An Investigation into ERP Measures of Attention and Awareness using Object-Substitution Masking

by

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Abstract

Attention and awareness are cognitive processes that can be investigated using electrophysiological recordings of brain activity. Fluctuations of electrical potentials in response to cognitive tasks reflect processes such as selective attention (N2pc) and visual working memory maintenance (SPCN). Previous research on these event-related potentials (ERPs) has demonstrated that they are affected by a variety of experimental manipulations, such as changes in set size, visual awareness, and memory fidelity. The current study aimed to examine how both set size and visual awareness (manipulated using object-substitution masking; OSM) affected the N2pc and SPCN components. Although researchers have previously examined the effect of set size and masking on these components, the manipulations have never been done concurrently. In the current study, it was found that completing an OSM task involved several stages of processing, reflected by temporally distinct ERP components. The N2pc was affected by set size, such that larger set sizes required greater attentional selection (i.e., larger N2pc amplitude) to locate the target. The SPCN component reflected separate effects of set size and mask, such that mask had an effect in the early delay period (eSPCN) and set size in the late period (lSPCN). Both early and late SPCN amplitudes were also related to response precision, such that more precise responses resulted in greater amplitude than less precise responses. Overall, results from this study demonstrate that the N2pc and SPCN components reflect multiple processes occurring over time, such as attentional selection, working memory encoding and maintenance, and the fidelity of information maintained in memory.
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<td>ANOVA</td>
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<td>CDA</td>
<td>Contralateral Delay Activity</td>
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<td>CI</td>
<td>Confidence Interval</td>
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<td>SPCN</td>
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An Investigation into ERP Measures of Attention and Awareness using Object-Substitution Masking

At any given moment, the human brain is presented with more visual information than it is possible to process. What information subsequently reaches awareness is determined by a combination of factors, such as the individual’s current goal and the amount of attention that is distributed to any particular item. Electroencephalogram (EEG) recordings of human brain activity have allowed for a greater understanding of the earliest stages of visual awareness. Due to its great temporal resolution, EEG recordings detect time-locked electrical activity in response to specific stimuli or cognitive events. This time-locked activity is called an event-related potential (ERP), and is an ideal measurement tool for studying when and why certain items reach awareness.

The N2pc (Eimer, 1996) and the SPCN (Klaver et al., 1999; McCollough, Machizawa, & Vogel, 2007) are two ERP components that are thought to reflect visual attention and awareness, respectively. In the current study, attention and awareness were both experimentally manipulated to determine the combined effects of these factors on the ERP components of interest. Selective attention was manipulated through changes in the number of items that needed to be searched to find the target (set size). Visual awareness can be manipulated through the use of visual masking paradigms, which impair the likelihood that an item will be accurately encoded and reported (for a review, see Kim & Blake, 2005). In the current study, object-substitution masking (OSM) was used to manipulate visual awareness. Behavioural measures of how these two manipulations affected report precision were also examined. Although researchers have previously studied the effects of set size and masking on ERPs and behaviour, these two
variables have not yet been manipulated together. In sum, the main goal of the current research was to better understand the underlying functions of the N2pc and SPCN by manipulating both awareness (masking) and attention (set size). Additionally, there was an examination of how the quality of visual representations, as measured behaviourally, was reflected by the amplitudes of the N2pc and SPCN.

**Visual Working Memory**

Items that are held and maintained in visual working memory (VWM) are usually assumed to be consciously accessible (Lamme, 2003; but see, Soto & Silvanto, 2014). Therefore, researchers often examine the contents of VWM to better understand the earliest stages of visual awareness (Emrich et al., 2011; Harris, Ku, & Woldorff, 2013; Pun et al., 2012). As the contents of VWM can be measured both behaviourally and neurally, tasks involving VWM processes are a good starting point for also studying visual awareness. For the purposes of the current study, visual awareness is defined as *access awareness*, or the ability to report having seen an item or a particular feature of that item (Block, 1995).

**Behavioural studies.** Visual working memory is a short-term storage system that allows for the maintenance and manipulation of visual information to be used in subsequent tasks. Baddeley (1992) conceptualized the visual store of working memory as the ‘visuospatial sketchpad’, in which visual information can be rehearsed along with the influences of top-down attentional control. The information held in VWM is distinguished from longer-term representations by the involvement of active maintenance, wherein the information is held in an ‘online’ state (Luck & Vogel, 2013). This can be observed as sustained neural activity in areas such as the intraparietal sulcus
(IPS) as well as distributed patterns of activity in early sensory cortex (Emrich et al., 2013; Harrison & Tong, 2009; Serences et al., 2009). During tasks involving VWM maintenance, one also often observes activity related to attentional monitoring and selection in the prefrontal cortex (Goldman-Rakic, 1995; Lebedev et al., 2004; Postle, 2006).

The nature of the VWM store has been examined extensively through behavioural studies. Many have shown that VWM is a capacity-limited store, meaning that it can hold a finite amount of visual information (i.e., Cowan 2001; Luck & Vogel, 1997; Luck & Vogel, 2013). The capacity of VWM is thought to be around 3 to 4 items, with individual variation in the number of items maintained. Capacity is often estimated through change detection tasks (Luck & Vogel, 1997; Phillips, 1974), wherein the individual must determine whether one item in a display has changed across a delay interval. Mathematical formulas allow for the calculation of a $k$ estimate, which represents an individual’s VWM capacity (Pashler, 1988; Cowan et al., 2005; Rouder et al., 2011). For example, Luck and Vogel (1997) showed participants an array of 1 to 12 coloured squares and told them to remember them across a brief delay period. A second set of squares was presented in the same locations and the participants were told to indicate whether or not one of the squares had changed colour. It was found that performance was almost perfect for 1 to 3 items then declined as set size increased thereafter, suggesting that VWM capacity reaches an asymptote at around 3 items.

Another way to measure the capacity of VWM is through a continuous report change detection task. This procedure provides the advantage of being able to concurrently estimate the representational quality or precision of the items held in VWM.
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(Bays & Husain, 2008). For example, Bays, Catalao, and Husain (2009) had participants remember an array of coloured squares across a delay (900 ms), then instead of simply indicating whether or not one square had changed colour, they had participants report the specific colour of a square. The participants’ response was made from a colour-wheel, allowing for any response in a 360-degree colour space. This design allows for three separate types of responses to be made: target responses, guesses, and non-target errors. Target responses occur when the participant correctly reports the feature of the target item (i.e., the target is red, and the participants chooses red with a given amount of error). Guesses are reflected by a uniform distribution of responses, wherein the participant makes a random choice. Finally, non-target errors occur when a participant reports a feature of an uncued item in the display (i.e., a distractor was green and the participant reported green as the target colour). A probabilistic mixture model (see Methods) can be applied to the data recorded from this task, allowing for the estimation of response likelihood for the three response types across conditions.

The circular analogue of the normal distribution (von Mises distribution) of target response error in a continuous report task provides additional information about the quality of VWM representations. This is because the width or standard deviation (SD) of the response error distribution reflects the inverse of response precision. Higher SDs of response error (wider distributions) indicate less precision and vice versa. Bays, Catalao, and Husain (2009) found that when non-target errors are taken into account, as the number of items in a memory display increased, the precision of responses decreased without reaching an asymptote at 3 items. These results were contrary to previous studies on VWM capacity (i.e., Zhang & Luck, 2008). Therefore, this procedure allows for an
estimation of not only how many items are being held in VWM on average, but also the precision with which those items are being remembered.

**Neural studies.** The previously described behavioural experiments have also been applied to studies that use EEG methodologies. An ERP called the sustained posterior contralateral negativity (SPCN) or contralateral delay activity (CDA) has been found to be affected by the number of items held in VWM (McCollough, Machizawa, & Vogel, 2007). The SPCN is a laterialized component, meaning that brain activity ipsilateral to the memory stimulus must be subtracted from the contralateral activity (Gratton, 1998). This subtraction removes any activity that is shared between hemispheres (i.e., sensory factors, general attention, arousal, effort) and leaves only task relevant activity in the difference wave. This activity is thought to then reflect VWM encoding and maintenance.

The SPCN is a negative going slow-wave component that begins approximately 200 – 300 ms after the offset of a memory array (Klaver et al., 1999; McCollough, Machizawa, & Vogel, 2007; Perez & Vogel, 2012). It reaches a maximum amplitude around 450 ms post-stimulus offset, with amplitude varying as a function of how many items are being remembered (Perez & Vogel, 2012; McCollough et al., 2007). The increased negativity persists throughout the delay period of the memory task, lasting as long as information is being maintained in VWM (Klaver et al., 1999; McCollough et al., 2007). The SPCN is strongest over posterior parietal electrode sites including electrodes P3/4, P7/8, P07/P08, and O1/2 (McCollough et al., 2007; Prime & Jolicoeur, 2010; Vogel & Machizawa, 2004). Neuroimaging studies have implicated areas in the intra-parietal (IPS) and intra-occipital (IOS) cortices as the source of the SPCN (Robitaille et al., 2010; Todd & Marois, 2004).
Measurements of the SPCN while performing change detection tasks have demonstrated systematic increases in amplitude as set size increases, reaching an asymptote at around 3 to 4 items (McCollough et al., 2007; Vogel & Machizawa, 2004). This finding is not confounded with increasing perceptual demands of the display nor the number of locations in which the items are placed (Ikkai, McCollough, & Vogel, 2010). Non-change detection tasks have also found the SPCN in response to maintaining information in VWM. For example, Emrich, Ferber, and Pratt (2009) found that the SPCN was present in a visual search task, in which items are implicitly remembered to avoid searching a previously searched location. Once again, SPCN amplitude reached an asymptote at VWM capacity, and correlated with an individual’s k estimate. Prime and Jolicœur (2010) used a mental rotation task and noted that the SPCN increased in amplitude as the degree of rotation increased. From this study, it seems that the SPCN is not only reflecting the amount of information stored in VWM, but also the manipulation of that information.

Departing from a strict capacity-related interpretation of the SPCN, other studies have found that other features of VWM also affect this component. For example, Pun and colleagues (2012) used a shape-from-motion task in which patterns of dots created an object while in motion, but no object when the display remained static. Critically, after the motion stopped, individuals remained aware of the object for a few seconds before it faded from awareness. They found that the amplitude of the SPCN reflected individual differences in perceptual persistence, demonstrating that the SPCN could also be used to determine visual awareness of an item.
There is also evidence that the precision with which an individual holds a representation in memory can affect the amplitude of the SPCN. Machizawa, Goh, and Driver (2012) had participants make fine (15 degree rotation) or coarse (45 degree rotation) discriminations of the orientation of lines in a change detection paradigm. Critically, participants were not informed about intermediate discrimination trials (30 degree rotation). It was found that when participants were pre-cued to make a fine discrimination, the amplitude of the SPCN was increased on intermediate trials at low loads. This demonstrates that the SPCN may reflect both the amount of information held in VWM and the precision of that information.

These results are not necessarily conflicting with the storage account of the SPCN, but they do suggest that the SPCN may reflect something more than the number of items held in VWM. Other areas of working memory research may help elucidate these findings. Katus and Eimer (2015) found that the tactile SPCN (tSPCN) reflected information that was held in the current focus of attention. In this task, participants memorized the location of a task-relevant pulse on one finger and judged whether the location was the same as at test stimulation. Two pulses were presented sequentially either on the same hand (stay trials) or on different hands (switch trials) within 1.5 seconds of one another. Participants were instructed which pulse was task-relevant before the beginning of each block. The tSPCN was contralateral to the relevant pulse on stay trials and increased in magnitude as the second pulse was remembered (i.e., with increasing load). However, on shift trials the polarity of the tSPCN switched after the presentation of the second pulse. Most importantly, the disappearance of a lateralized tSPCN did not affect behavioural accuracy. These results show that delay period activity
may indicate the current focus of attention and not only the amount of information stored in working memory.

Attention and working memory are linked processes that are difficult to separate. Some studies have found that it is possible to differentiate these two processes using electrophysiological measures (Jolicoeur, Brisson, & Robitaille, 2008; for a review see Cohen et al., 2012). The ability to study attention and memory separately allows for a greater understanding of not only the SPCN, but of other ERP components that occur in a similar time frame which may reflect the attentional processes that give rise to visual awareness.

