lower precision but the large uncertainty for this final parameter means that it is unclear whether this was the case.

Thus the addition of white noise appeared to initially decrease precision, with limited evidence for further decreases in precision. In comparison, for increases in mask duration the $a_1^2$, $a_2^2$ and $a_3^2$ means are negative but their HPDs are not all negative, indicating limited evidence for a decrease in precision as mask duration increased. Overall then, from these coefficients we can roughly say that there is a decrease in precision with increasing white noise whereas increasing mask duration has no clear effect on precision.

Table 1. Results from the ordinal regression-model based analysis of Experiment 1.

| variable | Posterior mean | 95% HPD | |
|---|---|---|---|
| $b_0$ | .21 | .04 | .39 |
| $b_1^1$ | .14 | -.12 | .41 |
| $b_2^1$ | -.73 | -.99 | -.45 |
| $b_3^1$ | -1.21 | -1.97 | .09 |
| $b_1^2$ | -.46 | -.71 | -.21 |
| $b_2^2$ | -.02 | -.28 | .25 |
| $b_3^2$ | -.06 | -.34 | .25 |
| $a_0$ | 2.08 | 1.88 | 2.31 |
| $a_1^1$, | -0.41 | -0.72 | -0.1 |
| $a_2^1$ | -0.03 | -0.35 | 0.27 |
| $a_3^1$ | -0.5 | -2.09 | 0.63 |
| $a_1^2$ | -0.15 | -0.46 | 0.15 |
| $a_2^2$ | -0.06 | -0.41 | 0.3 |
| $a_3^2$ | -0.08 | -0.48 | 0.31 |

Figure 3 shows the probability of random guessing (Figure 3a) and the predicted precision (Figure 3b) as a function of noise or mask level based on the regression model analysis of Experiment 1 (error bars indicate the 2.5% and 97.5% percentiles of the posterior predictive intervals). The shape of each line matches the description above that was derived from the coefficients, but it is instructive to see the predictions. A comparison of Figures 3 with Figure 2 shows that the estimates of guessing follow a very similar trend to the mean probability of guessing. This perhaps reflects the fact that performance in the task was relatively poor, and thus a lot of guessing was evident. Estimates of precision appeared to show a slight linear decrease as the mask began to trail the target. However, the posterior predictive intervals show a large overlap between all mask duration conditions. This indicates that there was little evidence of differences between these conditions. In contrast there was a much clearer trend for decreasing precision as noise density increased, although it is unclear whether increasing noise over 25% decreased precision given the large posterior predictive interval for the 75% condition.

Overall then, Experiment 1 appears to show that increasing noise density and mask duration have somewhat differing effects on precision and the rate of guessing, at least with the ranges that we measured them. Increasing mask duration led to a categorical increase in guessing responses, with little evidence for a decline in precision. In contrast for the simultaneous noise mask increasing noise density increased both guessing behaviour and decreased precision.

On the face of it, these results support the notion that an OSM mask that trails the target substitutes the percept, rendering it invisible and leading to guessing. Moreover, the fact that increasing simultaneous noise did not show this pattern appears to indicate that a trailing mask does something qualitatively different to simply adding noise into the system. However, our finding that a trailing mask does not increase variability is somewhat at odds with Harrison et al (2015) who found that it did, at least initially with variance increasing with a 150ms mask but not with further increases in mask duration.

Why did we fail to find this effect on variability? There were some differences in methods between the current study and that of Harrison et al (2015). For instance, in the current study the target location was indicated by a radial cue, in addition to the cue provided by the mask itself, there are also some differences in terms of the size and eccentricity of the presented stimuli. However, it is difficult to understand how any of these seemingly minor differences in methods could alter the effect that the OSM mask produced in the way seen.

Another possibility has to do with the modelling analysis as we used a different modelling procedure. In Harrison et al. the analysis was done by fitting a mixture model to the data and estimating mixture model parameters for each individual by minimising the fit of the predicted model to each individual's data.

In our study the method we used to model the data differed in three main respects. First the model was hierarchical-multilevel in that it fits individual and group level data simultaneously (Gelman 2015; Gelman & Hill, 2007). As noted previously, our approach enabled us to generate parameters for the group as a whole whilst still modelling individual level data. Second, we inferred the parameters using Bayesian inference rather than maximum likelihood estimation. One benefit of doing this is that we can calculate HPD intervals around the parameter estimates that reflect the uncertainty of these estimates enabling us to speak with more confidence about the effects of mask duration and noise on the guessing and precision parameters. Third, although we used the standard mixture model the relative weights of these parameters were regression functions of the mask duration and the noise level which were treated as ordinal variables. In other words, we assume a generalised linear model relating the guessing and precision parameters across mask duration levels and noise levels (note that the probability of guessing versus not guessing was estimated by logistic regression as the guessing rate is constrained to be between 0 and 1 whereas the log of the precision was estimated by linear regression).

It is possible that modelling the data in a very different way to Harrison et al (2015) yielded different answers; however, this is not a sufficiently useful explanation. Our modelling approach was preferable in this instance because we wanted confidence estimates for parameters, and, because assuming linear relationships between parameters as functions of mask duration and noise level provides a reasonable degree of constraint to the modelling.

