Title:

Awareness of visual events without concomitant spatiotopic information

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Abstract

To what extent does spatiotopic location accompany the representation of a visual event? Feature integration theory suggests that identifying a multi-feature object requires focus on its spatial location to integrate those features. Moreover, single unit data from neurons preferring complex objects, indicates that they have retinotopic receptive fields. It can therefore be predicted that identification of complex stimuli is contingent upon localization of their features by attention. To evaluate this, we presented participants with a brief array of characters with instructions to identify and locate the solitary letter. Surprisingly, subjects sometimes identified the target without knowing where it had been presented. However, when targets were marked by a single feature (color), there was no evidence of identifying the target without locating it also. These results indicate that consciously accessible representations of visual events can form despite being untethered to spatially specific neural activity in early visual areas.

Key words: visual binding, spatial location, visual search, awareness

Introduction

The ability to select information based on single features or combinations of features for further processing is a foundational ability of the visual system and understanding how information is localized in space is key for understanding selection. Previous studies indicate that feature maps in a pop-out search do not necessarily contain precise location information, as participants made frequent location errors while identifying a disjunctive feature. This implies that targets marked by a single feature are not necessarily bound to a location at the point of identification, which is a key facet of Feature integration theory (FIT; Treisman & Gelade, 1980). Furthermore, when attempting to rapidly perceive multiple items containing shape and color information, illusory conjunctions cause features to apparently migrate between different objects (Treisman & Shmidt, 1982) or appear spatially interposed between two nearby objects (Hazeltine et al, 1997). With respect to binding, however, Johnston and Pashler (1990) found that after adjusting for guesses, performance on identity when location is unknown and on location when identity is unknown is much lower (~10%) than what can be explained by Treisman's model and thus, the errors might be due to guessing/reporting artifacts. They concluded that after accounting for guesses, identification of a target defined by a single feature (e.g. color or shape) is tightly tied to successful localization of that item.

It is worth bearing in mind that there might not be one solution to the question of location and identity binding depending upon experimental factors such as stimulus type, exposure duration, familiarity, etc. As a result, we aim neither to support nor to refute the previous theories on the binding problem, but rather to better understand the common act of identifying a highly familiar, yet complex shape. On this point, VanRullen (2009) argued that two binding mechanisms coexist in the visual system. While arbitrary conjunctions (i.e. conjunctions that we do not have everyday experience with, such as finding a red disc amongst red squares and green discs) require focused attention to be perceived (named as on-demand binding), familiar conjunctions (e.g. natural scenes and familiar items) are recognized effortlessly through hardwired binding (i.e. patterns of brain connectivity resulting from experience) without requiring focused attention.

This account was necessary to explain the ability to discriminate complex objects without the obvious deployment of focal attention (Li, VanRullen, Koch & Petrona, 2002), a phenomenon that reveals the insufficiency of the FIT model to be generalized to all forms of visual identification.

There was no discussion about whether such hard-wired bindings require spatial localization, but insight into this question can be drawn from the properties of neurons in the visual system of monkeys. Finding neural activity that is position-invariant in the high levels of ventral stream (Gross, Bender & Rocha-Miranda, 1969) in conjunction with patient data regarding lesions of the visual system (Goodale, Milner, Jakobsen & Carey, 1991) promoted the theory of dichotomous operation of recognition of an object and its spatial position. However, studies on primates revealed that form-specific neurons in anterior inferotemporal cortex are also strongly sensitive to retinal position, meaning that form and location information are already bound together when these neurons are activated by their preferred stimulus (Dicarlo & Maunsell, 2002). Therefore, it may be expected that activation of a hard-wired binding sufficient to create a reportable visual percept for a highly familiar stimulus, such as a letter, automatically includes a representation of its specific location.

Moreover, theories on the neural mechanisms underlying conscious awareness of visual events typically posit that the early levels of the visual hierarchy play a key role in instigating and supporting the creation of a percept (Lamme, 2006; Roelfsema & Lange, 2016). These accounts add further support to the prediction that location information should always be part of a consciously accessible representation of a visual event.