**The Link between Attention and Visual Working Memory**

One ERP component that is thought to reflect selective attention is the N2pc (Eimer, 1996). This is a lateralized component similar to the SPCN that occurs between 180 – 280 ms following stimulus onset (Girelli & Luck, 1997; Jolicoeur, Brisson, & Robitaille, 2008). The N2pc is found maximally over posterior electrode sites, such as PO7/PO8 (Jolicoeur et al., 2008). It arises in response to the allocation of attention to a target and has greater amplitude when perceptual discrimination of a target is made more difficult (Luck & Hillyard, 1994; Luck et al., 1997; Mazza, Turatto, & Caramazza, 2009). The N2pc is seen as a large negativity over the contralateral hemisphere that immediately precedes the SPCN (Jolicoeur et al., 2008; Luck & Hillyard, 1994; Luck et al., 1997; Woodman & Luck, 2003). McCollough and colleagues (2007) noted that the SPCN was topographically more dorsal and medial than the N2pc, structurally separating the two components. Similarly using MEG, Becke et al. (2015) found that the N2pc and SPCN had different underlying current sources. Specifically, they found that the ventral
extrastriate sources of the SPCN were more anterior-lateral than those for the N2pc, suggesting that activity related to the SPCN occurs in a higher level of the extrastriate cortex than the N2pc (Becke et al., 2015).

Jolicoeur, Brisson, and Robitaille (2008) examined the differences between the function of the N2pc and the SPCN. It is possible that the SPCN simply reflects a continuation of the N2pc and that they are not functionally distinct components. They found that a manipulation of load only affected the SPCN and not the N2pc, suggesting that these two components are functionally separate. Although these components may be functionally distinct from an ERP standpoint, it has been argued that there is a behavioural overlap between the two. It has been proposed that these two processes should not be studied in isolation, because memory rehearsal is dependent on early perceptual encoding (Awh & Jonides, 2001; Awh, Vogel, & Oh, 2006; Cohen et al., 2012).

Neural evidence through fMRI data has shown that only items that receive attention have an active neural trace (Lewis-Peacock et al., 2011). However, they also found that items that were outside the focus of attention were still remembered after the delay period. These results corroborate with those found by Katus and Eimer (2015), wherein the active neural trace seems to represent the focus of attention, even though items without a neural trace were still reported accurately. Once again, it seems as though the neural activity associated with VWM may better reflect a combination of focused attention and memory rehearsal than the maintenance of information alone.

In ERP research this viewpoint has not been often adopted; visual attention and working memory are frequently studied separately, generally in distinct research areas.
For this reason, the proposed study aims to examine both the N2pc and the SPCN at various levels of visual awareness. It is possible to study the relationship between effective allocation of attention and subsequent visual awareness by measuring these two lateralized components.

**Object-Substitution Masking**

Visual masking is a useful technique for studying visual awareness because it selectively impairs the visibility of attended objects. Object-substitution masking (OSM) is a relatively new form of visual masking in which a four-dot mask affects the visibility of a briefly presented target (see Goodhew et al., 2013 for a review). The target and mask onset at the same time, but it is the delayed offset of the mask that induces impaired visibility of the target. Peak masking effects can be seen at mask offsets anywhere from 80 – 600 ms following target offset (Enns & DiLollo, 1997). OSM is an ideal paradigm for studying visual awareness because, unlike other forms of visual masking, the mask does not spatially overlap or obscure the target, leaving the sensory input of the target itself intact (Goodhew et al., 2013).

OSM is thought to occur due to a disruption in visual re-entrant processing (DiLollo, Enns, & Rensink, 2000). This occurs when there is a mismatch between the initial visual representation, (target and mask together), with the later image of the mask alone. The resulting perception is that there was never a target to begin with, effectively masking its presence. OSM has been studied in both behavioural and neural studies to better understand the mechanism through which it works.

**Behavioural studies.** Enns and DiLollo (1997) were the first to study OSM in a behavioural task. They concluded that distributed spatial attention was necessary for
OSM to occur. It was thought that targets in unattended locations were encoded with low resolution, therefore leaving them vulnerable to the four-dot mask when attention was directed towards them.

Di Lollo, Enns, and Rensink (2000) furthered their examination of OSM by conducting a series of studies manipulating certain aspects of the stimulus display. It was found that masking was affected as a function of an interaction between mask duration and set size. As mask duration increased, so did the overall masking effect (reduced accuracy). As set size increased, so did the masking effect but this effect was much greater at mask offsets after 80 ms. OSM was also found to be reduced by target pop-out effects and by spatial cueing, consolidating the link between masking and spatial attention.

In the previously mentioned studies, the target was a Landolt C in a random orientation, where the participant’s job was to indicate the orientation of the C following the masking procedure. The response is often forced-choice; the participant is presented with several options from which to choose the target orientation. If the participant was incorrect, they were assumed to be completely unaware of the target, resulting in an all-or-none conceptualization of visual awareness in OSM. However, it is possible that the effect of mask duration affects visual awareness in a gradual manner. By combining a continuous report procedure with an OSM paradigm, it is possible to obtain estimates of perceptual precision and to observe how the quality of visual representations are affected by masking. Because the target is never fully occluded by the four-dot mask, OSM makes it possible to measure these changes in representational quality.
Harrison, Rajsic, and Wilson (2015) used a continuous report procedure and examined the effect of re-entrant processes on a target’s representational precision within three conditions: simultaneous mask offset (0 ms delay), and two delayed offsets (150 and 300 ms). Participants could make their response from a continuous scale of orientations. In this case, they were told to reproduce the orientation of the target item by moving the target with the mouse. They then fitted the three-component mixture model to the data to obtain estimates of target responses, guesses and non-target errors (Bays et al., 2009). To estimate the precision of non-guess responses, the standard deviation of the circular analogue of the Gaussian distribution (von Mises) for non-guesses was calculated.

Results showed that precision decreased as mask delay offset increased. This suggests that the mask in OSM degrades the representation of the target without rendering it completely invisible. Therefore, visual awareness in this paradigm does not occur in an all-or-none fashion, instead the representational quality is affected as a function of re-entrant processing. These results suggest that OSM is a suitable paradigm for analyzing various degrees of representational precision without manipulating the number of to-be-remembered items. This is because in OSM paradigms, there is only one target despite the number of distractors. The independence of representational precision from set size makes OSM an interesting paradigm to study with EEG methodology.

**Neural studies.** Only a few ERP studies have been conducted using an OSM paradigm. Woodman and Luck (2003) examined the N2pc in response to a shape target OSM task amongst 20 distractor shapes. Targets with a simultaneous mask offset and delayed mask offset elicited equivalent N2pc components, suggesting that the targets
were localized whether or not they were accurately reported. These results implicate a separation of attention and perception, wherein a target may be selectively attended to but does not enter visual awareness. This is demonstrated by an equivalent electrophysiological response across the two conditions despite decreased behavioural accuracy in the delayed mask offset condition.

Kotsoni and colleagues (2007) analyzed the posterior P2 (220 ms post-stimulus offset) in response to an OSM task with a present/absent judgment. The posterior P2 was more positive when participants saw a delayed mask offset stimulus as compared to a simultaneous offset stimulus. They proposed that this reflected increased re-entrant processing requirements when the second image (mask alone) is incompatible with the first (target and mask). Although stimuli may require a greater amount of perceptual processing when masked, successful masking has been found to eliminate target encoding. The N170 is a component thought to reflect encoding of visual stimuli and is especially responsive to faces (Eimer, 2000; Rossion et al., 2000). This component was suppressed when presented with masked images of faces or houses, demonstrating that OSM affects target categorization early in perceptual processing (Reiss & Hoffman, 2007).

The effect of OSM on VWM processes has also been studied. Prime and colleagues (Prime et al., 2011) examined the N2pc and SPCN on correct versus incorrect trials. The SPCN was assumed to reflect attentional load. This component was only found on correct trials, suggesting that target information was more likely to reach VWM and therefore visual awareness when the participant made an accurate response. Consistent with the study by Woodman and Luck (2003), they found an N2pc in response to delayed
offset trials, indicating that attention was selectively deployed to the target. Within the delayed offset condition, the N2pc amplitude was smaller over incorrect trials than correct trials. Surprisingly, the N2pc and the SPCN were not observed in the simultaneous offset condition. This is interpreted as a result of a diffuse attentional state during these trials, allowing for the encoding of targets on both sides of the screen (in both hemispheres). If both targets were processed in each hemisphere, then the contralateral minus ipsilateral subtraction would cancel out any activity in response to one particular target, resulting in an absence of any lateralized component.

Combining the results of the above studies, Harris, Ku, and Woldorff (2013) examined multiple ERP components across correct and incorrect OSM trials. Faces and houses were used as the target stimuli to obtain measurements of the N170. Successful masking resulted in a reduction of all ERP components 130 ms or greater post-stimulus offset. On incorrect trials within the masked condition they observed an intact P1 but reduced N2pc, N170, and SPCN. These results also implicate the role of attentional deployment in effective masking, wherein there is a reduced N2pc for masked incorrect trials.

The majority of ERP studies with OSM have focused on a comparison between correct and incorrect trials, often measured in coarse ways such as making a present versus absent judgment. This technique is useful in measuring conditions of awareness versus unawareness but, as seen in the behavioural study by Harrison, Rajsic, and Wilson (2015), there may also be graded levels of awareness. For this reason in the current study trials were not split by correct and incorrect responses and were instead split by the precision with which the target was reported. Additionally, because both mask and set
size were manipulated in the present study, it became possible to evaluate their separate effects on report precision. It could be that increasing set size as well as masking the target both decrease report precision. These effects may interact so that at larger set sizes there is a greater effect of mask on report precision, or they may be independent from one another so that they exert separate effects on behavioural precision.

**Current Study**

In the current study, an object-substitution masking paradigm was used while measuring the SPCN and N2pc ERP components. Research on the underlying function of the SPCN is not well synthesized across research domains. While some VWM researchers have provided evidence that the SPCN represents VWM load (McCollough et al., 2007; Vogel & Machizawa, 2004), others posit that it represents the precision with which information is held or general attentional processes (Katus & Eimer, 2015; Machizawa, Goh, & Driver, 2012). The N2pc was also measured to contrast it with the SPCN, as they are thought to represent separate functions. This study examined four hypotheses/exploratory questions:

1. **Behavioural.** One aim of the current study was to replicate the findings of Harrison, Rajsic, and Wilson (2015) using the three-component mixture model analysis. In particular, the proportion of guess responses, non-target errors, and overall standard deviation was expected to increase from set size 2 to set size 4. There was also an expected increase in guess rate, non-target errors, and standard deviation when the target was masked.

2. **The effect of set size.** It was hypothesized that the N2pc would differ in amplitude as a function of set size, such that the mean amplitude would be greater at
larger set sizes (as seen in Mazza et al., 2009). This is because it is harder to localize the
target amongst more distractors, therefore requiring greater perceptual discrimination to
complete the task successfully (Luck & Hillyard, 1994; Luck et al., 1997).

Similarly, the amplitude of the SPCN was expected to increase (i.e. become more negative) as set size increased (McCollough et al., 2007; Vogel & Machizawa, 2004). In the current design there is always one target, therefore participants should only be encoding one item despite the number of distractors on the screen. But, an increasing amount of distractors on the screen makes it less likely that the target alone will be successfully selected and encoded. It also means that the target is more likely to be missed, and additional items may be encoded to compensate for this error. If the SPCN reflects how many items are held in memory, and increasing set size makes it more likely that other items will be stored in VWM, then it was proposed that the SPCN should have greater amplitude for larger set sizes. This would indicate that the SPCN reflects how much information is stored in VWM, whether due to inefficient filtering of distractors or a recovery strategy when the target has not been effectively located.

3 – The effect of mask. Due to inconsistent findings on the effect of OSM on N2pc amplitude (Woodman & Luck, 2003; Prime et al., 2011; Harris et al., 2013), it was unclear what effect the mask would have on this component. However, it was predicted that an N2pc would be elicited with equal amplitude in both the simultaneous and delayed offset conditions. This is because attention should be allocated toward the target before masking occurs. Therefore, no differences should be observed between the masked and unmasked conditions. Previous studies have only compared the amplitude of the SPCN on correct versus incorrect trials, not across masking conditions. If the SPCN
reflects visual awareness of a stimulus, then it should be larger in the unmasked condition. This is because it is more likely an individual will become aware of and successfully remember the target if it is not masked. Therefore, more information would be held in VWM, resulting in greater SPCN amplitude in the unmasked condition.

