Two items remembered as precisely as one: How integral features can improve visual working memory

Journal:	*Psychological Science*
Manuscript ID:	PSCI-12-2275
Manuscript Type:	Research article
Date Submitted by the Author:	22-Oct-2012

Complete List of Authors:	Bae, Gi Yeul; Johns Hopkins University, Psychological and Brain Sciences Flombaum, Jonathan; Johns Hopkins University, Psychological and Brain Sciences

Keywords:	Visual Memory, Short Term Memory, Size Discrimination, Auditory Perception

Two items remembered as precisely as one: How integral features can improve visual working memory

Gi Yeul Bae & Jonathan I. Flombaum
The Johns Hopkins University

Address for correspondence:
Gi Yeul Bae or Jonathan Flombaum
Department of Psychological and Brain Sciences
Johns Hopkins University
Ames Hall / 3400 N. Charles Street
Baltimore, MD 21218
gbae1@jhu.edu / flombaum@jhu.edu

Running Head: Integral features in VWM
Key words: Visual working memory, integral / separable features
Word count: Abstract (149); Body text (3,990); 28 references
Draft: Submitted to *Psychological Science* 10.22.12

Abstract

An ongoing debate concerns the limits of visual working memory for more than three items. But a consensus has emerged around the idea that a continuous commodity limits precision for three or fewer. Across many studies, memory precision appears worse for two items compared to only one. Here we challenge this consensus. We argue that memory for two items only appears less precise than memory for one because two items present observers with a correspondence challenge —the need to relate observations to their corresponding memory representations. The challenge does not arise when only one item is stored. In three experiments we prevent correspondence errors in two item trials by varying sample items along task irrelevant, but integral (as opposed to separable) dimensions. (Initial experiments with a classic sorting paradigm identified integral feature relationships). In three memory experiments, our manipulation produced equally precise representations of two items as of one.

Introduction

Despite its importance for a variety of human behaviors, visual working memory (VWM) appears severely limited. For a long time, researchers hypothesized that at least some of these limits are caused by an upper bound on the total number of objects the system can store, sometimes referred to as a 'magic number' of about four objects (Cowan, 2001; Luck & Vogel, 1997; Sperling, 1960). Recently, some have questioned the presence of a discrete limit, arguing instead that VWM is continuously limited by a dynamically distributed commodity (Bays & Husain, 2008; van den Berg, Shin, George, & Ma, 2012; Wilken & Ma, 2004). This commodity is thought to constrain the resolution with which objects and their features are stored. A vigorous debate surrounds these issues. But whether or not there is an upper bound on memory capacity, there appears to be consensus around the idea that within hypothesized bounds, working memory is continuously limited (Brady, Konkle, & Alveraz, 2011; Fukuda, Awh, & Vogel, 2010). Indeed, the severity of working memory limits are perhaps best reflected by the fact that even remembering just two things is harder than remembering one. Across a wide array of stimuli and experiments the precision of each of two items simultaneously held in memory appears lower than the precision of a single item (Anderson, Vogel, & Awh, 2011; Alveraz & Cavanagh, 2004; Bays, Catalao, & Husain, 2009; Bays & Husain, 2008; Wilken & Ma, 2004; Zhang & Luck, 2008).

In the current study, we challenge the consensus opinion that declines in precision for two items compared to one result from competition for a limited memory commodity. Instead we observe that a specific computational challenge plagues memory for two items but not for one, namely, a correspondence challenge. In order to use a memory to make a judgment about a presently viewed object (e.g. Luck & Vogel, 1997; Bays & Husain, 2008), an observer must determine which stored memories correspond to the observed object. Similarly, in order to use a memory to report the features of a cued object (e.g. Zhang & Luck, 2009; van den Berg et al., 2011), an observer must determine which stored memory a cue corresponds with. But if only one object is stored in memory, then no such computation is necessary. We suggest that, in fact, the precision of two objects in memory is no worse than the precision of one object in memory. Instead, in experiments with two objects, participants make correspondence errors, and those errors have been interpreted as reflecting declining precision.