Based on these findings and theories, we predicted that whenever people report the identity of a complex, highly familiar visual stimulus, they will also be capable of reporting its location. However, this was not the case. Subjects could identify familiar items (e.g. letters) in a brief display without having a sense of where they had been presented on about 1/3 of the trials with correct identity report, even after conservative corrections for guessing. This was a striking observation, as it suggested that location information was not always inherent in the mental representation of such items after they had been identified. Moreover, evidence for such location errors survived a correction for lucky guesses of identity.

The paradigm flashed arrays of stimuli on the screen and asked subjects to report a target letter among digits. Across several experiments that manipulated the set size and eccentricity of the array, failure in binding the target letter to its location was evident. The last experiment verified that such binding failures were not the result of the reporting method or forgetting by showing that such errors were not present when the target was marked by a color instead of its orthographic identity.

Experiment 1a

In the first experiment, we tested whether participants could report the location of a letter that they had previously identified.

Method

Participants: Twenty participants from the Pennsylvania State University undergraduate psychology subject pool received credits in exchange for participation. The sample size for each experiment was parameterized for the entire set of experiments before data collection, based on a compromise between the competing aims of finding robust effects, and being able to run multiple experiments to explore and replicate the effect. In initial pilot studies, a sample size of 20 participants was sufficient to show reliable evidence that location errors occur with a non-zero probability. The subjects were instructed in English and reported normal or corrected-to-normal visual acuity. The experimental design was approved by the IRB at Pennsylvania State University.

Apparatus: Participants were positioned on a chinrest 60 cm from a 17-inch, 1024 x 768 CRT monitor. Experiments were performed using Psychtoolbox 3 (Kleiner et. al. 2007) in MATLAB (build 2012b) operating on windows XP. Responses were made using a computer keyboard or a mouse depending on the task.

Stimuli and procedure. As shown in Figure 1, a fixation cross appeared in the center of a gray (127,127,127 in RGB) screen at the beginning of each of 96 trials. After a varied time interval (700-1000 ms), stimuli (height = $.86^\circ$) consisting of one letter chosen randomly from a set of capitalized letters (R, L, C, P, F, K, B, G, Y, V, H, X, T, J, D) and five digits (2-9) evenly spaced on a hypothetical circle (diameter = 4.54° visual angle) were presented for ~ 53 ms and then followed by hash-mark masks (height = 1.05°) for 100 ms. Participants were asked to report the identity of the letter by typing one of the 26 letters on the keyboard and the location of the letter by pressing a number from 1 to 6 that corresponded to the target location. The task did not impose speed pressure and subjects were allowed to use backspace to correct their responses. The order of the questions was randomized and counterbalanced during the experiment. Each experiment began with 7 slow trials that became progressively faster, from 1 sec to 100 ms stimuli presentation. These trials were excluded from the analysis.

Figure 1. A trial example for experiment 1a. A black fixation cross was presented for 700-1000 ms in the center of a gray background. Stimuli consisting of a letter and five digits were shown for roughly 53 ms and then masked for 100 ms. Participants were asked to report the letter and its location in each trial in random order.

Analysis

In the final analysis of each experiment, we measured accuracy and determined statistical significance using 95% confidence intervals estimated by a bootstrapping method with 500 resamples at the subject level.

Results

Accuracy for location report was 58% and for identity report was 70%, indicating that the task was challenging, but both were far above chance levels (Figure 2). Moreover, conditional probability of identity accuracy when location report was accurate was 86%, while location accuracy when identity was reported correctly was 71%. Thus, on 29% of trials, participants could report the identity of the letter without being able to report its location from among 6 locations.

Additional calculations, described in the supplementary materials, corrected for cases where the identity was presumably reported correctly with a lucky guess. From trials in which participants identified the letter successfully (observed value of 70%, of which 3% are likely to be lucky guesses, thus the estimate of true identification = 67.9%) they only reported the location accurately an estimated 68.3% of the time after further correction for location guesses. Thus,

from those trials with correct letter report, participants reported the wrong location an estimated 31.7% of the time, 95% bootstrapped CI[25%, 45%].