An arguable issue with Experiment 1 was that increasing mask duration beyond 80 ms had limited additional effect on overall error (it is not clear from the presentation of results in Harrison et al, 2015, if this was the case for their data). It is possible that the failure to find an effect of mask duration on precision might well have been due to this flattening of masking beyond the initial trailing condition. Another possible issue was the rather high rate of guessing in our data in all conditions. Participants in the experiment seemed to be rather poor at the task, even on unmasked trials. This suggests that participants may not have being taking sufficient time to adjust the stimulus to provide a true reproduction of their representation, but rather used the method of adjustment to make a rough indication of their representation. We therefore conducted a second study.

This second study had two main purposes. Firstly, given the difference between our findings and those of Harrison et al, we wished to determine if our findings, particularly regarding the failure to find any evidence of a loss of precision after OSM, would replicate. The new Experiment also used a slightly different paradigm. In Experiment 1 the manipulation of noise density of the simultaneous noise mask and the duration of the OSM mask were done independently. In Experiment 2 the density of the simultaneous noise mask and the duration of the OSM mask were varied orthogonally. This meant that, as well as having a common baseline condition, there were trials in which the target was masked *both* by simultaneous noise and by a trailing mask. The rationale of this was thus. According to additive factors logic (Sternberg, 1969) two manipulations which influence different serial processes will be additive in their effects, two manipulations which influence a common processing stage will have multiplicative effects[4]. Thus, if the OSM mask has its effect by increasing internal noise then the mask duration manipulation should produce an interaction with the noise density manipulation. If, however OSM does something different to increasing internal noise, then mask duration should have an *additive* effect on performance with respect to mask duration.

[4] Sternberg's proposal was originally expressed in terms of effect on response times. In masking accuracy measures alone are typically used. However additive factors logic has been applied to accuracy measures (e.g. Ghorashi, Spalek, Enns & Di Lollo, 2009; Ghorashi, Enns, Klein & Di Lollo, 2010). See Schweickert (1985) for a detailed discussion.