If correspondence errors account for apparent costs associated with remembering two memory items compared to one, then costs should be eliminated when correspondence errors are prevented (Bae et al., under review; Bae & Flombaum, 2012). To test this prediction, we sought a method that would support observers when making correspondence decisions. Logically, observers should use 'task irrelevant' features of objects to make correspondence decisions, since these are the features that usually do not change between a memory display and a probe display. In other words, observers should anchor correspondence decisions to stable features of the world, exactly the features that researchers often conceive of as task irrelevant. But in most working memory experiments, supposedly task irrelevant features are either identical among all memory items (e.g. they are all the same shape when color is the target)—providing no basis for correspondence decisions— or they are different along separable dimensions (e.g. shape is separable from color)— providing a problematic basis for correspondences because of known feature binding challenges (Treisman & Schmidt, 1982). Thus our goal was to design memory displays in which sample items differed along a stable feature dimension that could provide a sound basis for correspondence judgments.

To supply a reliable basis for correspondence judgments, we found inspiration in prior research that characterizes the ways that features combine in perception, work focusing on a distinction between integral and separable features. (Garner,1974; Garner & Felfoldy, 1970). Integral features are those that can be manipulated independently by vision scientists, but are not perceived independently by observers —luminance and hue, for example. Because they are not perceived independently, we hypothesized that adding integral feature distinctions to VWM stimuli would supply a reliable basis for correspondence judgments, thus erasing costs associated with remembering two compared to one. We tested this hypothesis in memory experiments for three different features: the luminance of two objects when they possessed the same hue (e.g. both were a version of red) or different hues (e.g. red and green); the sizes of two objects when they were either the same shape or different shapes; and in an auditory memory experiment, the amplitudes of two tones when they were either the same frequency or different frequencies. Hue and luminance are integral features, as are size and shape, and amplitude and frequency. We predicted equal performance for two items compared to one when the two items in memory comprised different integral feature values. Additionally, to validate the specific integral features employed, we conducted a conceptual replication of classic sorting experiments by Garner and Felfoldy (1970).

Experiments 1 and 2: Sorting integral features

To independently identify integral feature dimensions in vision we conceptually replicated a now classic experiment by Garner and Felfoldy (1970). We created a computer version of a sorting task (Figure 1) that requires comparing objects on the basis of a feature dimension. In Experiment 1, three colored squares with different luminance values were presented simultaneously on a computer screen and participants were asked to find the brightest and second brightest ones. Crucially, the three colored squares could be from the same hue family or from different hue families. We predicted that performance with items sharing a hue would be better than with items from different hue families because hue and luminance are integral features. This was the logic underlying Garner's experiments. Experiment 2 applied the same logic to size and shape. Participants were instructed to identify the smallest and then the second smallest item, by area, in a set of three. The items were either all the same shape, or they were each a different shape. We expected worse performance in the sets comprising different shapes.

<u>Method</u>

Participants. Two groups of 10 Johns Hopkins undergraduates participated in exchange for course credit. One group participated in the luminance sorting experiment, and the other participated in the size sorting experiment. All had normal or corrected-to-normal visual acuity. The protocols for these and all other reported experiments were approved by the Johns Hopkins University IRB.

Apparatus & Stimuli. Participants sat 60 cm from an iMAC computer such that the display subtended approximately 39.56° by 25.35°. Stimuli used in the experiments are shown in Figure 1. The lights were turned off during testing.