Figure 2. Experiment 1a results (i.e. Before correction for guesses). The first and third bars show the accuracy of identity and location respectively. The second bar depicts identity accuracy for trials in which participants correctly reported the target location. The last bar represents location accuracy for trials in which the target was correctly identified. Error bars represent standard errors and the horizontal dashed lines represent chance levels.

Experiment 1b

To test if the results were attainable when stimuli are presented farther in the visual periphery, we replicated experiment 1a with increased eccentricity.

Method

This experiment was identical to experiment 1a, except that the eccentricity was doubled (9.1° visual angle). A new set of 20 students was recruited.

Results

As represented in Figure 3 and Table 1, the results were consistent with the previous experiment. Identity accuracy was 63% and location accuracy was 49%. Conditional analyses revealed that identity accuracy was 73% when location was known, and location accuracy was 64% when identity was known.

From trials in which participants identified the target letter correctly (observed value of 62.7%, of which 4.3% are likely to be lucky guesses, estimated true value = 60%) they reported the correct location only an estimated 57% of the time after location guessing correction. This means that participants missed the location of target letters that they identified 38.6% of the time, 95% bootstrapped CI[38%, 48%].

Figure 3. Experiment 1b results (i.e. Before correction for guesses). Bars represent the same parameters as in Figure 2.

Experiments	Observed Identity Accuracy	Observed location accuracy given correct identification	Estimated location accuracy given correct identification after correction for location guesses	Estimated location accuracy given correct identification after correction for identity & location guesses	Estimated percentage of true location report errors
1a	70%	71%	65.2%	68.3%	31.7%
1b	62.7%	64.3%	57.2%	61.4%	38.6%

Table 1, Performance on identity and location in trials where identity had been reported successfully. The last column (numbers in bold) represents location report error rate in successful identity reports after correction for all guesses. Note that participants missed the location more than 30% of the time, even when they reported the target identity.

Discussion

Experiments 1a and 1b provided insight about the concurrence of location and identity binding for familiar target items, however, as location was constrained to six evenly spaced locations, it could not be determined if errors reflected a coarsely grained location representation or a more severe lack of location information. To define these terms for our purposes, precise location responses would be largely confined to the quarter of the circle that contained the target, coarse-grained responses would be largely confined to the half of the circle that contained the target, and uninformed responses would be essentially uninformed by the target's location.

One way to evaluate the quality of location response errors with these data is to measure the frequency of responses for two locations adjacent to the target and two locations that are distant from the target in trials where the target identity was reported successfully but location was not. The data showed that these two sets of locations (adjacent and distant) had roughly the same response frequency, and both were substantially lower than the responses for the actual position

of the target (Experiment 1a and 1b respectively: adjacent : 14%, 16%; distant: 10.5%, 14%; accurate responses: 71%, 64.3%) This is suggestive that location reports are either precise or relatively uninformed with little evidence for a coarse-grained location representation that spans half of the display, since adjacent locations were selected only slightly more often than the distant locations. To more directly measure the quality of these location response errors, we devised experiments 2 and 3.

Experiment 2a

To measure location precision, the stimulus locations and response method were modified to a continuous form in which stimuli could occur at any location on a circle and participants chose a specific location with a mouse click.

Method

Keeping most parameters identical to Experiment 1b, stimuli were presented at random locations on an invisible circle and masked (Figure 4). We defined a minimum threshold for the distance between locations (1° of visual angle) of which two stimuli were not allowed to be closer. Participants reported the letter identity as before and reported location by moving the mouse cursor and clicking on a circle.

Figure 4. Experiment 2a trial example. Participants were asked both location and identity questions in each trial, but the question of identity has not been included in the figure. The white arrow indicates the mouse pointer that had to be clicked on the circle to complete a response.