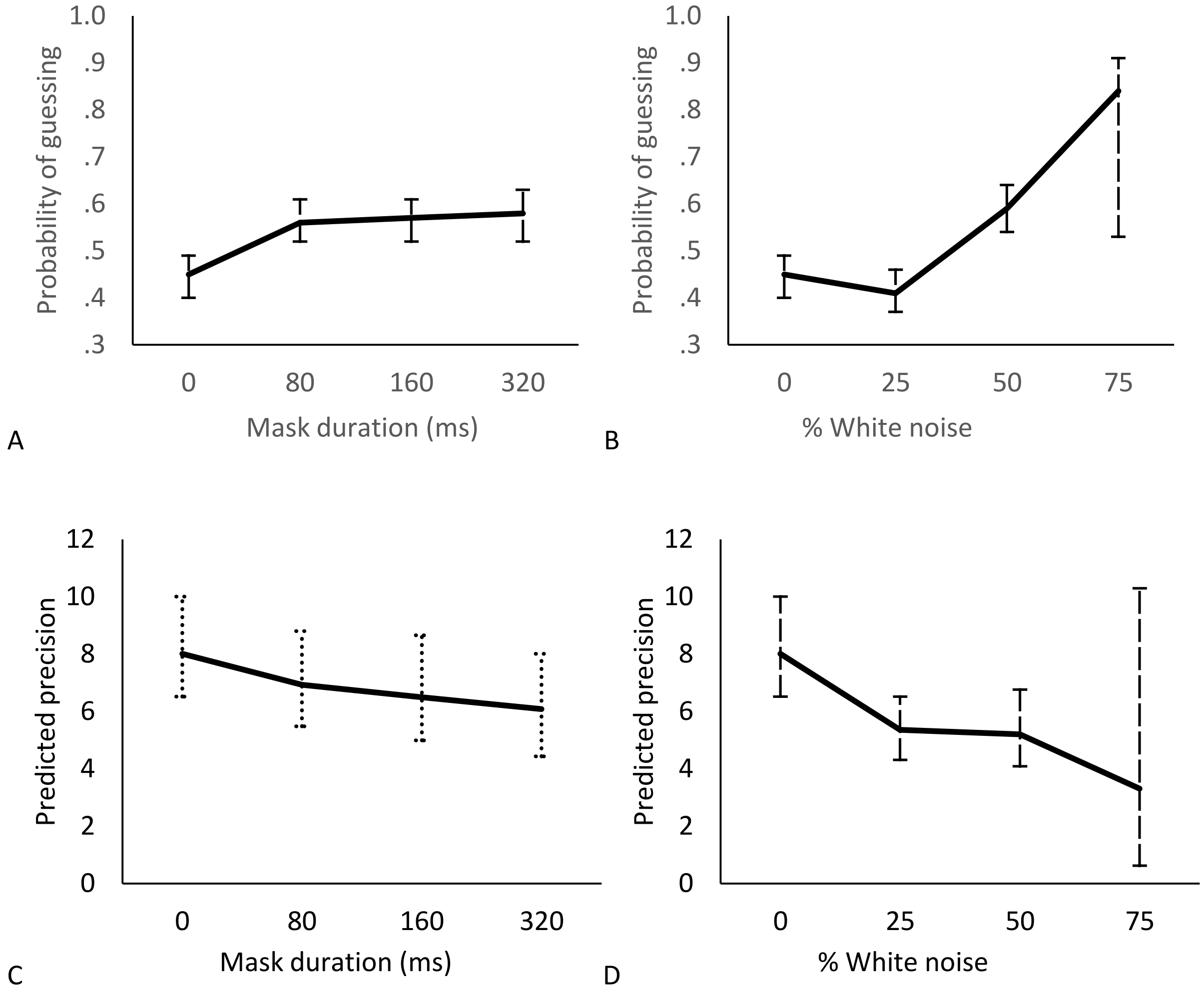



Figure 3. A) and B) show the probability of random guessing. B) and C) the predicted precision as a function of noise (0%, 25%, 50%, 75%) or mask duration (0 ms, 80 ms, 160 ms, 320 ms) based on the regression model analysis of Experiment 1. Error bars indicate the 2.5% and 97.5% percentiles of the posterior predictive intervals.

## Experiment 2

### Method

*Participants*. There were 12 participants, comprising undergraduate Psychology students recruited from Oxford Brookes University and one of the authors. All had normal or corrected-to-normal vision. Participants were either given course credit or £5 for participation.

*Design.* The amount of simultaneous white noise (0%, 25%, 50%) and mask duration (0ms, 80ms, 320ms) were manipulated orthogonally. Four dots were always presented when the target onset. When there was white noise the area within the four-dot mask was filled with the appropriate amount of noise. The white noise had the same onset and offset as the target. The four-dot mask either offset with the target (0ms) or lingered onscreen for 80ms or 320ms.

*Stimuli and Procedure*. The stimuli and procedure were the same as described for Experiment 1. Stimuli were presented on a 19" flat screen Sony Trinitron CRT.

### Results

Mean error for each condition is presented in Figure 4. Several trends stand out. First, increasing mask duration seemed to have a clear effect, increasing error linearly when noise was 0% and 25% and nonlinearly when mask noise was 50%. There also seemed to be a consistent effect of mask noise, with increased error as mask noise increased. A 3x3 repeated measures ANOVA on error size with noise (0%, 25%, 50%) and mask duration (0ms, 80ms, 320ms) as factors showed a significant effect of noise, $F(2, 22) = 49.77$, $p < .001$, $\eta_p^2 = .82$, a significant effect of mask duration, $F(2, 22) = 20.36$, $p < .001$, $\eta_p^2 = .65$ and a significant interaction between noise and mask duration $F(4, 44) = 9.60$, $p < .001$, $\eta_p^2 = .47$.

To determine whether there were linear increases in error with increasing mask duration/noise an ANOVA was conducted at each level of noise with mask duration as a factor and at each level of mask duration with noise as a factor (*p* values were Bonferroni corrected for multiple comparisons). For each level of noise there was a significant effect of mask duration (0%, $F(2, 22)$ = 7.32, $p$ =.024, $\eta_p^2$ =.40; 25%, $F(2, 22)$ = 11.66, $p$ =.006, $\eta_p^2$ =.51, 50% $F(2, 22)$ = 18.28, $p$ <.03, $\eta_p^2$ =.62). Crucially there was evidence for a linear effect only when noise was 0% ($p$ =.018) and 25% ($p$ =.012).

At a noise level of 50% there was evidence for both a linear effect ($p$ =.018) and a quadratic effect ($p$ < .03). At each mask duration there was a significant effect or marginally significant effect of noise (0 ms, $F(2, 22)$ = 7.84, $p$ =.066, $\eta_p^2$ =.41; 80 ms, $F(2, 22)$ = 54.04, $p$ =.006, $\eta_p^2$ =.83, 320 ms $F(2, 22)$ = 25.05, $p$ <.03, $\eta_p^2$ =.70). Importantly, there was evidence for a linear effect of noise when mask duration was 0 ms ($p$ =.066), 80 ms ($p$ <.03) and 320 ms ( $p$ < .03). The significant interaction between noise and mask duration therefore appeared to be due to the effect of mask duration being linear except when noise was 50% whereby error increased markedly as mask duration increased from 0 ms to 80 ms and then lessened slightly as mask duration increased from 80 ms to 320 ms.

Overall then, analysis of the errors indicates several important features. Firstly, unlike Experiment 1 responses were much more accurate and there was a clear effect of mask duration evident at each level of noise. This may be a consequence of differences in the experiment itself. For instance, it might arguably be because of the exclusion of the largest noise condition (75% noise density). Importantly, the fact that the addition of simultaneous noise increased error at all levels of mask duration seems to suggest that mask duration and noise have at least partially independent effects on precision. At the same time, the evidence of an interaction indicates that mask duration has a greater impact the more a target stimulus is degraded by the presentation of simultaneous noise.

Thus, the error data seems to indicate that simultaneous noise has both an additive and a multiplicative effect on OSM. The multiplicative nature seems to suggest that in part OSM degrades perception by adding further noise to the noise created by the simultaneous mask. We now turn to the modelling to see whether increasing noise and mask duration leads to differing effects on guessing and precision.