4 – The effect of representational precision. As a continuous report procedure was used, it was possible to obtain estimates of behavioural response precision for each condition. As has been previously found, it was hypothesized that both larger set sizes and the mask would decrease report precision (Bays et al., 2009; Harrison et al., 2015). However, the relationship between N2pc/SPCN amplitude in an OSM task and response precision has yet to be examined. It was hypothesized that the N2pc would correlate with response precision, such that better attentional selection would lead to subsequently more precise responses. It was also hypothesized that the amplitude of the SPCN would vary as a function of response precision, such that more negative SPCN amplitudes would reflect more precise responses. This would suggest that the SPCN is not just a reflection of how much information is stored in VWM, but also the quality of that information.

Methods

Participants

Twenty-six undergraduate participants were recruited from Brock University using posters and the online Psychology subject pool. A total of 20 participants ($M_{\text{age}} = 20.45, SD_{\text{age}} = 2.35$; 9 males) were included in the final analyses. Two participants were excluded based on poor behavioural performance (for behavioural exclusion criteria see Behavioural Participant Exclusion section). Three other participants were rejected based on artifact detection during the EEG recording: greater than 35% of their total trials were
rejected due to blinks and/or lateral eye movements during target stimulus presentation. One final participant was excluded due to technical problems during the EEG recording session that resulted in flat-lined ERPs.

All participants were required to answer a self-report questionnaire over the phone to ensure that they had no psychiatric illnesses, no head-injuries within the past 5 years, and that they were right-handed (see Procedures; Appendix A). Participants were remunerated $15/hour or 1 credit/hour.

**Stimuli and Task Design**

**Eye-fixation training task.** As developed by Guzman-Martinez and colleagues (2009), participants were first given a 10-minute rapid eye-fixation training task before the main study. This task provides immediate feedback on the stability of eye fixation, which is crucial to minimizing muscle movement artifacts in EEG data. Individuals who have never participated in an EEG study are often unaware of their eye movements, making it important to train them to maintain a stable fixation (Guzman-Martinez et al., 2009). The display consisted of a fine-grained random dot pattern consisting of 50% black and 50% white pixels. These dots flickered at 37.5 Hz by switching colours (white dots become black and vice versa). When the eyes do not move, this display fuses and becomes a solid grey colour. When the eyes make any movement the pattern is disrupted and the random dots ‘pop out’ to the observer, providing instant feedback on their performance. Participants performed this task until they verbally confirmed that they were able to maintain a stable fixation by voluntarily reducing the pop-out effect.

**Lateralized change detection task.** A lateralized change detection task was run as part of the larger study protocol (for task design see Luck & Vogel, 1997); however, as
it is not germane to the current study, the task design is not further elaborated in this section. For an illustration of the change detection task see Appendix B.

**Lateralized object-substitution masking task.** The lateralized OSM task was the main task during the session and took approximately one hour to complete (Figure 1). Trials began with a fixation screen for 200 ms. Following this, an arrow facing either left or right replaced the fixation dot for 200 ms, indicating which side of the screen was relevant for the following task on each trial. Participants were instructed to pay attention to the side of the screen that the arrow pointed to without moving their eyes. Next, a fixation dot was presented for a jittered time interval between 200 – 500 ms to ensure that EEG waveforms would not become synchronized across trials.

Next, the memory sample appeared for a total of 17 ms (similar to previous OSM designs i.e., Harris et al., 2013; Harrison et al., 2015). This display consisted of 2 or 4 Landolt Cs (1 x 1 visual degree) in random orientations. There was a minimum of 30 degrees between the orientations of any two Landolt Cs presented on the screen. These Cs appeared in any of 4 locations on a semi-circle, with the closest Landolt C 2 visual degrees away from fixation, and the farthest 2.8 visual degrees away. There was an equivalent screen on the non-cued side of the screen to balance visual inputs. Participants were instructed to notice and remember the orientation of the Landolt C that was surrounded by four dots (1.5 x 1.5 visual degrees). On half of the trials the mask had a simultaneous offset with the target (0 ms delay) and on the other half there was a delayed offset (300 ms). Following this, there was either a 583 or 283 ms delay period, depending on the mask condition, for a total of 600 ms after the presentation of the memory array to
capture the SPCN. Participants were not informed that half of the time the target was masked.

Next, participants made a free response wherein they rotated the orientation of a probe Landolt C, which was presented in the spot that the target was located. The gap of the Landolt C followed the mouse as it moved. Participants used the mouse to make an orientation response (0 – 359°) and their response was recorded in degrees once the mouse was clicked. There were 120 trials per condition (2 sides x 2 set sizes x 2 mask offsets) resulting in 960 trials in total.
Figure 1. Example of a set size 2, masked trial of the lateralized object-substitution masking task. Participants were cued to one side of the screen by an arrow and then told to find the target and remember its orientation on the cued side only. Responses were recorded using continuous report, such that the target orientation could be reported anywhere from 0-359 degrees.
Procedure

Procedures were cleared by the Brock University Biosciences Research Ethics Board (see Appendix C). Potential participants were first given an interview (either on the phone or over e-mail) to determine their eligibility for the study (see Appendix A). Questions included handedness, mental health, previous head-injuries, and general demographic information. After having met these requirements, they were given information about the nature of EEG studies (i.e., having to wear a cap, having electrode gel placed in their hair) and then scheduled an appointment lasting 3 hours including set-up.

During the session participants first provided written consent prior to set-up (see Appendix D). After the consent form had been read and signed, participants were fitted with a 64-electrode EEG cap from the BioSemi ActiveTwo system (BioSemi, Amsterdam). After set up, participants completed an eye-fixation training task as described previously.

The next task was the lateralized whole report change detection task. This task had 150 trials and took approximately 10 minutes to complete. Participants were given practice trials until they felt comfortable with the task. Next, participants received instructions on the OSM task and were given 18 practice trials (or more if needed to make them feel comfortable with the task). Instructions about eye movements and blinks were given and the experimenter monitored the online EEG for any movements during stimuli presentation. All participants were instructed not to blink during stimuli presentation and told to instead make these movements during the response period and during break screens. Participants were given verbal feedback to correct these movements.
during their practice trials. The task consisted of 960 trials with trial types pseudo-
randomized and breaks every 20 trials.

Following the OSM task, participants were debriefed and given the opportunity to 
ask the experimenter questions. They were either compensated 1 course participation 
credit/hour or $15/hour.

**EEG Recording and Preprocessing**

Electrophysiological data was DC-recorded at 512 Hz from 64 active Ag/AgCl 
electrodes placed at the standard 10-20 locations using an electrode cap (BioSemi, 
Amsterdam). Horizontal and vertical eye movements were monitored with bipolar 
horizontal (HEOG) and vertical (VEOG) electrooculogram electrodes. The data was 
online referenced to the common mode sense (CMS) and the driven right leg (DRL) 
electrodes.

All EEG preprocessing was done in Matlab R2014a with the EEGLAB (Delorme 
& Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014) toolboxes. Data was re-
referenced offline to the average of the mastoids. A 40 Hz low-pass and 0.1 Hz high-pass 
Butterworth filter was also applied offline. Trials with large eye movements and/or eye 
blinks were excluded from the analysis (greater than 32 microvolts HEOG artifacts 
and/or greater than 80 microvolt VEOG peak-to-peak threshold). An average of 14.8% of 
all trials were rejected, leaving an average of 818 trials per participant to be included in 
the final analyses. ERPs were time-locked to the onset of the memory array, with a 
baseline correction 100 ms preceding stimulus onset. The data was epoched from –200 
pre-stimulus to 800 ms post-stimulus to create the averaged ERPs.
Two participants had channels that were interpolated due to noise present in the recording that could not be removed by filtering alone. A spherical spline interpolation was conducted, which takes into account all of the channels (for more information, see Perrin et al., 1989). One participant had channel PO4 interpolated, and the other had channels P2 and P8 interpolated. All of the analyses for these two participants were performed on the interpolated data.

Difference waves were calculated by subtracting ipsilateral from contralateral channels, collapsing across the side on which the stimuli were presented. The difference waves reflect activity related solely to the processing of the target because activity related to the sensory processing of the stimuli is subtracted out during the calculation (i.e. ipsilateral sensory responses). There were four difference waves reflecting activity in each experimental condition: set size 2/unmasked, set size 2/masked, set size 4/unmasked, and set size 4/masked.

**Behavioural Data Analysis**

To examine whether the manipulation had the desired effect on precision, the behavioural data was analyzed with the three-component mixture model analysis using the MemToolBox 1.0 (Suchow, Brady, & Alvarez, 2013). Bays, Catalao, and Husain (2009) defined this model based off of a two-component model of behaviour described by Zhang and Luck (2008). This earlier probabilistic model proposed two sources of error in a continuous report task: variability in remembering a target feature (i.e., colour or orientation) and the probability of making a random guess. Bays et al. (2009) added another source of error to this model: the probability of reporting a distractor item instead of the target. Both target and distractor responses are drawn from a von Mises distribution
with the same standard deviation (i.e. the width of the distribution). The formula for this model is defined as:

\[ p(\hat{\theta}) = (1 - \gamma - \beta)\phi_{\sigma}(\hat{\theta} - \theta) + \gamma \frac{1}{2\pi} + \beta \frac{1}{m} \sum_{i=1}^{m} \phi_{\sigma}(\hat{\theta} - \theta_i^{*}) \]

In the current study, \( \hat{\theta} \) is the reported orientation, \( \theta \) is the target value in radians, \( \gamma \) is the proportion of trials on which a random response is made, \( \beta \) is the probability of making a non-target error, \( \phi_{\sigma} \) represents the standard deviation of the von Mises distribution of responses, and \( \theta_i^{*} \) are the orientation values of the \( m \) distractor items (Bays et al., 2009).

Each type of response has its own probability density function (Bays et al., 2009): target responses comprise of a von Mises distribution centered on the target value with a given variability; non-target responses consist of multiple distributions centered on the non-target values, and a guess component consisting of a fixed uniform distribution. The standard deviation (SD) of response error is also obtained from the von Mises distribution as an estimate of behavioural precision (note: the inverse of SD = precision). For each participant, maximum likelihood estimates for each parameter within each experimental condition were obtained using maximum likelihood estimation (MLE; Bays et al., 2009; Suchow, Brady, & Alvarez, 2013). MLE is a procedure used to find parameter estimates that best fit the model given the current dataset (Dempster, Laird, & Rubin, 1977; Suchow, Brady, & Alvarez, 2013).

In sum, the three-component mixture model analysis provides an estimate of target rate (1 – guess rate – non-target error rate), guess rate, non-target error rate, and standard deviation for each participant in all experimental conditions.
Behavioural Participant Exclusion

As previously stated, based on behavioural results two participants were excluded from the statistical analyses. One participant had a non-target error rate greater than 3 SDs above the mean in both the set size 2, unmasked ($M = 0.01, SD = 0.02$), and set size 4, unmasked ($M = 0.03, SD = 0.03$) conditions. Upon analyzing the boxplots for all conditions, this participant was also found to have scores outside 3 times the interquartile range (IQR) for non-target errors in the set size 2, unmasked condition ($> Q3 (0.01) + IQR (0.01) * 3 = .04$), for guess rate in the set size 4, unmasked condition ($>.49$), and for target rate in the set size 4, unmasked condition ($<.41$). The second participant had a standard deviation in the set size 4, masked condition ($M = 27.09, SD = 13.34$) that was 3 SDs greater than the mean. This was supported by examination of the boxplots for this condition, wherein their score was greater than 3 times the IQR ($> 56.92$).

Statistical Analyses

Test assumptions. The assumption of normality was checked for all behavioural variables and ERP amplitudes in each condition. This was done through visual inspection of all frequency histograms. Although some of the behavioural and ERP variables were skewed, it was decided not to transform these variables. This is because ANOVAs are relatively robust to violations of normality (Glass, Peckham, & Sanders, 1972; Schmider et al., 2010). As all variables had two levels, the assumption of sphericity was not examined.