Results

Participants successfully reported the target identity 48% of the time (of which 7.7% are likely to be lucky guesses such that the estimated number of true identifications is 44.3%). Figure 4 illustrates the spatial distribution of location reports relative to the target's true location. This distribution is characterized by a clear middle peak, and what looks like a uniform component. Probabilistic mixture modeling (Bays et al., 2009; Zhang & Luck 2008) was used to characterize the precision of location reports as distinct components. A two-parameter mixture model consisting of a Gaussian distribution centered at the target location and a uniform distribution corresponding to locations that are not presumably available in working memory was used. In the analysis, the K parameter represents precision (i.e. higher precision corresponds to higher K value and lower standard deviation) and pU represents the probability of responding with spatial

accuracy so poorly that it approaches a uniform distribution relative to the target's location. In this model fitting process, the K value was 30.86 (corresponding to a standard deviation (SD) of 10° of the 360° circle), CI[25.43%, 37.5%], and the pU component was 29.5%, CI[25.5%, 32.6%]. A correction for lucky guesses of identification can be applied, such that the true estimated proportion of times that subjects identified the target without knowing its location was 21.8%.

These results indicate that participants usually had a fairly precise memory of the location of the identified letter (i.e. standard deviation is low for that component of the mixture) but in over 20% of the trials, they were highly inaccurate in reporting its location. Note that it is difficult to be sure these are guesses, or extremely imprecise location estimates (Schurgin et al. 2018; Pratte 2018).

Figure 5. Data from Experiment 2a (i.e. Before correction for guesses). Histogram of location responses relative to the target (0 refers to target location in each trial) for trials in which participants could **correctly identify** the target (48% of trials, of which 7.7% are likely to be lucky guesses, estimated true value = 44.3%). Note that the polar histogram is in logarithmic scale to make the spatial distribution of the low-probability responses more visible.

Experiment 2b

To see how the number of stimuli changed participants' performance, we replicated experiment 2a with 8 stimuli.

Method

This experiment is similar to the previous experiment except that participants had to identify and localize a letter amongst 7 other distractors instead of 5.

Results

Participants reported the letter correctly 41% of the time. The results have been depicted in figure 5. The K value for correctly reported identities (observed value of 41% of which 10.3%

are likely to be lucky guesses, estimated true value = 36.8%) was 24.28 (SD = 11.46° from the 360° circle), CI[14.08%, 39.23%] and the pU was 43%, CI[35.6%, 48.7%]. Correcting for lucky guesses of identity produced an estimated pU of 32.7%. This suggests that the probability of responding with poor spatial accuracy increased when more stimuli were presented.

Figure 6. Data from Experiment 2b (i.e. Before correction for guesses). A histogram of location responses for **correctly identified** targets (41% of trials, of which 10.2% are likely to be lucky guesses estimated true value = 36.8%).

Experiment 3

One might argue that since the masks remained on the screen for 100 ms, participants used mask locations to anchor their memory of the target location. To avoid this confound, we conducted experiment 3 in which all possible locations on the circle were masked (figure 6).

Method

The only difference that distinguished Experiment 3 from 2b was that all locations were masked to prevent subjects from storing mask locations.

Figure 7. A trial example from Experiment 3 (There were 60 hash marks in the actual display).

Results

In this experiment, participants reported the letter identity correctly 41% of the time (10.3% are likely to be lucky guesses, estimated true value = 36.8%)¹. Location estimates from the correct report trials are shown in Figure 7. The K value for successful identity reports dropped to 9.94 (SD = 18.6° from the 360° circle), CI[7.09, 13.4], nevertheless, this is still a reasonably precise memory of target location with nearly all of the central mass within less than 90 degrees. The pU was 34%, CI[26.5%, 38.7%] in this task. Correcting for correct guesses of identity produces an estimated pU of 23.7%.

These results show that even without masks as location anchors, the location of an identified letter is either represented with a fair degree of precision or had very poor spatial information.

Figure 8. Data from Experiment 3 (i.e. Before correction for guesses). A histogram of location responses for **correctly identified** targets (41% of trials, of which 10.2% are likely to be lucky guesses, estimated true value = 36.8%).

Experiment 4

So far, it has been observed that location information is not always available in the mental representation of an identified letter. This deficit may reflect a loss of location due to the rapid stimulus display and the method of responding. We were interested to know if the same results would be obtained when a single feature (e.g. color) marks the target and its location. To address this, the paradigm was changed so that all of the stimuli were letters, and the target letter was red in color.