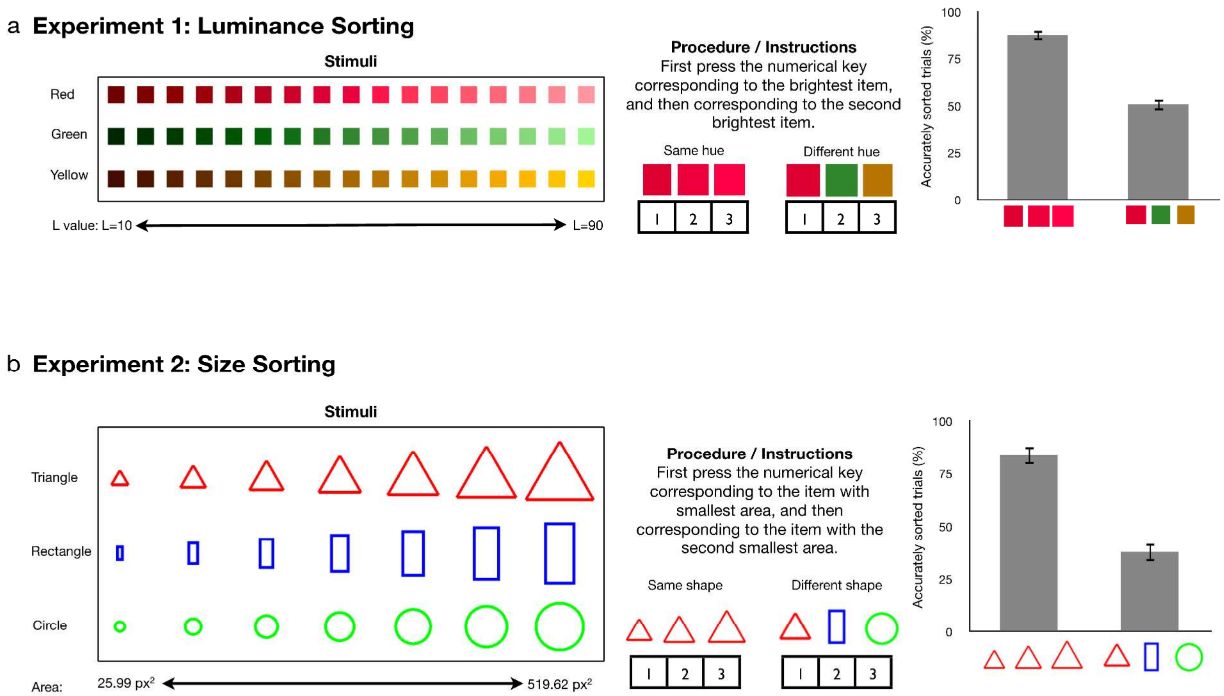

Figure 1. Experimental design and results for the luminance (a) and size (b) sorting experiments. a. A set of 51 colored chips were generated with 17 possible luminance values in CIE L*a*b color space (L values between 10 and 90, in steps of 5). Hue families were defined by a and b L*a*b coordinates (Red: a = 80, b = 38; Green: a = -40, b = 38; Yellow: a = 20, b = 98). Within a column, stimuli shared the same L (luminance) value. On each trial, from this set of 51 possible colors, 3 were selected and presented in a random order horizontally at the center of a black screen. In half of trials, colors were selected from the same hue family (e.g. reds in the case shown), and the other half involved an item from each of the 3 hue families. Regardless of the composition of the stimulus set, the task was to sort the presented items from brightest to darkest by pressing keys corresponding to the numbers under each item. (Numbers shown in the figure were not presented in the display; but participants learned during practice that 1 through 3 designated left to right). Accuracy was measured as the percentage of trials correctly sorted. b. Identical procedures were employed in the size sorting experiment, except here, three shapes were used. The task was to sort stimuli from the one occupying the smallest area to the one occupying the largest area. Objects in each column occupied equal area. Error bars reflect ±1 S.E. of the mean.

Procedure. On each luminance sorting trial, 3 colored squares were picked from a set of 51 possibilities (Figure 1a). On half of trials, all the colors presented were from the same hue family, and in the other half, each item was a different hue. In all trials, the three squares varied in luminance via the L coordinate in L*a*b space. They were positioned horizontally in a random order. A participant's task was to pick the brightest and then second brightest by pressing numerical keys corresponding to their positions on the screen.