Outlier treatment. All variables in each condition were checked for outliers with scores outside 3 times the IQR. There were no statistical outliers for any of the behavioural variables or ERP amplitudes.
Hypothesis testing. All main hypotheses examining behavioural and ERP differences across conditions were analyzed using a 2 x 2 repeated measures ANOVA. The relation between ERP amplitudes and behavioural performance was analyzed using Pearson’s correlation coefficient.

Results

Behavioural Results

Response error. Before running the data through the mixture model analysis, response error was calculated as the difference between the participants’ response and the target orientation in degrees on every trial. For each condition, the circular standard deviation of the response error was calculated (variability of response error in degrees). A Set Size (2) by Mask Condition (2) repeated measures ANOVA was conducted on response error in each condition. There was a main effect of Set Size, $F(1,19) = 105.57, p < .001$, partial $\eta^2 = .847$, and Mask Condition, $F(1,19) = 133.63, p < .001$, partial $\eta^2 = .876$ (see Figure 2), such that individuals had greater response error at set size 4 ($M = 41.74, SD = 6.41$) than at set size 2 ($M = 32.51, SD = 9.04$), and greater response error for masked trials ($M = 45.86, SD = 7.42$) than unmasked trials ($M = 28.40, SD = 5.63$). The interaction between Set Size and Mask Condition was not significant, $F(1,19) = 1.96, p = .178$, partial $\eta^2 = .093$. 
Figure 2. Mean response error by condition. Within-subjects error bars represent the 95% CI.

Mixture model. The data were run through the three-component mixture model analysis, which uses response error to determine the proportion of trials on which a target, non-target, or guess response were made. The width or standard deviation of the response error distribution reflects overall precision in an experimental condition. A Set Size (2) by Mask Condition (2) repeated measures ANOVA was conducted on all parameter estimates (guess rate, non-target error rate, standard deviation, and target rate; see Table 1 and Figure 3 for descriptive statistics; see Table 2 for a summary of the ANOVA results).

Guess rate. There was a significant main effect of Set Size on guess rate, $F(1,19) = 24.20, p < .001$, partial $\eta^2 = .560$. Participants were making more guesses at set size 4 than at set size 2. The main effect of Mask Condition was also significant for guess rate,
\[ F(1,19) = 62.35, p < .001, \text{ partial } \eta^2 = .766, \] such that more guesses were made when the target was masked. There was a significant interaction between Set Size and Mask Condition for guess rate, \( F(1,19) = 4.42, p = .049, \text{ partial } \eta^2 = .189. \) The interaction shows that there was a bigger effect of Mask Condition on guess rate at set size 4 than at set size 2.

**Non-target error rate.** There was a significant main effect of Set Size on non-target error rate, \( F(1,19) = 41.25, p < .001, \text{ partial } \eta^2 = .685. \) More non-target errors were made at a higher set size. Non-target error rate was also greater in the masked condition, \( F(1,19) = 42.44, p < .001, \text{ partial } \eta^2 = .691. \) The interaction between Set Size and Mask Condition was also significant, \( F(1,19) = 24.24, p < .001, \text{ partial } \eta^2 = .561, \) indicating that the mask affected non-target error rate more so at set size 4 than at set size 2.

**Target rate.** There was a significant main effect of Set Size on target rate, \( F(1,19) = 120.86, p < .001, \text{ partial } \eta^2 = .864. \) More target responses were made at a lower set size. Participants also made significantly more target responses when the target was unmasked, \( F(1,19) = 126.78, p < .001, \text{ partial } \eta^2 = .870. \) The interaction term was also significant, \( F(1,19) = 24.30, p < .001, \text{ partial } \eta^2 = .561, \) such that the effect of Mask Condition was greater at set size 4 than set size 2.

**Standard deviation.** There was a significant main effect of Set Size on standard deviation, \( F(1,19) = 15.45, p < .001, \text{ partial } \eta^2 = .448. \) Participants were less precise (greater standard deviation) at set size 4 than set size 2. They were also less precise when the target was masked, \( F(1,19) = 39.90, p < .001, \text{ partial } \eta^2 = .677. \) The interaction was
not significant for standard deviation, $F(1,19) = .635, p = .435$, partial $\eta^2 = .032$. Unlike
the other dependent variables (except response error), the lack of a significant interaction
term indicates that overall precision of responses was independently affected by set size
and mask condition.

Table 1

Descriptive Statistics for Behavioural Results by Set Size and Mask Condition

<table>
<thead>
<tr>
<th>Condition</th>
<th>Guess Rate M</th>
<th>SD</th>
<th>Non-Target Error Rate M</th>
<th>SD</th>
<th>Standard Deviation M</th>
<th>SD</th>
<th>Target Rate M</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Set Size 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unmasked</td>
<td>0.08</td>
<td>0.08</td>
<td>0.01</td>
<td>0.01</td>
<td>16.83</td>
<td>3.73</td>
<td>0.91</td>
<td>0.08</td>
</tr>
<tr>
<td>Masked</td>
<td>0.23</td>
<td>0.12</td>
<td>0.04</td>
<td>0.04</td>
<td>22.34</td>
<td>5.88</td>
<td>0.73</td>
<td>0.14</td>
</tr>
<tr>
<td><strong>Set Size 4</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unmasked</td>
<td>0.12</td>
<td>0.12</td>
<td>0.03</td>
<td>0.02</td>
<td>19.15</td>
<td>4.31</td>
<td>0.85</td>
<td>0.12</td>
</tr>
<tr>
<td>Masked</td>
<td>0.34</td>
<td>0.16</td>
<td>0.15</td>
<td>0.09</td>
<td>25.90</td>
<td>9.62</td>
<td>0.51</td>
<td>0.17</td>
</tr>
<tr>
<td><strong>Unmasked</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Masked</td>
<td>0.10</td>
<td>0.10</td>
<td>0.02</td>
<td>0.02</td>
<td>17.99</td>
<td>4.02</td>
<td>0.88</td>
<td>0.10</td>
</tr>
<tr>
<td><strong>Masked</strong></td>
<td>0.29</td>
<td>0.14</td>
<td>0.10</td>
<td>0.07</td>
<td>24.12</td>
<td>7.75</td>
<td>0.62</td>
<td>0.16</td>
</tr>
</tbody>
</table>

*Note.* Bolded = Marginal means for the main effects.
Figure 3. Means for each parameter estimate by condition. Error bars represent the within-subjects 95% CI.
Table 2

**ANOVA Summary Table for Behavioural Results by Set Size and Mask Condition**

<table>
<thead>
<tr>
<th>Variable</th>
<th>$F$</th>
<th>$p$</th>
<th>Partial $\eta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set Size</td>
<td>67.22</td>
<td>&lt; .001</td>
<td>.685</td>
</tr>
<tr>
<td>Guess Rate</td>
<td>24.20</td>
<td>&lt; .001</td>
<td>.560</td>
</tr>
<tr>
<td>NTE Rate</td>
<td>41.25</td>
<td>&lt; .001</td>
<td>.685</td>
</tr>
<tr>
<td>SD</td>
<td>15.45</td>
<td>&lt; .001</td>
<td>.448</td>
</tr>
<tr>
<td>Target Rate</td>
<td>120.86</td>
<td>&lt; .001</td>
<td>.864</td>
</tr>
<tr>
<td>Mask</td>
<td>37.84</td>
<td>&lt; .001</td>
<td>.904</td>
</tr>
<tr>
<td>Guess Rate</td>
<td>62.35</td>
<td>&lt; .001</td>
<td>.766</td>
</tr>
<tr>
<td>NTE Rate</td>
<td>42.44</td>
<td>&lt; .001</td>
<td>.691</td>
</tr>
<tr>
<td>SD</td>
<td>39.90</td>
<td>&lt; .001</td>
<td>.677</td>
</tr>
<tr>
<td>Target Rate</td>
<td>126.78</td>
<td>&lt; .001</td>
<td>.870</td>
</tr>
<tr>
<td>Set Size x Mask</td>
<td>10.64</td>
<td>&lt; .001</td>
<td>.727</td>
</tr>
<tr>
<td>Guess Rate</td>
<td>4.42</td>
<td>.049</td>
<td>.189</td>
</tr>
<tr>
<td>NTE Rate</td>
<td>24.24</td>
<td>&lt; .001</td>
<td>.561</td>
</tr>
<tr>
<td>SD</td>
<td>0.64</td>
<td>.435</td>
<td>.032</td>
</tr>
<tr>
<td>Target Rate</td>
<td>24.30</td>
<td>&lt; .001</td>
<td>.561</td>
</tr>
</tbody>
</table>

*Note.* NTE = non-target error, SD = standard deviation.
ERP Results

Seven posterior channel pairs were analyzed: P1/2, P3/4, P5/6, P7/8, PO7/PO8, P9/10, and O1/2. Upon examination of the grand average ERP plot of the difference waves (see Figure 5), the latencies of the three components of interest were defined as: the N2pc (200 – 350 ms), early SPCN (eSPCN: 350 – 500 ms), and late SPCN (lSPCN: 500 – 650 ms). The contralateral and ipsilateral grand average waveforms were compared over these three latencies to determine whether the lateralized components observed at each condition were statistically significant (see Figure 4). A repeated-measures ANOVA was run for each of the three components to compare the effect of Laterality (contralateral or ipsilateral) in each experimental condition. The main effect of Laterality was significant for all conditions over the time period of the N2pc, (all $F$s > 4.55, all $p$ values < .047, all partial $\eta^2$s > .192), the eSPCN, (all $F$s > 8.54, all $p$ values < .010, all partial $\eta^2$s > .312), and the lSPCN, all $F$s > 13.25, all $p$ values < .003, all partial $\eta^2$s > .410. Therefore, it was concluded that the three components of interest were present in all conditions as demonstrated by more negative ERP amplitudes toward contralateral targets than ipsilateral targets.
Figure 4. Contralateral and ipsilateral waveforms for the grand average of 7 posterior channel pairs in the (a) set size 2, unmasked, (b) set size 2, masked, (c) set size 4, unmasked, and (d) set size 4, masked conditions.
Figure 5. Grand average ERP waveforms measured at seven posterior channel pairs for each experimental condition. An average of approximately 200 trials per condition are included per participant in the grand average.

Upon examining the grand average plot, it appeared that there were differential effects of the experimental conditions on the SPCN at separate time points: one occurring during an early latency (350 – 500 ms) and one during a later latency (500 – 650 ms; see similar results in Luria & Vogel, 2011; Peterson et al., 2015). To determine whether there were statistically separate effects of Set Size and Mask Condition at the different time points, a Set Size (2) x Mask Condition (2) x Time Point (2) repeated measures ANOVA was conducted on the grand average of the seven posterior channel pairs. There was a significant Set Size x Time Point interaction, $F(1,19) = 17.54, p < .001$, partial $\eta^2 = .480$, 
and a marginally significant Mask Condition x Time Point interaction, $F(1, 19) = 3.36, p = .082$, partial $\eta^2 = .150$ (see Figure 6). Paired samples t-tests showed that there was not a significant effect of Set Size on mean amplitude at the early time point, $t(19) = -.610, p = .549$, but there was at the late time point, $t(19) = 2.71, p = .014$. There was a significant effect of Mask Condition at the early time point, $t(19) = 3.82, p = .001$, but not at the late time point, $t(19) = 1.40, p = .177$. This provides evidence that there were separate effects of the two manipulations at the early and late SPCN, providing rationale for splitting the analyses of the SPCN.

Figure 6. (a.) Overall ERP amplitude as a function of time period (early or late) and set size. (b.) Overall ERP amplitude as a function of time period and mask condition. Error bars represent the standard error of the mean.

**N2pc.** For each ERP component of interest, a Set Size (2) by Mask Condition (2) repeated-measures ANOVA was run with the grand average mean amplitude. There was not a significant main effect of Set Size at the grand average, $F(1, 19) = 2.48, p = .132$, partial $\eta^2 = .115$. However, the N2pc was analyzed separately at channel pair PO7/PO8 because that is where there was the greatest N2pc amplitude, $(M = -.731, SE = .242)$. 
There was a significant main effect of Set Size at this channel pair, $F(1,19) = 5.32, p = .032$, partial $\eta^2 = .219$ (see Figure 7). This demonstrates that the N2pc had greater amplitude at set size 4 ($M = -.945, SE = .312$) than at set size 2 ($M = -.516, SE = .193$).