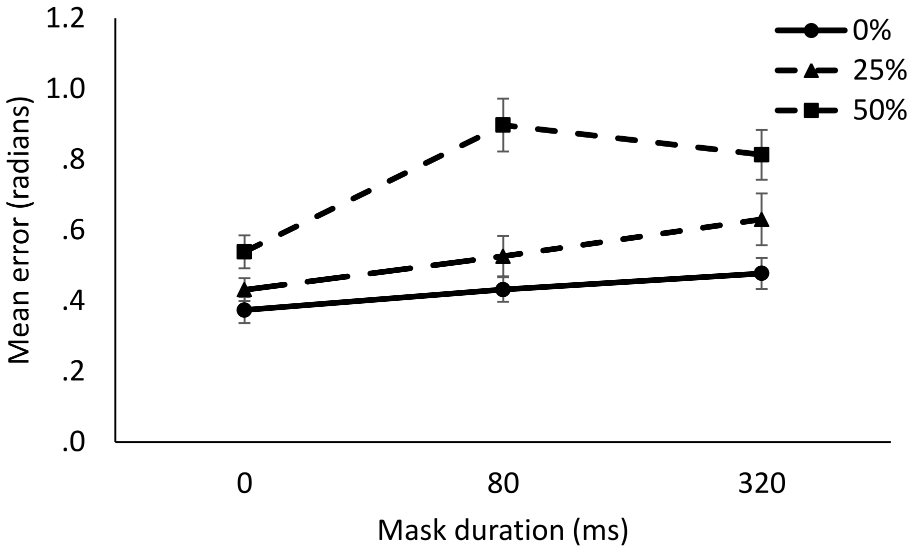



Figure 4. Mean error (in radians) as a function of increasing white noise (0%, 25%, 50%, 75%) and increasing duration of the four-dot mask. Error bars indicate +/- 1 standard error.

<u>Modelling</u>

The same modelling as described in Experiment 1 was completed, with the only difference being that the modelling was based on a different data set. Here, we have $x_{1_i} \in \{1\ ,2, 3\}$ that indicates the rank of the noise level, from lowest to highest percentages, i.e. 0%, 25% and 50%, and $x_{2_i} \in \{1\ ,2, 3\}$ that indicates the mask duration, from shortest duration to longest, i.e., 0 ms, 80 ms and 320 ms. We then model the log odds of $\gamma_i$ and the log of $\kappa_i$ as the following linear functions of the ordinal variables $x_1$ and $x_2$.

$$\log\left(\frac{\gamma_i}{1-\gamma_i}\right) = \sum_{k=1}^{x_{1_i}} b_k^1 + \sum_{k=1}^{x_{2_i}} b_k^2$$

$$\log(\kappa_i) = \sum_{k=1}^{x_{1_i}} a_k^1 + \sum_{k=1}^{x_{2_i}} a_k^2$$

All $b_k^1$, $b_k^2$, $a_k^1$, $a_k^2$ have Normal priors, i.e. N(0, 100.0), i.e. a variance of 100.0. The coefficients $b_1^1$, $b_2^1$, $b_3^1$ and $a_1^1$, $a_2^1$, $a_3^1$ provide the coefficients for the ordinal regression that correspond to the three levels of the noise predictor. The coefficients $b_1^2$, $b_2^2$, $b_3^2$ and $a_1^2$, $a_2^2$, $a_3^2$ provide the coefficients for the ordinal regression that correspond to the three levels of the mask predictor. The values of these coefficients are shown in Table 2. We see a very similar pattern of the effect of the noise and mask on $\gamma$ (the probability of guessing is 1- $\gamma$). For noise, $b_1^1$ refers to the coefficient for zero noise. As noise increases there is an increasing probability of guessing i.e., as shown by reliably negative values of $b_2^1$ and $b_3^1$. In contrast, for mask duration $b_1^2$ is the coefficient of zero mask duration. As mask duration increases there seems to be a categorical effect on guessing with a reliably negative value of $b_2^2$ and a zero value of $b_3^2$. This appears to replicate the findings of Experiment 1 and shows that the different types of masking have differing effects on $\gamma$

The effect of noise and mask on $\kappa$ appears to differ in comparison to Experiment 1 with evidence for a decrease in precision as noise increases and as mask duration increases (Figure 5c and 5d). Figure 6 shows the probability of random guessing (Figure 6a) and the predicted precision (Figure 6b) as a function of noise or mask level based on the regression model analysis of Experiment 2 (error bars indicate the 2.5% and 97.5% percentiles of the posterior predictive intervals). This figure makes very clear the effects of mask duration and noise. There is a categorical effect of mask duration on guessing rate, which is not observed for increases in noise. In comparison, increasing trailing mask duration and noise leads to a steady decline in precision, with the decline in precision being of a similar amount across the ranges of mask duration and noise.

Thus, although responses were much more accurate in Experiment 2, the main trends in the data were broadly replicated and the main modelling results also replicated. The only key difference was that the precision data now showed an effect of trailing mask duration, with increasing mask duration leading to reduced precision. It is possible that the high amount of error in Experiment 1 masked such an effect. As in Experiment 1, the central finding was that increasing noise and increasing mask duration appeared to do two quite different things within the parameters tested. Increasing mask duration such that the mask trailed the target introduced a stable amount of guessing, whereas increasing noise led to a linear increase in the amount of guessing.