An identical procedure was employed in the size sorting experiment (Figure 1b). Three objects with either the same shape different shapes were presented horizontally. Participants were tasked with picking the smallest and then the second smallest item by area. Each experiment included 120 trials and 10 practice trials.

Results and Discussion

Proportions of accurately sorted trials are shown in Figure 1. Luminance sorting performance was worse when the items were from different hue families, $t(9) = 8.90$, $p < .05$, $d = 3.04$. Similarly, size sorting performance was worse for differently shaped items, $t(9) = 12.48$, $p < .05$ $d = 3.73$.

These results evidence what is perhaps a cardinal rule of perception: that it is often more than the sum of its parts. Features that are independently controllable by vision scientists may not combine independently (or separably, as Garner put it). For current purposes, the consequent point is that it can be challenging to compare objects along one dimension when they are different along another, seemingly irrelevant, but integral dimension. We exploit this fact in the forthcoming memory experiments.

Experiments 3 and 4: Preventing memory errors with integral features

Armed with specific knowledge about dimensions that are integral, and with the knowledge that differences in one integral dimension can render challenging comparisons along another, we sought to prevent correspondence problems in a working memory experiment. The logic was as follows. We employed a basic feature-judgment working memory task (e.g. Bays & Husain, 2008). An observer is instructed to remember, for example, the luminance of either one item or two. At test, a single probe item appears, and the observer must compare its luminance to that of the corresponding memory item. In a two item trial, if the items share the same hue family, our main point is that a correspondence error can take place. The observer may compare the probe to the wrong memory item, potentially leading to an erroneous task response (and leading to worse performance in two item trials compared to one). In contrast, what might happen if the two objects differ along an integral dimension? Though observers may generally make correspondence errors, we know from Experiments 1 and 2 that mistaken correspondences should, in this situation, lead to difficult and unintuitive comparisons: e.g. which is brighter, the green one I see or the red one I remember? The unintuitive nature of the comparison could potentially lead an observer to realize (not necessarily explicitly), that she has made a correspondence mistake, and the observer may then address the task comparison to the correct memory item instead.

Thus we predicted that two items would be remembered as precisely as one when the two items differed along an 'irrelevant,' but integral feature dimension. When they shared the same feature value along that dimension, however, we predicted typical costs for two compared to one. Based on the results of Experiments 1 and 2, we tested these predictions in the cases of memory for luminance, with objects that differed (or not) in hue, and in memory for size, with objects that differed (or not) in shape.

<u>Method</u>

Participants. A new group Johns Hopkins undergraduates participated, 10 in Experiment 3 and 10 in Experiment 4. All participants had normal or corrected-to-normal visual acuity.

Apparatus, stimuli, & procedure. Apparatus and stimuli were identical to those used in the sorting experiment. Experimental procedures are depicted in Figure 2. In the luminance experiment (Experiment 3, Figure 2a), one or two squares were presented in random positions around a central fixation. Each square was assigned one from 17 possible luminance values. Additionally, each square was assigned a hue (i.e. it was drawn from one of the 3 rows in Figure 1a). There were two kinds of two item trials. In the *Same Integral Feature* trials, both squares possessed the same hue. In *Different Integral Feature* trials, they each possessed a different hue. Participants were asked to memorize the luminance of