There was not a significant main effect of Mask Condition, $F(1,19) = 1.85, p = .190$, partial $\eta^2 = .089$, or a Set Size by Mask interaction, $F(1,19) = 0.0004, p = .985$, partial $\eta^2 = 0.00002$.

Figure 7. Mean amplitude of the N2pc at channel pair PO7/PO8 for all set size and mask conditions. Negative is up. Within-subjects error bars represent the 95% CI.

eSPCN. There was a significant effect of Mask Condition on the grand average amplitude of the eSPCN, $F(1,19) = 14.58, p = .001$, partial $\eta^2 = .434$, (see Figure 8). This shows that the amplitude of the eSPCN was greater when the target was masked ($M = -.840, SE = .176$) than when the target was unmasked ($M = -.514, SE = .163$). There was
not a significant effect of Set Size on the eSPCN, $F(1,19) = .372, p = .549$, partial $\eta^2 = .019$, or a Mask by Set Size interaction, $F(1,19) = 2.13, p = .161$, partial $\eta^2 = .101$.

![Figure 8](image-url)

**Figure 8.** Mean amplitude of the eSPCN at all channel pairs for all set size and mask conditions. Negative is up. Within-subjects error bars represent the 95% CI.

**lSPCN.** There was a main effect of Set Size for the grand average amplitude of the lSPCN, $F(1,19) = 7.32, p = .004$, partial $\eta^2 = .278$ (see Figure 9). Thus, the mean amplitude of the lSPCN was greater at set size 4 ($M = -.843, SE = .172$) than at set size 2 ($M = -.646, SE = .148$). There was not a significant effect of Mask Condition, $F(1,19) = 1.96, p = .177$, partial $\eta^2 = .278$, or a Set Size by Mask interaction, $F(1,19) = 2.01, p = .172$, partial $\eta^2 = .096$. 

**ISPCN.** There was a main effect of Set Size for the grand average amplitude of the ISPCN, $F(1,19) = 7.32, p = .004$, partial $\eta^2 = .278$ (see Figure 9). Thus, the mean amplitude of the ISPCN was greater at set size 4 ($M = -.843, SE = .172$) than at set size 2 ($M = -.646, SE = .148$). There was not a significant effect of Mask Condition, $F(1,19) = 1.96, p = .177$, partial $\eta^2 = .278$, or a Set Size by Mask interaction, $F(1,19) = 2.01, p = .172$, partial $\eta^2 = .096$. 

**Note:** The values and symbols used in the figures are placeholders and should be replaced with actual data and analyses from the study.
Figure 9. Mean amplitude of the lSPCN at all channel pairs for all set size and mask conditions. Negative is up. Within-subjects error bars represent the 95% CI.

ERP Correlations with Behavioural Performance

To determine the relation between ERP amplitudes and behavioural performance, a series of bivariate correlations with Pearson’s r were conducted between mean ERP amplitudes, all four variables from the mixture model analysis (guess rate, non-target error rate, standard deviation, and target rate), as well as response error. For brevity, only the most relevant results are presented.

N2pc. Mean N2pc amplitude at set size 2 correlated with SD at set size 2 ($r = .583, p = .007$), and standard deviation in both the set size 2, masked ($r = .596, p = .006$) and set size 2, unmasked ($r = .505, p = .023$) conditions. Unmasked N2pc amplitude at set size 2 correlated with unmasked SD at set size 2, $r = .497, p = .026$. Masked N2pc amplitude at set size 2 also correlated with masked SD at set size 2, $r = .484, p = .030$. 
ATTENTION, AWARENESS, AND OBJECT-SUBSTITUTION MASKING

(see Figure 10 for scatterplots of major correlations). This denotes that the greater the N2pc amplitude (more negative), the more precise the mean response (the smaller the SD). This relation was only prevalent at set size 2. Refer to Table 3 for all correlations between N2pc amplitude and SD.

Interestingly, the correlations between N2pc amplitude and target rate were less consistent. N2pc amplitude in the set size 2, masked condition correlated with target rate in multiple conditions (see Table 4), but not with target rate in the set size 2, masked condition. These results are less reliable than those found for SD, indicating that the N2pc (attentional selection) may play a greater role in affecting representational quality than the overall threshold of awareness. No other consistent correlations were found between the N2pc amplitude and behavioural measures.

Figure 10. Correlation scatterplots between mean N2pc amplitude at set size 2 and (a) SD at set size 2, (b) SD at set size 2, masked, (c) SD at set size 2, unmasked, (d) N2pc
amplitude at set size 2, unmasked and SD at set size 2, unmasked, and (e) N2pc amplitude at set size 2, masked and SD at set size 2, masked.

Table 3

*Correlations Between N2pc Amplitude and Standard Deviation Within Each Condition*

<table>
<thead>
<tr>
<th>N2pc Amplitude</th>
<th>1.</th>
<th>2.</th>
<th>3.</th>
<th>4.</th>
<th>5.</th>
<th>6.</th>
<th>7.</th>
<th>8.</th>
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<tbody>
<tr>
<td>Standard Deviation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Set Size 2</td>
<td>.583**</td>
<td>.591**</td>
<td>.485*</td>
<td>.360</td>
<td>.349</td>
<td>.346</td>
<td>.485*</td>
<td>.416</td>
</tr>
<tr>
<td>2. Unmasked</td>
<td>.505*</td>
<td>.497*</td>
<td>.438</td>
<td>.343</td>
<td>.343</td>
<td>.321</td>
<td>.439</td>
<td>.382</td>
</tr>
<tr>
<td>3. Masked</td>
<td>.596**</td>
<td>.612**</td>
<td>.484*</td>
<td>.347</td>
<td>.330</td>
<td>.340</td>
<td>.484*</td>
<td>.411</td>
</tr>
<tr>
<td>7. Unmasked</td>
<td>.493*</td>
<td>.472*</td>
<td>.445*</td>
<td>.303</td>
<td>.300</td>
<td>.286</td>
<td>.401</td>
<td>.360</td>
</tr>
</tbody>
</table>

*Note.* ** = p < .001, * = p < .05.
Table 4

*Correlations Between N2pc Amplitude and Target Rate Within Each Condition*

<table>
<thead>
<tr>
<th>N2pc Amplitude</th>
<th>Target Rate</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Set Size 2</td>
<td>- .36</td>
<td>- .19</td>
<td>** .524**</td>
<td>- .14</td>
<td>- .15</td>
<td>- .09</td>
<td>- .18</td>
<td>- .28</td>
<td></td>
</tr>
<tr>
<td>2. Unmasked</td>
<td>- .42</td>
<td>- .23</td>
<td>** .597**</td>
<td>- .27</td>
<td>- .27</td>
<td>- .17</td>
<td>- .28</td>
<td>- .38</td>
<td></td>
</tr>
<tr>
<td>3. Masked</td>
<td>- .29</td>
<td>- .14</td>
<td>- .43</td>
<td>- .06</td>
<td>- .10</td>
<td>- .10</td>
<td>- .20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Set Size 4</td>
<td>- .36</td>
<td>- .21</td>
<td>** .493**</td>
<td>- .13</td>
<td>- .11</td>
<td>- .13</td>
<td>- .16</td>
<td>- .27</td>
<td></td>
</tr>
<tr>
<td>5. Unmasked</td>
<td>- .32</td>
<td>- .17</td>
<td>** .477**</td>
<td>- .22</td>
<td>- .23</td>
<td>- .13</td>
<td>- .21</td>
<td>- .26</td>
<td></td>
</tr>
<tr>
<td>6. Masked</td>
<td>- .29</td>
<td>- .18</td>
<td>- .39</td>
<td>- .05</td>
<td>- .08</td>
<td>- .08</td>
<td>- .21</td>
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<td></td>
</tr>
<tr>
<td>7. Unmasked</td>
<td>- .36</td>
<td>- .18</td>
<td>** .528**</td>
<td>- .22</td>
<td>- .24</td>
<td>- .24</td>
<td>- .23</td>
<td>- .31</td>
<td></td>
</tr>
<tr>
<td>8. Masked</td>
<td>- .33</td>
<td>- .19</td>
<td>** .454**</td>
<td>- .07</td>
<td>- .03</td>
<td>- .12</td>
<td>- .11</td>
<td>- .23</td>
<td></td>
</tr>
</tbody>
</table>

*Note.* ** = \( p < .001 \), * = \( p < .05 \).
eSPCN. Mean eSPCN amplitude at set size 2 correlated with SD in the unmasked conditions, $r = .445, p = .049$. All other correlations were not consistent enough to make any firm conclusions about the relation between eSPCN amplitude and behaviour (see Table 5). Although many of the correlations were medium strength (i.e., ~ .40), they did not reach significance, which may be due to low power from a small sample size ($N = 20$).

Table 5

*Correlations Between eSPCN Amplitude and Standard Deviation Within Each Condition*

<table>
<thead>
<tr>
<th></th>
<th>1.</th>
<th>2.</th>
<th>3.</th>
<th>4.</th>
<th>5.</th>
<th>6.</th>
<th>7.</th>
<th>8.</th>
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</thead>
<tbody>
<tr>
<td>eSPCN Amplitude</td>
<td>Standard Deviation</td>
<td>1.</td>
<td>2.</td>
<td>3.</td>
<td>4.</td>
<td>5.</td>
<td>6.</td>
<td>7.</td>
</tr>
<tr>
<td>1. Set Size 2</td>
<td>.443</td>
<td>.422</td>
<td>.393</td>
<td>.368</td>
<td>.369</td>
<td>.340</td>
<td>.414</td>
<td>.371</td>
</tr>
<tr>
<td>5. Unmasked</td>
<td>.451*</td>
<td>.369</td>
<td>.461*</td>
<td>.381</td>
<td>.412</td>
<td>.325</td>
<td>.413</td>
<td>.391</td>
</tr>
<tr>
<td>6. Masked</td>
<td>.264</td>
<td>.234</td>
<td>.252</td>
<td>.157</td>
<td>.091</td>
<td>.204</td>
<td>.164</td>
<td>.229</td>
</tr>
<tr>
<td>7. Unmasked</td>
<td>.445*</td>
<td>.368</td>
<td>.452*</td>
<td>.381</td>
<td>.406</td>
<td>.331</td>
<td>.409</td>
<td>.391</td>
</tr>
<tr>
<td>8. Masked</td>
<td>.350</td>
<td>.334</td>
<td>.310</td>
<td>.245</td>
<td>.198</td>
<td>.269</td>
<td>.273</td>
<td>.293</td>
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</tbody>
</table>

*Note.* $* = p < .05.$
**ISPCN.** Mean ISPCN amplitude at set size 2 correlated with non-target error rate at set size 2, $r = .494, p = .027$ (see Table 6). The greater the ISPCN amplitude, the greater the average non-target error rate at set size 2. It was also found that the mean amplitude of the ISPCN correlated with guess rate in the unmasked conditions, $r = .472, p = .035$ (see Table 7). This shows that in unmasked conditions (averaged across set size) the larger the ISPCN amplitude, the greater the guess rate. No other consistently significant correlations were found between the mean ISPCN amplitude and the other behavioural measures.
Table 6

Correlations Between lSPCN Amplitude and Non-Target Error Rate Within Each Condition

<table>
<thead>
<tr>
<th>Non-Target Error Rate</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
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</thead>
<tbody>
<tr>
<td>1. Set Size 2</td>
<td><strong>.494</strong>*</td>
<td><strong>.483</strong>*</td>
<td>.424</td>
<td>.412</td>
<td>.398</td>
<td>.378</td>
<td><strong>.467</strong>*</td>
<td>.422</td>
</tr>
<tr>
<td>2. Unmasked</td>
<td>.281</td>
<td>.328</td>
<td>.197</td>
<td>.162</td>
<td>.153</td>
<td>.151</td>
<td>.249</td>
<td>.182</td>
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<tr>
<td>4. Set Size 4</td>
<td>-.326</td>
<td>-.372</td>
<td>-.234</td>
<td>-.226</td>
<td>-.154</td>
<td>-.264</td>
<td>-.271</td>
<td>-.264</td>
</tr>
<tr>
<td>5. Unmasked</td>
<td>-.076</td>
<td>-.066</td>
<td>-.072</td>
<td>-.052</td>
<td>.057</td>
<td>-.143</td>
<td>.001</td>
<td>-.116</td>
</tr>
<tr>
<td>6. Masked</td>
<td>-.334</td>
<td>-.387</td>
<td>-.236</td>
<td>-.232</td>
<td>-.180</td>
<td>-.252</td>
<td>-.293</td>
<td>-.258</td>
</tr>
<tr>
<td>7. Unmasked</td>
<td>.013</td>
<td>.035</td>
<td>-.008</td>
<td>.001</td>
<td>.095</td>
<td>-.083</td>
<td>.072</td>
<td>-.051</td>
</tr>
<tr>
<td>8. Masked</td>
<td>-.130</td>
<td>-.180</td>
<td>-.067</td>
<td>-.065</td>
<td>-.026</td>
<td>-.093</td>
<td>-.103</td>
<td>-.085</td>
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</tbody>
</table>