Theoretically, this appears to support the OSTM model rather than the AGM model. If the effect of mask duration was simply to add noise to the target representation, then the mask duration and noise manipulation should have produced similar consequences in terms of the amount of guessing. It appears however that, within the parameters used here, using an OSM mask results in a stable amount of guessing. We return to why this might be the case in the General Discussion. At the same time the trailing mask was found to have *some* effect on target precision. Interestingly this effect on precision seemed to increase linearly as mask duration increased, suggesting that mask duration effects are not caused by an increasing amount of substitution but by adding noise to the target representation (consistent with the AGM). Of course, it remains a possibility that, for mask durations between 0ms and 80 ms, guessing increases, and that it is simply maximal at 80ms. Nevertheless, the important finding is that increasing the length of the trailing mask beyond 80ms did worsen performance, but that this decrement in performance was not due to guessing, but a decline in precision.

Table 2. Results from the ordinal regression-model based analysis of Experiment 2.

| Variable | Posterior mean | 95% HPD | |
|---|---|---|---|
| $b_1^1$ | 1.33 | -12.63 | 14.12 |
| $b_2^1$ | -.63 | -.92 | -.34 |
| $b_3^1$ | -.75 | -1.02 | -.5 |
| $b_1^2$ | 1.41 | -11.3 | 15.43 |
| $b_2^2$ | -.88 | -1.17 | -.61 |
| $b_3^2$ | .06 | -.21 | .32 |
| $a_1^1$ | 1.31 | -11.62 | 15.82 |
| $a_2^1$ | -.05 | -.2 | .09 |
| $a_3^1$ | -.32 | -.49 | -.15 |
| $a_1^2$ | .85 | -13.55 | 13.94 |
| $a_2^2$ | -.17 | -.34 | -.02 |
| $a_3^2$ | -.22 | -.39 | -.03 |

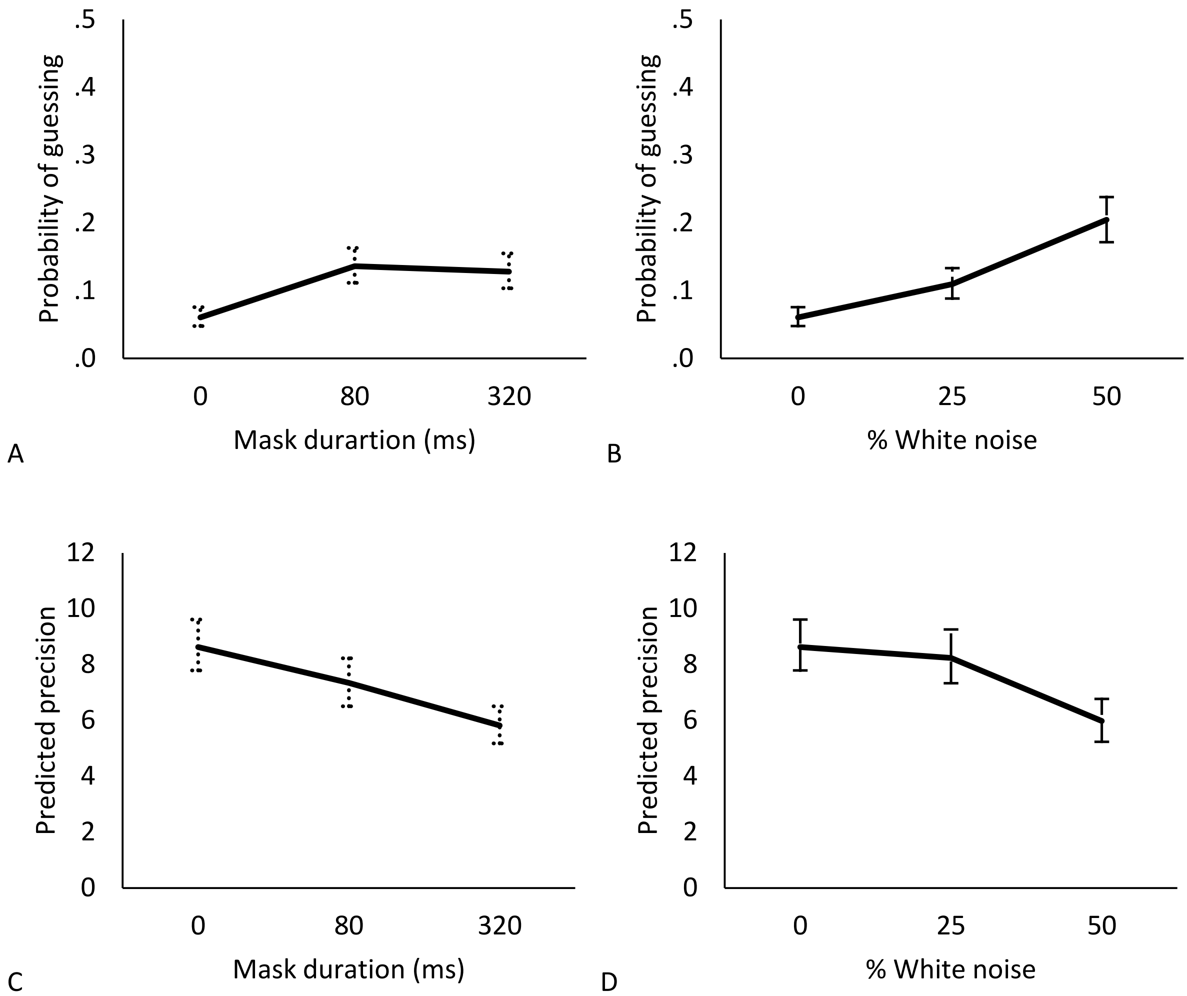
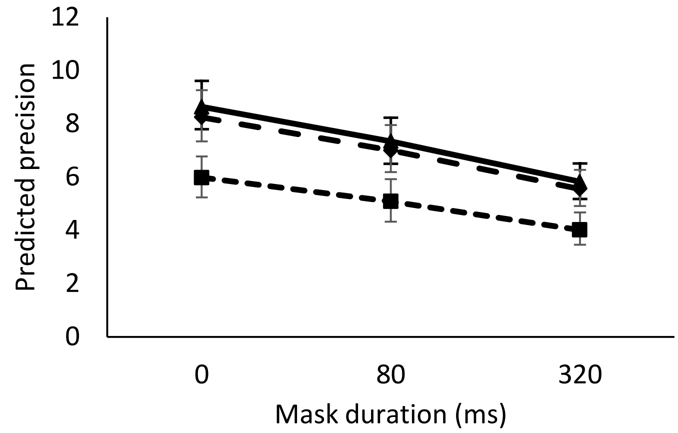