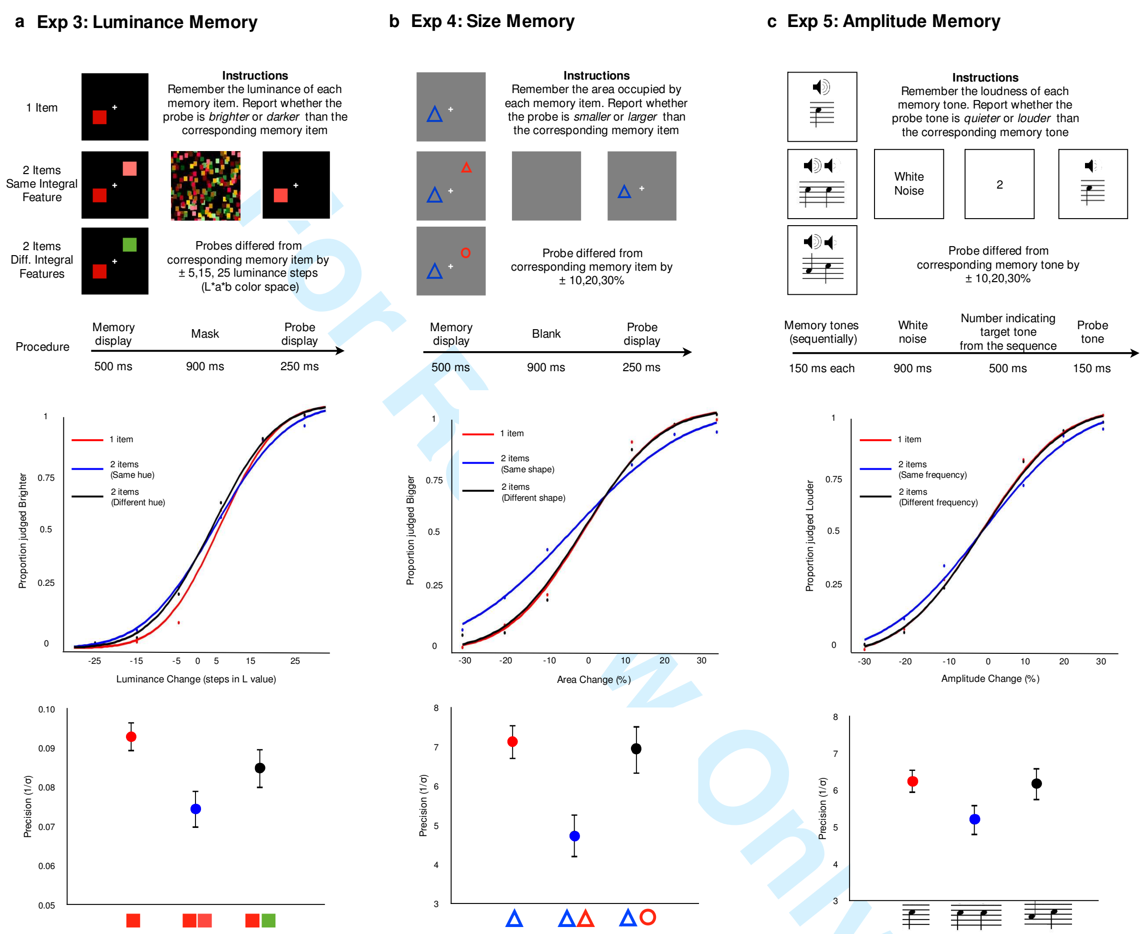

Figure 2. Experimental procedures (top row), estimated response functions (middle row), and estimated precisions (bottom row) for each condition of each memory experiment a. Luminance judgment task. One or two items from stimuli set used in the luminance sorting experiment were used as sample items. Response functions (middle) were estimated in terms of the probability of a brighter response as a function of the magnitude of luminance change. Bottom row plots reciprocals of standard deviations of estimated functions. b. Size judgment task. One or two items from the stimuli set in Experiment 2 (size sorting) were used. Estimated response functions and reciprocals of their standard deviations shown in the middle and the bottom rows c. Amplitude judgment task. Amplitudes were normalized to a range of 0 to 1. One or two tones with amplitude ranging between 0.4 and 0.7 were presented sequentially followed by white noise The probe tone was 10, 20, or 30 % louder or softer than its correspondent. Estimated response functions and reciprocals of standard deviations shown in the middle and the bottom row. Error bars reflect ±1 S.E.

each item. After a brief mask display, a probe item appeared in the same position as one of the corresponding memory items. Participants judged whether the probe was darker or brighter than its correspondent. A probe differed from its corresponding memory item by ± 5, 15, or 25 L value steps. There were 432 trials plus 10 practice trials.