*Note.* * = p < .05.
Table 7

*Correlations Between lSPCN Amplitude and Guess Rate Within Each Condition*

<table>
<thead>
<tr>
<th>ISPCN Amplitude</th>
<th>Guess Rate</th>
<th>1.</th>
<th>2.</th>
<th>3.</th>
<th>4.</th>
<th>5.</th>
<th>6.</th>
<th>7.</th>
<th>8.</th>
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</thead>
<tbody>
<tr>
<td>1. Set Size 2</td>
<td>.250</td>
<td>.287</td>
<td>.177</td>
<td>.162</td>
<td>.265</td>
<td>.052</td>
<td>.294</td>
<td>.117</td>
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<tr>
<td>2. Unmasked</td>
<td>.353</td>
<td>.366</td>
<td>.285</td>
<td>.311</td>
<td>.419</td>
<td>.179</td>
<td>.422</td>
<td>.241</td>
<td></td>
</tr>
<tr>
<td>3. Masked</td>
<td>.152</td>
<td>.202</td>
<td>.085</td>
<td>.045</td>
<td>.132</td>
<td>-.038</td>
<td>.175</td>
<td>.020</td>
<td></td>
</tr>
<tr>
<td>4. Set Size 4</td>
<td>.370</td>
<td>.459*</td>
<td>.235</td>
<td>.313</td>
<td>.356</td>
<td>.239</td>
<td>.430</td>
<td>.251</td>
<td></td>
</tr>
<tr>
<td>5. Unmasked</td>
<td>.447*</td>
<td>.460*</td>
<td>.364</td>
<td>.361</td>
<td>.466*</td>
<td>.227</td>
<td>.495*</td>
<td>.307</td>
<td></td>
</tr>
<tr>
<td>8. Masked</td>
<td>.207</td>
<td>.305</td>
<td>.087</td>
<td>.141</td>
<td>.175</td>
<td>.096</td>
<td>.250</td>
<td>.098</td>
<td></td>
</tr>
</tbody>
</table>

*Note.* * = \( p < .05 \).
**Precision and ERPs**

Considering that awareness (Mask Condition) did not have the predicted effect on the eSPCN or lSPCN, (i.e. greater amplitude for unmasked conditions), how the *precision* of responses would affect the amplitudes of these components was analyzed as well. It was originally hypothesized that there would be greater SPCN amplitude in the unmasked condition due to increased awareness of the stimulus. Therefore, it would also be expected that both time points of the SPCN would have greater amplitude when responses were more precise. This would indicate that the participant held a greater amount of information about the target stimulus in memory.

Precise and imprecise responses were determined by condition for each participant by splitting trials into thirds based on response error (response orientation – target orientation in degrees). The first third of trials (i.e. closest to 0, or to the target orientation) were considered precise, and the last third (i.e. closest to 180, or the opposite of the target orientation) were considered imprecise. In this way, precise and imprecise trials could be considered as correct and incorrect responses, respectively. Examining precise and imprecise ERP amplitudes for each condition would lead to insufficient trial numbers per condition (8 conditions x 2 sides = 16 ERP bins; ~ 30-40 trials per bin). To avoid this problem, precise and imprecise ERP amplitudes were averaged over each manipulated variable (Mask Condition or Set Size). This led to two separate analyses that focused on the effect of Mask Condition and Set Size on the eSPCN and lSPCN respectively.

**Precision by mask condition.** Considering that the main effect of Mask Condition was only significant for the eSPCN in previous analyses, only the eSPCN was
examined in the following analyses. First, a repeated measures ANOVA between Precision (precise or imprecise) and Laterality (contralateral or ipsilateral) was conducted for the unmasked and masked conditions separately (see contralateral and ipsilateral waveforms in Figure 11). This analysis was done to ensure that an eSPCN was being elicited in all conditions, as Prime and colleagues (2011) previously found that the SPCN was not statistically significant in masked/incorrect trials, as well as in unmasked/correct trials.

![Figure 11. Contralateral and ipsilateral waveforms for the grand average of 7 posterior channel pairs in the (a) unmasked, imprecise, (b) unmasked, precise, (c) masked, imprecise, and (d) masked, precise conditions.](image)

In the unmasked condition there was a main effect of Laterality, $F(1,19) = 9.50$, $p = .006$, partial $\eta^2 = .333$, and there was not a significant interaction between Laterality and Precision, $F(1,19) = 2.13$, $p = .161$, partial $\eta^2 = .101$. This denotes that an eSPCN was
present in the unmasked condition irrespective of response precision. In the masked condition there was also a significant main effect of Laterality, $F(1, 19) = 19.25, p < .001$, partial $\eta^2 = .503$, and no interaction between Laterality and Precision, $F(1, 19) = 1.86, p = .189$, partial $\eta^2 = .089$. Once again, these results show that the eSPCN was present in the masked condition, irrespective of response precision.

For the difference waveform, a Mask Condition (2) x Precision (2) repeated measures ANOVA was conducted at the grand average for the eSPCN. There was a main effect of Mask Condition when looking at the grand average, $F(1, 19) = 5.501, p = .030$, partial $\eta^2 = .225$ (see Figure 12) with a larger eSPCN for masked trials than for unmasked trials. This is consistent with previous findings. There was no main effect of Precision, $F(1, 19) = 2.80, p = .111$, partial $\eta^2 = .128$, or a Mask by Precision interaction, $F(1, 19) = .108, p = .746$, partial $\eta^2 = .006$. 
Figure 12. Grand average ERP waveforms measured at seven posterior channel pairs. Lines represent four conditions split by precision (precise or imprecise) and mask (unmasked or masked).

To further explore the effect of response precision on the eSPCN, each channel pair of interest was analyzed separately. It was found that at channel pair P7/P8, there was a main effect of Mask, $F(1,19) = 6.15, p = .023$, partial $\eta^2 = .244$, and a main effect of Precision, $F(1,19) = 4.86, p = .040$, partial $\eta^2 = .204$. The interaction was not significant, $F(1,19) = .136, p = .716$, partial $\eta^2 = .007$. This means that Mask Condition and Precision were exerting separate effects on eSPCN amplitude at this channel pair, such that greater precision and the mask both increase eSPCN amplitude (see Discussion for further explanation).
**Precision by set size.** As the effect of Set Size was significant for the ISPCN in previous analyses, only the ISPCN for the Precision by Set Size analysis was analyzed. First, to determine whether an ISPCN was present in all conditions irrespective of response precision, a repeated-measures ANOVA was conducted with Laterality (contralateral or ipsilateral) and Precision (2 x 2) separately for set size 2 and set size 4 (see Figure 13 for contralateral and ipsilateral waveforms). For set size 2 there was a significant main effect of Laterality, $F(1,19) = 13.58, p = .002$, partial $\eta^2 = .417$, but the interaction between Laterality and Precision was not significant, $F(1,19) = .361, p = .555$, partial $\eta^2 = .019$. Accordingly, at set size 4 there was a main effect of Laterality, $F(1,19) = 29.83, p < .001$, partial $\eta^2 = .611$, and no interaction between Laterality and Precision, $F(1,19) = 3.20, p = .090$, partial $\eta^2 = .144$. These results indicate that at both set size 2 and set size 4 an ISPCN was present when either precise or imprecise responses were made.
Figure 13. Contralateral and ipsilateral waveforms for the grand average of 7 posterior channel pairs in the (a) set size 2, imprecise, (b) set size 2, precise, (c) set size 4, imprecise, and (d) set size 4, precise conditions.

For the difference waveform, a repeated-measures 2 (Set Size) x 2 (Precision) ANOVA was conducted on the ISPCN at all channel pairs of interest. At the grand average, there was a main effect of Set Size, $F(1,19) = 21.17, p < .001$, partial $\eta^2 = .527$, and a marginal main effect of Precision, $F(1,19) = 3.35, p = .083$, partial $\eta^2 = .150$. The interaction was not significant, $F(1,19) = .498, p = .489$, partial $\eta^2 = .026$, (see Figure 14).
Figure 14. Grand average ERP waveforms measured at seven posterior channel pairs. Lines represent conditions split by precision (precise or imprecise) and set size (2 or 4).

At channel pair PO7/PO8 there was a main effect of Precision, $F(1,19) = 4.534, p = .047$, partial $\eta^2 = 0.193$, and a significant main effect of Set Size, $F(1,19) = 18.85, p < .001$, partial $\eta^2 = .498$ (see Figure 15). The interaction term was not significant, $F(1,19) = .204, p = .657$, partial $\eta^2 = .011$. This indicates that larger set sizes and more precise responses both increase ISPCN amplitude, and that these effects are independent from one another.
**Figure 15.** Grand average ERP waveforms measured at channel pair PO7/PO8. Lines represent conditions split by precision (precise or imprecise) and set size (2 or 4).

**Discussion**

A comprehensive model of the effect of object-substitution masking on attention, awareness, and visual representational quality has yet to be identified. The current study aimed to address this paucity of research by examining behavioural and electrophysiological responses to manipulations of set size and masking, as well as the corresponding effects of these manipulations on the quality of subsequently reported representations in an OSM task. It was found that set size, masking, and behavioural precision had different effects on each ERP component of interest, and that these effects did not interact with one another. Of particular interest, all three variables affected the amplitude of the SPCN component at different latencies. These findings contradict previous studies, which find that the SPCN is only affected by VWM load. The current
study provides evidence that these two components reflect multiple processes occurring over time related to attentional selection, visual awareness, VWM maintenance, and the quality of visual representations held in memory.

**Behavioural effects.** The behavioural results showed that both set size and mask condition had a significant effect on all parameter estimates obtained from the three-component mixture model analysis. Set size had the expected effect on all parameter estimates, mainly decreasing performance at set size 4 compared to set size 2, (i.e., greater guess rate, non-target error rate, standard deviation, response error and lower overall target rate). The mask had the same effect on performance, with the masked condition decreasing performance as compared to the unmasked condition. Importantly, the results found by Harrison, Rajsic, and Wilson (2015) were replicated, in that the mask increased estimates of SD (decreased precision).

Both manipulations interacted with one another such that there was a greater effect of mask condition at set size 4 than set size 2 for guess rate, non-target error rate, and target rate. However, there was not a significant interaction for SD or raw response error. This indicates that set size and mask condition exert separate effects on response precision. Larger set sizes and masking decrease the quality with which items reach awareness, but do so independently of one another. If the manipulations have separate effects on behaviour, then it is possible that they also exert separate effects on the ERPs of interest, and that these effects can be traced back to report precision.

**Early and late SPCN.** In the current study, the effect of the set size and mask manipulations had separate effects on SPCN amplitude depending on which time period was examined. The time course of the two effects could be clearly delineated upon
examining the grand average plot of all posterior channel pairs of interest (see Figure 5), and there were statistically separate effects of the manipulations at the two time points (see Figure 6). Therefore, all of the ERP analyses were conducted after the post hoc decision to separate the SPCN into an early (350 - 500 ms) and late (500 - 650 ms) component.

The underlying functions that these separate components reflect was explored through examination of the literature. Several studies have discovered a similar split in SPCN amplitude, with effects that are present early in the delay period but disappear by a later time point. To the best of my knowledge, all of these findings were gleaned from post hoc analyses. For example, Luria and Vogel (2011) examined the process of object binding in VWM as reflected by the SPCN. The most important comparison was between the maintenance of a one-coloured object (i.e. a yellow square) and an object consisting of a colour-colour conjunction (i.e. a blue and yellow square). They found a conjunction cost for the SPCN during the early interval (450-600 ms), which dissipated during the late interval (750-1000 ms)\(^1\). This means that the SPCN amplitude was greater for the bi-coloured square than for the one-coloured square only during the first 150 ms of the retention interval.