Method

¹ Note that this value happens to match that of Experiment 2b precisely by chance.

This experiment is similar to experiment 3 with the following changes: Stimuli were one red letter (target) and seven black letters (distractors). Masks were hash marks comprised of two black and two red lines (Figure 8). Participants were instructed to report the identity and location of the red letter.

Figure 8. A trial example of Experiment 4 (There were 34 hash marks in the actual display).

Results

Identity was successfully reported 27% of the time (19.3% are likely to be lucky guesses, true value = 21.8%) The K value was 19.84 (SD = 13 ° from the 360° circle), CI[7.09, 13.4] and pU was 16%, CI[11, 19.7] for correctly identified letters (Figure 10). The pU that mixture model estimated for successful letter identification was only 16%. Given that 19% of correct reports were likely to be lucky guesses, there is no evidence that they were not aware of the location of the identified letter, since the estimated proportion of pU responses was only 16%. This result shows that the failure of location report is not a consequence of the rapid presentation format. The results of experiments 2, 3 and 4 have been summarized in Table 2.

Figure 10. Data from Experiment 4 (i.e. Before correction for guesses). A histogram of location responses for **correctly identified** targets (27% of trials, of which 19.3% are likely to be lucky guesses, estimated true value = 21.8%).

Experiments	Identity Accuracy (%)	Location errors Given correct identification (pU%)	Estimated location errors Given correct identification after correction for identity guesses (%)
2a	48%	29.5%	21.7%
2b	41%	43%	32.7%
3	41%	34%	23.7%
4	27%	16%	0%

Table 2. Data from experiments 2a, 2b, 3 and 4. The last column shows the location guessing rate for correct identity reports, after correction for all guesses. As it is evident, participants missed the target location more than 20% of the time on trials in which they successfully identified the letter (except in Experiment 4, where the target was denoted by color).

General Discussion

The first experiments (1a & 1b) suggested that participants reported the wrong location of a target about 30% of the time after a guessing correction, but it did not allow us to measure the quality of such location errors. Experiments 2 and 3 used a modified procedure and a two-parameter mixture modeling to measure the magnitude of location errors. We found that in cases where people identified the letter, they either had a precise representation (corresponding to the K component) or a very poor representation of the target 's location.

One hypothesis in cases where participants missed the location of the identified target might be that, focal attention was deployed to extract target identity, but there was no encoding of that location information in memory. This implies that encoding of location information is not a necessary consequent of focal attention, which is possible, since attention and memory are distinct processes. Another hypothesis could be that on some trials, the target was identified without the aid of focal attention. The latter is in line with the hardwired binding model (VanRullen, 2009), which obviates focal attention for binding features of familiar/natural conjunctions.

In the last experiment (4), however, there was no evidence of identification without localization, a finding that is particularly strong, since identification was harder in this experiment compared to the letter-digit experiments. The consequent lack of location errors, highlights a key difference between the processing of targets indicated by simple features that can be processed at earlier levels of the visual hierarchy, and targets indicated by more complex conjunctions that are discriminated by later levels. Namely, it seems possible to activate a high-level representation of a complex, familiar stimulus without a corresponding link to its spatial location. This presumably

happens because the ultra-rapid masking in our study interrupts the processing at earlier levels, before a binding between higher-level and lower-level representations can be established. This idea of needing to link higher and lower level representations to maintain a sense of stimulus location is in line with the Selective Tuning model of Tsotsos (2002), which presents a formalized account of recurrent binding processes in the ventral visual pathway.

On the other hand, identification without a clear sense of location is harder to reconcile with the location-specific representations found in monkey inferotemporal cortex (Dicarlo & Maunsell 2002; Beeck & Vogels, 2000). In those studies, single neurons with highly-specific shape preferences also had highly specific retinotopic specificity as well. The findings here suggest that a reportable form of awareness (i.e. report accuracy clearly above chance level in a forced choice discrimination; Cheesman & Merikle, 1984) can be formed in response to a visual event without including even the uppermost tiers of the visual hierarchy.