The size memory experiment (Experiment 4, Figure 2b) was nearly identical to Experiment 3, except as follows. Memory objects were circles and triangles used in Experiment 2. *Same Integral Feature* trials included two objects with the same shape. *Different Integral Feature* trials included two different shapes. The objects were always different colors (i.e. red and blue). One item trials included either a circle or a triangle. The task was to remember the area occupied by each item. After a short blank, a probe item appeared at the same position as a corresponding memory item. The size of a probe was ± 10, 20, or 30% relative to the corresponding memory item. Participants made a keypress to indicate whether the probe item was larger or smaller than the corresponding memory item. There were 216 trials plus 10 practice trials.

Note that in Experiment 3 a probe always possessed the same hue as its corresponding memory item, and that in Experiment 4 a probe always possessed the shape as its corresponding memory item.

Analysis. In order to compare the quality of memory representations, we used a probit regression model to fit psychometric functions in each memory load and integral feature condition (Figure 2, middle of each panel). The reciprocal of the standard deviation of these estimated functions (plotted in the lower portion of each panel of figure 2) was regarded as reflecting the precision of memory representations (Bays & Husain, 2008; Palmer, 1990).

Results and Discussion

Figure 2 graphs the response functions obtained from each experimental condition, and estimates of representational precision derived from these functions. Overall, there were significant effect of condition: luminance experiment $x^2(2) = 15.8$, $p < .001$, $d = 3.97$; size experiment, $x^2(2) = 26.4$, $p < .001$, $d = 5.13$. Planned comparisons explored differences between one item trials and the two kinds of two item trials. For both luminance and size, a typical cost arose for remembering two items compared to one when the two items shared an integral feature value (hue or shape). Statistically, these cost are seen in the significant difference between the estimated standard deviations of the response functions for the relevant experimental conditions: luminance, $z = -3.892$; size $z = -4.357$; $p < .001$ for both. These costs were eliminated for two items compared to one when the two items included different integral features: luminance $z = -1.62$; size $z = 0.32$; $p > .1$ for both. Representational precision was also significantly better in the different integral feature two item conditions compared to the same integral feature conditions: luminance, $\chi^2(1) = 5.5$, $p = .019$, $d = 2.34$; size $\chi^2(1) = 16.6$, $p < .001$, $d = 4.07$.

These results are consistent with the prediction that preventing correspondence errors eliminates VWM costs for two objects compared to one. In the typical case —that is, when the objects share integral feature values— we used a standard approach to evidence costs by comparing estimated response function standard deviations, a measure thought to reflect representational precision. But the point is that these increases in standard deviation do not reflect bona fide changes in precision; instead, they reflect an incidence of correspondence errors in trials with two items, whereas in trials with one no such errors can take place.

Experiment 5: Integral features in auditory working memory

To demonstrate the generality of the results in Experiments 3 and 4, we extended our manipulation to an auditory working memory experiment. A classic set of integral auditory features are amplitude and frequency (Garner, 1976 ; Wood, 1975). Accordingly, in our memory experiment, participants were asked to remember the amplitude (loudness) of either one tone, or two tones played serially. When two tones were played, they possessed either the same frequency as one another, or different frequencies. A test tone was then judged as louder or softer than the corresponding memory tone (which was cued by an Arabic numeral referring to either the first or the second one heard). We predicted that with identical frequencies, there would be a memory cost for remembering the amplitude of two tones compared to one. But with different frequencies, we predicted that no such cost would arise.

Method

Participants. A new group of 12 Johns Hopkins undergraduates participated.

Apparatus, stimuli, & procedure. Auditory stimuli were delivered in stereo through headphones (Peltor aviation head set model: 7050).