These results were interpreted from a feature-integration standpoint (Treisman, 1988), wherein binding two colours into one object is believed to be an attentionally demanding process that takes time to complete. Thus, the change in SPCN amplitude

\(^1\) Upon comparing the present results with the previous literature, it is apparent that the timing of the early and late components of the current SPCN have a much earlier latency. This discrepancy is most likely due to timing differences between the present and previous studies. As the current study had a shorter stimuli presentation and delay period than the previous studies, this led to an overall earlier SPCN latency. However, the duration of these two components are comparable between all studies (150-250 ms each).
across the delay period for the bi-coloured stimulus was interpreted to reflect an “evolving VWM representation” (Luria & Vogel, p.10) across the early and late intervals. These results are consistent with a two-stage model of object binding (Braet & Humphreys, 2009; Luria & Vogel, 2011), which posits that weakly bound features in the early retention interval are later fully bound by spatial attention into a single object (Hyun, Woodman, & Luck, 2009).

Similarly, Peterson and colleagues (2015, Experiment 2) separately examined an early (400 – 600 ms) and late (800 – 1000 ms) SPCN in a task examining the Gestalt grouping cue of uniform connectedness (Palmer & Rock, 1994). They found that the benefit related to the grouping cue (as reflected by a smaller SPCN amplitude in the grouped compared to the ungrouped condition) did not emerge until the later period of the retention interval. Once again, the authors interpreted this as a result of binding processes in VWM, which require time and attention to be completed successfully. That is to say, it takes time to use the grouping cue to store multiple objects as one, which is reflected by decreased SPCN amplitude (i.e., fewer items stored in VWM).

A similar interpretation can be applied to the present findings, wherein multiple stages are required to successfully resolve the target representation when presented with the mask. The successful binding (or unbinding) of target and mask may be first reliant on sufficient attention (Di Lollo et al., 2000; Hyun et al., 2009), as reflected by the N2pc. Next, it is necessary to resolve the conflict between target and mask (eSPCN), followed by maintaining the target representation in VWM (lSPCN). The two stages related to object binding might arise in the time period of the early and late SPCN, such that the early stage is required to bind the target representation into one object and the late stage...
reflects maintenance of the target in memory for later report. This model of OSM is speculative, as it was not directly tested through experimental manipulation in the current design. However, future research may benefit from incorporating a two-stage model of OSM processing into experimental designs. This would allow for a better understanding of how targets are successfully encoded and maintained despite being visually masked.

**ERPs and set size.** It was found that the manipulation of set size had a statistically significant effect on two of the ERP components of interest: the N2pc and the lSPCN. A set size of four items led to greater amplitudes for both of these components than a set size of two. The finding that the N2pc amplitude was greater for larger set sizes is consistent with previous studies which have found that increasing the difficulty of target discrimination increases N2pc amplitude (Luck & Hillyard, 1994; Luck et al., 1997). When there are more distractors on the screen, it makes it more difficult to perceptually localize the target item, therefore increasing the mean N2pc amplitude (Mazza et al., 2009). This may be due to a greater need for target enhancement when more distractors are present, especially when fine discriminations about a target feature (i.e., orientation) are required to complete the task successfully (Mazza et al., 2009). Therefore, in the current study the N2pc seems to reflect attentional selection of an item amongst distractors.

Results for the lSPCN were also consistent with previous research on the effect of set size on SPCN/CDA amplitude (Ikkai et al., 2010; Luck & Vogel, 2013; McCollough et al., 2007). The larger the set size, the greater the lSPCN amplitude, reflecting a greater amount of information stored in VWM (Emrich et al., 2009; Ikkai et al., 2010). However, the present findings differ from previous research in that the current set size manipulation
was not a manipulation of VWM load (i.e. how many items one is told to hold in memory). Instead, if participants were successfully completing the task they should only hold one item in memory: the target. Therefore, the observed difference in lSPCN amplitude between set size 2 and 4 indicates that participants may have been holding more information in VWM than necessary. This would indicate that lSPCN amplitude would correlate with the amount of items held in VWM. The more distractors held in memory, the more non-target errors a participant would be expected to make. However, a consistent pattern of correlations between lSPCN amplitude and non-target error rate was not observed. It is possible that the mixture model analysis is not a sensitive enough behavioural measure to reveal significant relationships with electrophysiological activity (van den Berg & Ma, 2014). It is also likely that multiple processes, such as decision-making, occur between the maintenance and report stages of the task; these additional cognitive processes could dampen the relation between neural activity and behavioural performance. In sum, in the current study the lSPCN reflects set size/load related activity during VWM maintenance.

**ERPs and masking.** The mask manipulation only had a significant effect on the eSPCN amplitude. There was greater amplitude for masked as compared to unmasked targets. This finding is opposite to what was predicted; because it is more likely that the target will reach awareness in the unmasked condition, it was hypothesized that the SPCN amplitude would be greater (i.e. more negative) in the unmasked condition, regardless of accuracy. Therefore, because the opposite was found for the eSPCN component, it is proposed that processes related to resolving the mask itself are causing the differences in amplitude and not differences in target awareness.
It is possible that the differences observed in eSPCN amplitude between masked and unmasked conditions were due to sensory differences regarding the longer duration of the mask on the screen in the masked condition (i.e. mask present for 300 ms longer in masked condition or the mask offset during this interval). To rule out this possibility, there was a visual examination of the contralateral and ipsilateral waveforms for all conditions. The mask seemed to have a similar effect on both the contralateral and ipsilateral channels (Figure 4). Therefore, after computing the difference waves by subtracting the contralateral minus ipsilateral waveforms, any differences arising due to sensory processing of the mask should be eliminated. Consequently, the difference waves should represent only the cognitive processes related to the side of the screen on which the task was completed.

To examine which cognitive processes this difference in amplitude may represent, there were a series of correlations between individual participants’ eSPCN amplitudes and behaviour. However, there were no consistent correlations between either overall amplitude, the difference in ERP magnitude (i.e. masked minus unmasked eSPCN amplitude) and behaviour as measured by the three-component mixture model. The lack of significant correlations makes it difficult to conclude what the activity over the time period of the eSPCN is reflecting. Perhaps because this activity is occurring early in the delay period, the processes occurring in the later delay period subsequently wash out any effect the eSPCN may have had on behaviour.

As the activity over the time period of the eSPCN did not correlate with the current behavioural measures, any interpretation of the processes it reflects is speculative. As previously stated, this time period could reflect encoding processes related to
resolving the conflict between mask and target representations; in particular, processes related to binding the mask and target into one object. This is consistent with explanations of OSM as an object-level phenomenon, wherein the brain treats the mask and target as one object: the mask alone (Goodhew et al., 2011; Goodhew et al., 2014; Lleras & Moore, 2003). In the masked condition, successful binding may require additional attention to override the object updating process, which results in a representation of the mask alone in successful masking. Fittingly, participants were on average 62% accurate (target rate) on the masked trials, indicating that they were correctly overriding the object updating process on the majority of trials. Therefore, this process may be reflected in the grand average ERP waveforms as greater amplitude over the time period of the eSPCN for the masked condition. Additional evidence for this binding process is provided by the analyses of the eSPCN by response precision, wherein the masked/precise trials elicit greater amplitude than the masked/imprecise trials. This interpretation will be expanded upon in the following sections.

Response precision and masking. ERPs were also examined by precision of responses averaged over set size or mask condition. For the effect of mask and precision, only the eSPCN component was analyzed because it was the only component that demonstrated a significant effect of mask. In accordance with the overall ERP waveforms, the masked condition had greater eSPCN amplitude than the unmasked condition. Additionally, when segmented by precision of response, the eSPCN amplitude was greater for precise than imprecise trials. This second finding is consistent with the original hypothesis for the SPCN: that SPCN amplitude would be greater towards targets that reached awareness (i.e. reported precisely) as compared to successfully masked
targets (i.e. reported imprecisely). This is also consistent with previous research demonstrating that the SPCN has greater amplitude towards items that reach awareness (Harris et al., 2013; Pun et al., 2012). When one is aware of an item, more information is held in VWM, which is subsequently reflected by greater SPCN amplitude.

The main effect of response precision did not interact with mask condition, denoting that precision was having the same or a similar effect in both the unmasked and masked conditions. This finding is consistent with the proposed binding process that may occur during the time period of the eSPCN. In the masked/precise condition, more attention may be required to override the object updating process, which usually results in a representation of the mask alone. This could be another explanation for why the amplitude of the eSPCN is greater for the masked/precise trials than for the masked/imprecise trials.

Overall, these findings are novel in that the SPCN amplitude was found to not only reflect binary distinctions of awareness (i.e. hits versus misses, correct versus incorrect), but also the precision of responses. Future studies would benefit from employing a continuous report examination of awareness and examining varying levels of precision.

Response precision and set size. For the effect of set size and precision, only the lSPCN component was analyzed as the eSPCN showed no main effect of set size. There was a significant main effect of set size and precision. As discussed previously, the effect of set size is consistent with the SPCN literature, which has shown that SPCN amplitude increases as more items are held in VWM (see Luck & Vogel, 2013 for a review).
However, the present findings are novel in demonstrating that both set size and response precision are reflected by the SPCN.

For the eSPCN, there was also greater amplitude for precise responses than imprecise responses. This is likely reflecting the greater amount of information held in VWM when having made a precise response. Precision had a similar effect on lSPCN amplitude regardless of set size. These findings provide evidence that both the eSPCN and the lSPCN are related to variation in behavioural precision.

**Limitations and future directions.**

The current study is limited by several factors. First, it has been argued that summary statistics obtained from the mixture model analysis may not be as reliable as raw data (van den Berg & Ma, 2014). This may be why there were not many significant correlations between behaviour and ERP amplitudes, as the parameters obtained by the mixture model could be too coarse. In the current study, raw error was also examined and similar results were obtained as the correlations between ERP amplitudes and SD. In this case, raw hit or miss responses may have stronger correlations with ERP amplitudes, more so than the parameter estimates or raw error.

Second, multiple non-independent variables were manipulated in this study, leading to possible interactions between their effects on the ERPs. The study design made it difficult to tease apart the exact effect of each manipulation on the ERP amplitudes. Future studies would benefit from examining each underlying hypothesis (i.e. binding hypothesis) in a more controlled setting, such as varying the time of mask offset to manipulate binding difficulty. Finally, the current study is only applicable to one type of visual masking: object-substitution masking. The same effects on N2pc and SPCN
amplitude may not be seen in different types of masking paradigms, such as meta-
contrast or backwards masking. Therefore, future studies should focus on expanding the
current manipulations to other forms of visual masking to see if the findings are
replicable.

**Conclusion**

The current study was an investigation into the role of attention and awareness on
behavioural and electrophysiological measures of these processes during OSM. This
study differs from previous studies examining neural measures of OSM in that both set
size and mask were manipulated to tease apart their separate effects on the N2pc and
SPCN. As well, participants were asked to make continuous report judgments of target
orientation, allowing for an examination of visual representational quality and its relation
to neural effects. It was found that set size, mask, and response precision all have separate
effects on N2pc and SPCN amplitude. The results indicate that the N2pc reflects
processes related to attentional selection of a target item amongst multiple distractors. In
contrast, the SPCN component had temporally distinct effects of the manipulations in the
early and late time periods. The eSPCN amplitude varied systematically with changes in
mask, with greater amplitudes toward masked than unmasked items, indicating that the
early portion of the SPCN may reflect binding or encoding processes in VWM. The
lSPCN was affected by changes in set size, possibly reflecting changes in VWM
maintenance with increasing load. Additionally, both the set size and masking
manipulations affected response precision, which was reflected by the early and late
SPCN components. There was greater amplitude towards precise than imprecise
responses. In contrast to previous studies concerning SPCN function, the current findings
show that the SPCN reflects more than VWM load and is instead affected by a multitude of factors, such as visual awareness, VWM load, and representational precision.