Figure 5. A) and B) show the probability of random guessing and C) and D) show the predicted precision as a function of noise (0%, 25%, 50%) or mask duration (0ms, 80ms, 320ms) based on the regression model analysis of Experiment 2. Error bars indicate the 2.5% and 97.5% percentiles of the posterior predictive intervals.

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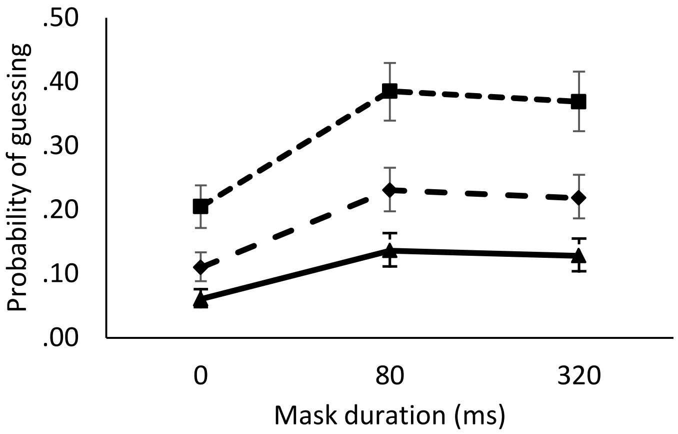


B

Figure 6. A) the probability of random guessing as a function of noise (0%, 25%, 50%) and mask duration (0ms, 80ms, 320ms); B) the predicted precision as a function of noise (0%, 25%, 50%) and mask duration (0ms, 80ms, 320ms). Values are based on the described regression model analysis of Experiment 2. Error bars indicate the 2.5% and 97.5% percentiles of the posterior predictive intervals

**General Discussion**

In two experiments we compared the effect of OSM -as indexed by trailing mask duration- against the effect of a simultaneous noise mask on the perceptibility of a target. We did this to determine the extent to which OSM can be conceived as an effect associated with increased in noise.

The first experiment found that both OSM and simultaneous noise, when imposed on a target, resulted in increased guessing responses in reporting about the target's critical feature. The simultaneous noise manipulation also had a further effect: on a proportion of trials in which observers were not guessing the precision of the responses tended to be reduced. This effect was not evident for the OSM manipulation at either of the two levels of mask duration. Thus, Experiment 1 indicated that the main effect of OSM was to reduce the probability that the target -or at least the target's critical feature[5]- was perceived at all. On trials where the critical feature was perceived, observers were as precise at reporting its position as they were in the absence of a trailing mask (though there did appear to be a slight declining trend in precision). Therefore Experiment 1 failed to produce evidence that OSM had any effect in terms of degrading the target percept. Instead, it suggested that OSM was essentially an all-or-none process in which the target feature was either as fully available for report as unmasked conditions or was obliterated from perception resulting in the observer producing a randomly set response.

Experiment 2 gave a further test of the effect of OSM on masking. Experiment 1 had shown that the simultaneous noise mask did have an effect on precision. Experiment 2 was motivated to further compare the perceptual effects of OSM with those of added noise by determining if their combined effects would interact or only show additive effects. This question was specially motivated by the question of whether OSM has its effect, in part, by generating noise within the visual system,

[5] Note that this result says nothing about whether they could still perceive other aspects of the target. For instance, even where observers were guessing about the target's critical gap position the observers may still have been fully aware of the presence of a target object at that location.

something which is predicted by the AGM model of OSM (Põder, 2013). To explore this, the OSM (trailing mask) and simultaneous noise conditions were factorially combined. It was found that the effects of OSM and noise were interactive in nature. That is, the addition of the noise increased the susceptibly of the target to the effects of the trailing mask. The regression model was able to unpack this interaction in terms of the effect on different types of response errors. Broadly, the results were similar to Experiment 1, in that increasing mask duration led to a categorical effect on guessing but increasing noise led to a linear increase in guessing. A different pattern was found for precision however. Experiment 2 presented clear evidence for reductions in precision for both increasing noise and increasing mask duration (recall that in Experiment 1 there was a trend for decreasing precision as mask duration increased, but this was not statistically supported).