These results also have clear implications for our understanding of the formation of conscious mental events. In previous work, it has been suggested that visual stimuli exceeding a particular threshold of activation are able to recruit a recurrent circuit that links lower-level visual areas with a broad distribution of other cortical areas (Lamme & Roelfsema, 2000). However, in cases where identity can be remembered without location, it seems that stimuli can rise to the level of awareness without being anchored by the lower level representations that exist in strongly retinotopic cortical areas. Such visually evoked representations can seemingly exist in a free-floating form that is untethered to a spatial reference. This finding does not invalidate previous theories regarding the neural correlates of awareness, but it changes our understanding of how far recurrence must penetrate into the visual hierarchy to support awareness. The implication is that information evoked by the stimulus can evoke representations that are almost purely conceptual/semantic, shedding any location-specific information in the process.

Acknowledgments:

The authors would like to thank Chloe Callahan-Flintoft, Ryan O'Donnell and undergraduate research assistants in Wyble lab. This work was supported by the NSF grant 1734220.

Authors Contributions:

SH did the programming, data analysis, writing and conceptualization. BW helped with analysis, interpretation and writing.

Data Availability:

All the experiments, results and analysis are available at <https://osf.io/sqn6x/>

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Supplementary Materials:

Supplemental 1: Guessing correction formulas

To ensure that the observed failures to report location of identified targets were not the result of lucky guesses of identity, a correction for possible guessing was applied, and the result was subtracted from the observed proportions of trials to produce estimates of the proportions of trials in which subjects correctly perceived either identity or location. Note that the essential conclusion is also supported by the uncorrected results. The guessing procedure is conservative with respect to our claim, in that it reduces the proportion of trials in which identity was reported without location.

Guessing correction procedure for identity for all experiments:

Step 1: true value of identity accuracy was calculated for all experiments as follows

$$Observed_Value = Est_True_Value + Chance_level (1 - Est_True_Value)$$

Where *Observed_Value* is the observed identity accuracy, *Est_True_Value* is the estimation of the percentage of trials in which the subjects successfully identified the target. *Chance_level* is the chance of responding correctly on trials in which they had not perceived the target and were guessing at random using a conservative ratio ($1/15$). Note that subjects did not know the number of letters used in the experiment. Therefore, $1/26$ is probably a more likely guessing baseline, but $1/15$ is more conservative as it increases the chance that any correct identity report was a lucky guess.

Step 2: Calculation of what percentage of the observed value results from lucky guesses

$$Lucky_guesses = \frac{Observed_Value - Est_True_Value}{Observed_Value}$$

This proportion of lucky guesses was calculated and then subtracted from the estimated proportion of guessing responses in experiments 2a, 2b, 3 and 4.

Guessing correction for location (For experiments 1a and 1b):

Since location report errors were discrete in experiments 1a and 1b rather than estimated distributions, a different procedure for corrections was used to correct for guesses for location responses where identity was successfully reported. We present this second as it is more complex and harder to understand.

Step 1: Calculate location accuracy conditional on correct report of identity

Step 2: Correct this value for location guesses

$$\begin{aligned} &Obs_Location_Given_Identity_Accuracy \\ &= Est_True_Value_of_Location + \left(\frac{1}{6}\right) (1 - Est_True_Value_of_Location) \end{aligned}$$

Step 3: Calculation of identity lucky guesses

$$Obs_Identity_Accuracy = Est_True_Value + \left(\frac{1}{15}\right)(1 - Est_True_Value)$$

$$Lucky_identity_guesses = \frac{Obs_Identity_Accuracy - Est_True_Value}{Obs_Identity_Accuracy}$$

Step 4: subtract *Lucky_identity_guesses* from *Location_Given_Identity_Accuracy* to estimate corrected location accuracy

$$\begin{aligned} &Location_Given_Identity_Accuracy_corrected = \\ &Obs_Location_Given_Identity_Accuracy - Lucky_identity_guesses \end{aligned}$$