Future studies would benefit from examining the early and late portions of the SPCN separately to better understand the temporally evolving nature of visual representations held in VWM. The present findings have important implications for the underlying function of the SPCN and its temporal nature, which has been often neglected in electrophysiological studies of VWM. As well, these findings provide evidence that behavioural precision has an effect on ERP waveforms that are thought to reflect visual awareness. In sum, the present results provide evidence that the N2pc component reflects attentional selection, whereas the SPCN component reflects multiple aspects of holding and manipulating information in VWM. Although previous research on SPCN function suggests that it is solely a measure of VWM capacity, the current results implicate that it reflects multiple VWM processes, such as encoding, binding, maintenance, and representational precision.
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Appendix A – Eligibility Phone Interview

Phone-Interview Script

“Hi, this is (insert name) calling from the (Brock Visual Cognitive Neuroscience Lab/Brock Face Perception Lab).

I’m calling you today because you’ve expressed interest in participating in one of our studies. Before I can schedule you for participation, I would like to tell you a bit more about the experiment, as well as ask you a few questions to make sure that you qualify.

As a participant in this study, you will be asked to respond to visual stimuli presented on a computer screen while undergoing electroencephalography (EEG). EEG is a non-invasive electrophysiological recording device that allows us to record the electrical activity from your brain indirectly via your scalp. In order to record this activity, an electrode cap will be placed on your head, and small amounts of gel placed on your head/in your hair. The cap will be held in place by an elasticized strap below your chin. Additional recording electrodes will also be placed around your eyes to measure eye-movements and eye-blinks. During the computerized tasks, you will also be asked to make judgments (i.e., button responses, mouse movements) in response to simple visual features (e.g., colours, lines) and/or faces. You may also be required to hold these visual stimuli in memory for short time periods and recall them after a short delay. Because this experiment involves differentiating colours, we will also perform a short test to assess your colour vision. Participation will take approximately 2 - 3 hours, and you will be given frequent breaks during the tasks (~ every 5 – 10 minutes). For your time we will reimburse you $15/hour ($7.50/half hour) or 1 research credit/hour (0.5 credits/half hour).

Do you have any questions about this procedure?

Would you still be interested in participating?”

If no:

“Thank you for your time. I will be sure to destroy your contact information so that we do not contact you in the future.”

If Yes:

“OK, great! Before I schedule you for an appointment, I need to ask you a few questions to make sure that you qualify. These questions will assess whether you fit with in the population we are interested in for this study. Please know that these answers will be kept confidential, and if you do not qualify for the study or choose not to participate, your answers will be destroyed and no record will be kept.”
ATTENTION, AWARENESS, AND OBJECT-SUBSTITUTION MASKING

QUESTIONS

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<tr>
<td>1.</td>
<td>How old are you?</td>
</tr>
<tr>
<td>2.</td>
<td>Are you right handed?</td>
</tr>
<tr>
<td>3.</td>
<td>Do you have any condition that might affect the nervous system? (e.g. multiple sclerosis, epilepsy, fibromyalgia) Yes No</td>
</tr>
<tr>
<td>4.</td>
<td>Have you ever had any serious psychiatric difficulties or mental-health issues? (e.g., Schizophrenia, clinical depression, ADHD) Yes No</td>
</tr>
<tr>
<td>5.</td>
<td>Have you ever had a head injury/ concussion/ loss of consciousness? -If yes, record details. Yes No</td>
</tr>
<tr>
<td>6.</td>
<td>Do you have hair extensions, braids or temporary hair dye? Yes No</td>
</tr>
</tbody>
</table>

If “yes” is answered to any of these questions:

“Thank you very much for your information. Unfortunately, based on your responses I’m afraid you do not fit within the population we are interested in studying for this particular experiment. I will be sure to delete these emails, as well as your contact information, in order to ensure that this information remains confidential. Thank you very much for your time. If you have any further questions you can feel free to contact Dr Emrich/Dr Mondloch at (provide phone number and extension).”

If “no” is answered to all of the questions:

“Thank you very much for your information. It appears based on these answers that you fit our criteria for the population we are interesting in studying for this experiment. Are you still interested in participating?”

If yes, schedule appointment.
Appendix B – Lateralized Change Detection Task Design and Figure

Following the eye fixation training, behavioural estimates of VWM capacity were estimated using a colour change detection task. The change detection task was a lateralized version of the whole report change detection task as described by Luck and Vogel (1997) (Figure A1). Participants were first cued to one side of the screen by an arrow for 200 ms. This was the side of the screen that they were told to pay attention to for the following trial. Next, they were presented with an array of 2, 4, or 6 uniquely coloured squares for 500 ms. These squares were placed in random positions on a 3 x 2 grid. The minimum distance from fixation to the center of the square was 2 visual degrees, while the maximum distance was 4 degrees. Participants were told to hold this information over a 1000 ms delay period in which only the fixation dot was shown. Following this delay, the same number of squares reappeared on the screen. One of the squares may have changed colour, or the colours could have remained the same. Participants responded with the 's’ key if the display was the same, or the ‘d’ key if the test display was different from the memory array. The inter-trial interval lasted 500 ms.

This task consisted of 150 trials and took approximately 10 minutes to complete. Behavioural results from this test allowed for calculations of the K-estimate (Pashler, 1988). Pashler’s K is a number which represents the approximate capacity of VWM and is calculated by the formula: $K = \text{Set Size} \times (\text{Hits} - \text{False Alarms})$. The highest value from all set size calculations is considered the estimate of the individual’s VWM capacity, and this number can be correlated with performance on other tasks, as well as with ERP amplitudes (i.e., Vogel & Machizawa, 2004).
Figure A1. Lateralized change detection task design. Participants respond with the s key if the test array was the same as the memory array or the d key if it was different.
Appendix C – Research Ethics Board Study Approval

Brock University
Research Ethics Office
Tel: 905-688-5550 ext. 3035
Email: reb@brocku.ca

Bioscience Research Ethics Board

Certificate of Ethics Clearance for Human Participant Research

DATE: 7/27/2015

PRINCIPAL INVESTIGATOR: EMRICH, Stephen - Psychology

FILE: 13-272 - EMRICH

TYPE: Faculty Research

TITLE: Electrophysiological measures of selection and storage for features and faces

ETHICS CLEARANCE GRANTED

<table>
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<th>Initial Clearance Date: 7/30/2014</th>
<th>Expiry Date: 7/29/2016</th>
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Initial Clearance Date: 7/30/2014
Expiry Date: 7/29/2016

The Brock University Bioscience Research Ethics Board has reviewed the above named research proposal and considers the procedures, as described by the applicant, to conform to the University's ethical standards and the Tri-Council Policy Statement.


The Tri-Council Policy Statement requires that ongoing research be monitored by, at a minimum, an annual report. Should your project extend beyond the expiry date, you are required to submit a Renewal form before 7/29/2016. Continued clearance is contingent on timely submission of reports.

To comply with the Tri-Council Policy Statement, you must also submit a final report upon completion of your project. All report forms can be found on the Research Ethics web page at http://www.brocku.ca/research/policies-and-forms/research-forms.

In addition, throughout your research, you must report promptly to the REB:

a) Changes increasing the risk to the participant(s) and/or affecting significantly the conduct of the study;

b) All adverse and/or unanticipated experiences or events that may have real or potential unfavourable implications for participants;

c) New information that may adversely affect the safety of the participants or the conduct of the study;

d) Any changes in your source of funding or new funding to a previously unfunded project.

We wish you success with your research.

Approved:

______________________________
Sandra Peters, Chair
Bioscience Research Ethics Board

Note: Brock University is accountable for the research carried out in its own jurisdiction or under its auspices and may refuse certain research even though the REB has found it ethically acceptable.

If research participants are in the care of a health facility, at a school, or other institution or community organization, it is the responsibility of the Principal Investigator to ensure that the ethical guidelines and clearance of those facilities or institutions are obtained and filed with the REB prior to the initiation of research at that site.
Appendix D – Consent Form

INFORMED CONSENT

Date: August 1, 2015
Project title: Electrophysiological measures of selection and storage for features and faces.

Principle Investigators (PI):
Dr. Stephen M. Emrich, Assistant Professor
Department of Psychology
(905) 688-5550 ext. 6181
semrich@brocku.ca

Dr. Cathy Mondloch, Professor
Department of Psychology
(905) 688-5550 ext. 5111
cmondloch@brocku.ca

INVITATION
You are invited to participate in a research study being conducted in the Visual Cognitive Neuroscience Lab and the Face Perception Lab at Brock University. The purpose of this study is to examine the neural mechanisms involved in the perception, short-term memory and attentional selection of simple features and faces.

WHAT’S INVOLVED
As a participant, you will be asked to respond to visual stimuli presented on a computer screen while undergoing electroencephalography (EEG). EEG is a non-invasive electrophysiological recording device that allows us to record the electrical activity from your brain indirectly via your scalp. In order to record this activity, an electrode cap will be placed on your head, and small amounts of gel placed on your head/in your hair. The cap will be held in place by an elasticized strap below your chin. Additional recording electrodes will also be placed around your eyes to measure eye-movements and eye-blinks. During the computerized tasks, you will also be asked to make judgments (i.e., button responses, mouse movements) in response to simple visual features (e.g., colours, lines) and/or faces. You may also be required to hold these visual stimuli in memory for short time periods and recall them after a short delay. Because this experiment involves differentiating colours, we will also perform a short test to assess your colour vision. Participation will take approximately 2 - 3 hours, and you will be given frequent breaks during the tasks (~ every 5 – 10 minutes).

POTENTIAL RISKS AND BENEFITS
Participation in this research will help advance our understanding of how the human brain processes visual information. In addition, for your time you can either receive (a) credit (0.5 credit hours/30 minutes) for experiment participation as part of a requirement for courses at Brock University, such as PSYC 1F90 (where applicable), OR (b) a remuneration of $15/hour (i.e., $7.50 for every 30 minutes).

There are no known or anticipated risks associated with participation in this study.

CONFIDENTIALITY
All of the information provided in this study will be identified by an arbitrary participant number and will not be linked to your identity, in any way.
Data collected during this study will be stored in the laboratory of Dr. Stephen Emrich or Dr. Cathy Mondloch. Only researchers in these laboratories will have access to these materials. Data will be kept for 10 years following publication, after which time the electronic files will be erased and paper copies will be shredded.

**VOLUNTARY PARTICIPATION**

Participation in this study is voluntary. If you wish, you may decline to answer any questions or participate in any component of the study. Further, you may decide to withdraw from this study at any time and may do so without any penalty or loss of benefits to which you are entitled. If you decide to withdraw from the study after beginning the computerized portion of the experiment, your data will be destroyed immediately. If you choose to withdraw after completion of the study you data cannot be destroyed because it will be identified with an anonymous participant number.

**PUBLICATION OF RESULTS**

Results of this study may be published in professional journals and presented at conferences. Feedback about this study will be available once the study is complete (estimated: August 2016) by contacting Dr. Stephen Emrich at the address or phone number listed at the top of this consent form. Only information about the results of the entire study will be available, not information on individual performance.

**CONTACT INFORMATION AND ETHICS CLEARANCE**

If you have any questions about this study or require further information, please contact Stephen Emrich or Cathy Mondloch using the contact information provided above. This study has been reviewed and received ethics clearance through the Research Ethics Board at Brock University (File # [13-272-1]). If you have any comments or concerns about your rights as a research participant, please contact the Research Ethics Office at (905) 688-5550 ext. 3035 or reb@brocku.ca

Thank you for your assistance in this project. Please keep a copy of this form for your records.

**CONSENT FORM**

I agree to participate in this study described above. I have made this decision based on the information I have read in the Information-Consent Letter. I have had the opportunity to receive any additional details I wanted about the study and understand that I may ask questions in the future. I understand that I may withdraw this consent at any time.

Name:

__________________________

Signature: __________________________ Date: __________________

Witnessed by:

Name:

__________________________

Signature: __________________________ Date: __________________
FEEDBACK
I would like to receive the summary of the research results. (check one): YES ________
NO ________

email address to send research summary to:
___________________________________________________

For participation in this experiment, I wish to receive:  Experiment Credit ________
Paid remuneration ________

Hours Participated: ____________  Credits/Reimbursement  Received: ________

Course to receive credit: __________________________________________

Experimenter Signature: __________________________________________
Date: __________