Thus, in Experiment 2, OSM had the effect of reducing the likelihood that the critical feature could be reported; where it could be reported it tended to be done so with less precision than under masked conditions, an effect most pronounced when the target was also subject to simultaneous noise. The discrepancy between Experiment 1 and 2 in terms of the effect of the trailing mask on precision estimates is likely due to the overall difference in accuracy between the tasks, with overall performance being rather better in Experiment 2.[6]

Our main aim was to compare OSM effects with those of simultaneous noise, and by doing so understand something about if and how OSM effects might be related to processes associated with noise within the visual system. Both OSM and noise mask parameters resulted in a monotonic increase in guessing responses. However, adding additional white noise increases guessing in a broadly linear manner –guessing rates increased in correspondence with the increase in noise level. The mask duration variable did not behave like this in our given conditions: an increase in guessing

[6] The presented subtended visual angles were actually slightly smaller in Experiment 2 that Experiment 1. This means that -if at all- performance should have been slightly worse, not better, in Experiment 2. More likely, the better performance is some consequence of the different variety and value range of conditions in the study which has, in some way, affected the adopted response strategy

was seen between 0 and 50ms but there were no further increase with further extension to the trailing mask duration beyond this. Thus, mask duration as a variable does not operate in the same way as that of simultaneous noise, at least within the parameters tested.

Substitution verses attentional gating

What can explain the rather categorical nature of the trailing mask function with respect to guessing? The object substitution mechanism initially proposed in the OSTM and implemented its associated mathematical model (CMOS) are time-dependent ones (Di Lollo et al. 2000): that as mask duration increases the percept of the target becomes progressively weaker and so the ongoing percept of the mask dominates over a time course of a few hundred milliseconds. Indeed, consistent with this, many studies using standard forced-choice discrimination measures of masking have tended to report that the mask has effects at mask durations well beyond the 80 ms duration plateau we found (Di Lollo et al., 2000; Enns, 2002; Tata, 2002; Tata & Giaschi, 2004)[7], The adjustment task, in giving a more sensitive measure of errors, may also be giving a better picture of the nature of the actual underlying OSM masking function, one in which masking processes are confined to the initial tens of milliseconds of processing, rather than hundreds of milliseconds, as previously assumed.

This rather categorical nature of the masking function is arguably more supportive of an object substitution account than a noise one. It does not seem that increasing the mask duration results in increasing noise, and therefore a steady decline in perceptibility. Rather, it seems that when the mask reaches a duration exceeding that of the original target itself, that the visual system

[7] Some studies, using standard forced-choice discrimination paradigms, while also finding that masking tends to increase with increases in mask durations beyond 80ms, have sometimes also reported that very prolonged mask durations (e.g. >~640ms) can produce a small amount of OSM recovery, i.e. meaning that a U-shaped function is obtained with respect to mask duration (Goodhew, Visser, Lipp, & Dux, 2011; Goodhew, Dux, Lipp, & Visser, 2012).

has enough evidence for the mask to become the dominant representation in consciousness, meaning that the representation of the target features are overwritten. A potential mechanism that may underpin this overwriting is if the competition between target and mask representations is spatial in nature. There is evidence that mask-target spatial competition (overlap) is one factor underpinning OSM (Kahan & Mathis, Guest, Gellatly & Pilling, 2011; Kahan & Enns, 2010). It is feasible that such spatial competition is not especially dependent upon the temporal aspects of the mask, once the mask reaches a critical duration it disrupts the representation of the target enough so that the participant instigates a guess response.

Though the main effect of OSM was on guessing responses there was also some evidence of a linear decline in precision with mask duration. The trend was evident in both our experiments but was in most evidence in Experiment 2. Here there was a decline in precision which was broadly linear in nature associated with mask duration. Such an effect is one consistent with the AGM account (Põder, 2013), which argues that OSM occurs as a consequence of increased internal noise in the visual system generated by the trailing four-dot mask. Furthermore, the fact that simultaneous noise and OSM interact with each other also indicates that the two forms of masking share a common underlying process. One can argue that OSM and simultaneous noise interact because each operates as a separate source of noise (one internal one external) which each has the same perceptual consequences in terms of degrading the visibility of the critical feature

It is possible to construct an explanation of this mask duration by simultaneous noise interaction couched in terms of the OSTM. The OSTM specifies that OSM is affected by any manipulation that increases the number of required iterations for a stable percept to emerge. Thus in this case, the addition of external noise means an increased number of iterations are required for a percept to form, resulting in a greater susceptibility of the target to the trailing mask. However, the OSTM has greater difficulty with accounting for the finding that OSM reduces the *precision* of non-guess responses. If the trailing mask, on trials where it has an effect, obliterates the target percept entirely then no loss of precision should not occur, the only increase should have been found in guessing responses.

While the standard OSTM has some difficulty accounting for this aspect of the results, the revised *object updating account* (Llearas & Moore, 2003) has more success. As we earlier described, the updating account accepts some of the basic tenets of the OSTM, particularly in terms of the architecture of the visual system. However, the updating account argues that the percept of a masked object is not substituted (i.e. obliterated) from consciousness, but rather has its features overwritten rendering them no longer available for report. The updating account is currently underspecified in terms of describing what the consequences of this overwriting process are. The implicit assumption seems to be that the process leads to a complete loss of the original feature values (Llearas & Moore, 2003; Moore & Llearas, 2005). However, it is possible to argue within this theoretical framework that the overwriting process is not total and leaves a residual trace of the target representation after updating. Such an updating theory with these given additional assumptions could also account for our data.

OSM and conscious perception

The debate regarding OSM can be seen as part of a broader set of questions about conscious perception. In particular, theoretical debates in consciousness research have focused on whether conscious perception should be thought of as dichotomous or graded in nature (see Bachmann, 2013; Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006; Miller & Schwarz, 2014; Overgaard, Rote, Mouridsen, & Ramsoy, 2006; Windey & Cleeremans, 2014).

The Global Neuronal Workspace Theory (GNWT) of Dehaene and colleagues (Dehaene et al., 2006; Dehaene & Changeux, 2011) is a particularly influential neurocognitive theory of consciousness (Windey & Cleeremans, 2014). On this account consciousness is viewed as strictly dichotomous: either something is consciously perceived or is not. Consciousness of a stimulus only occurs if an initial feedforward sweep of information through the brain meets a threshold required to pass through to a second processing stage, at this point top-down information then amplifies the signal. On trials in which the stimulus is consciously perceived these bottom-up and top-down inputs reinforce each other until a broad network of different brain areas are synchronously activated in a process known as 'global ignition'. It is at this point that the stimulus has entered the 'global workspace' and the observer experiences conscious awareness. The process of global ignition is argued to be instantaneous, meaning that the change from unconscious to conscious is always sudden, rather than gradual.

The architecture of the GNWT is different to the OSTM; despite this, there are clear parallels in terms of the assumption of the interplay between bottom-up and top-down activity in generating conscious precepts, in the view that consciousness emerges only after a period of preconscious stimulus processing, and in viewing consciousness as a strictly capacity-limited process. On this last point the GNWT assumes only one item can enter the global workspace at any time (Dehaene et al., 2006; in OSTM re-entrant activity is implicitly or explicitly assumed to be restricted to a single display item (Di Lollo et al., 2000; Goodhew et al., 2011). Following from this, both theories essentially view the failure to consciously perceive a masked target as a problem of conscious *access*. The masked target fails to reach consciousness because its percept is beaten in competition with the percept associated with the longer duration mask.

Though the OSTM and GNWT make broadly similar claims about why masking affects conscious perception of a target, the GNWT has been elaborated more in terms of understanding the unconscious processing of masked stimuli, rather than the mechanisms of masking itself (Dehaene & Naccach, 2001). Importantly, both models conceive of masking as a discrete all-or-none process. In the OSTM the brief target reaches a threshold of iterative stability in the re-entrant cycle resulting in it forming part of the conscious percept; if it fails to reach this criterion then it is the mask alone which is what emerges in consciousness. The GNWT argues that masking affects the process whereby the neural representation of a target is mobilised into a self-sustaining state within the global workspace. A brief target is vulnerable to masking because this process of mobilisation into the workspace takes significantly longer than the initial process of generating a target signal at the initial stage (Dehaene &Naccach, 2001).

Our results show that OSM does often have the effect of abolishing conscious perception of the target in the manner the GNWT would predict. However, at the same time, our results suggest that masking is not entirely all-or-none in character. This is indicated by the decrease in precision as mask duration increases (seen particularly in Exp. 2). One interpretation is that there is sometimes partial awareness of the masked target, resulting in an increase in errors. This may be because that when masked, the target sometimes reaches consciousness only in a partial form (Overgaard et al., 2006). It can also be argued that the effect on precision is associated with processing at an entirely pre-conscious stage. In other words, the conscious target percept is always discrete entity; however, the representation that is consciously accessed is sometimes incomplete or distorted due to the trailing mask. Such a process is essentially one which Põder's model purports, that the target representation is degraded before it selected for conscious access.

## Conclusions

There have been a range of potential theories about the underlying mechanisms of OSM. For some time, the pre-eminent theories suggested that the mask either substituted or led to an updating of the target representation. However, recently this idea was questioned and an alternative perspective put forward that the suggests that OSM arises when the mask is inadvertently selected because it is in close temporal proximity to the target, and that this degrades the target representation leading to reduced accuracy in target report. These theories create contrasting predictions about whether OSM should lead to an increase in guessing or a decrease in the precision of the representations. In two experiments, we contrast the effects of a common onset mask with a white noise mask and show they have different effects. Nevertheless, we also show that OSM leads to both an increase in guessing, but also a loss in precision. This suggests that several underlying mechanisms contribute to the masking effect, one of which is that of a substitution or updating of the target percept by the mask percept. Where this substitution does not occur, the mask has an additional effect of increasing the internal noise levels associated with the target stimulus leading to report of the target stimulus but with reduced precision compared to trials without a trailing mask.

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