The procedure is depicted in Figure 2c. On each trial, one or two pure tones of either 220 Hz or 400 Hz were played. In two item trials, the tones were separated by a 500 ms blank screen and a 150 ms burst of white noise. The amplitudes of the tones were chosen randomly from the range of 57.1 dB to 64.6 dB, with a minimum difference of 1.25 dB. Participants were instructed to remember the 'loudness' of each tone. After a second burst of white noise (in two item trials), a 1 or 2 was displayed indicating which tone from the sequence to compare with the upcoming probe. The probe tone was then played. It always had the same frequency as its correspondent, but varied in amplitude by ± 10, 20, or 30%. Participants judged whether a probe's amplitude was softer or louder than its correspondent. In half of the two item trials, the two memory tones had the same frequency. In the other half one was 220 Hz and the other was 400 Hz. There were 216 trials plus 10 practice trials.

Results and Discussion

Estimated response functions and precision for each condition and set size are depicted in Figure 2c. Experimental condition had a significant effect on precision, $x^2(2) = 8.0$, $p = .018$, $d = 2.83$. Planned comparisons revealed that precision for remembering the amplitudes of two items was significantly lower than for one when they shared the same frequency, $z = -2.478$, $p = .013$; but this cost was eliminated when they possessed different frequencies, $z = -0.165$, $p > .05$). Again, in the to item trials, precision in the different frequency condition was significantly better than in same frequency condition, $x^2(1) = 5.4$, $p = .02$, $d = 2.32$. As in Experiments 3 and 4, two items were remembered as precisely as one when the items differed along a task irrelevant, but integral feature dimension.

General Discussion

We investigated the quality of VWM for two items compared to one in situations where the two memory items differed or not along a task irrelevant, but integral feature dimension. To identify integral dimensions, Experiments 1 and 2 adapted a paradigm by Garner & Felfoldy (1970), and demonstrated that differences in one integral feature dimension can produce a challenge for comparing items along another integral dimension. Exploiting this fact, we employed a common VWM experiment that relies on comparisons between a memory and a probe item at test. In Experiments 3-5, the probe and the test item always shared the same integral feature value. The critical manipulation involved the integral feature value of an untested memory item in two item trials. When the two memory items shared the same integral feature value, we observed an apparent and typical decline in memory quality compared to trials with only a single memory item. But when the two memory items possessed different integral values, we did not observe declines in performance.

We emphasize that regardless of the exact cause of this improvement, this is, to our knowledge, the only of many recent studies to eliminate entirely a memory cost for two items compared to one (Bays&Husain, 2008; van den Berg, 2012; Zhang&Luck,2008; but see Bae et al., under review). The presence of such a cost is a critical prediction of both flexible-resource (Bays & Husain, 2008; van den Berg et al., 2012) and hybrid-resource theories (Alvarez and Cavanagh, 2004; Anderson, Vogel, & Awh, 2011) of VWM. Indeed, according to such theories, the quality of two items in memory should always be roughly half that of a single item. It is important that although the memory items differed along an integral dimension, it was unknown to participants which would be probed, *and the same feature of each item had to be remembered* (i.e., luminance, size, or amplitude). Thus the effects cannot be explained in terms of different pools of resources dedicated to the storage of different features. Instead, any account of these results must address the integral feature similarities and dissimilarities among the items in the memory displays.

We have supplied one such account, leveraging the fact that two item trials usually present observers with a correspondence problem, though one item trials do not. We hypothesized that differences along an integral feature dimension would prevent attendant correspondence errors by supplying observers with a reliable and salient anchor for correspondence decisions. In general, any theory which acknowledges noisy or probabilistic representations of object features must also acknowledge that correspondence computations are necessary for retrieving a memory, though the mechanisms underlying these computations are rarely discussed (but see Bae et al., under review; Levillain & Flombaum, 2012).

There is a second potential account of these results, also appealing to correspondence challenges and errors, but during perception as opposed to during test. Specifically, researchers often conceive of perception and encoding into memory as the noisy sampling of features from images (Girshick, Landy, Simoncelli, 2011; Vul, Hanus, & Kanwisher, 2009; Vul & Rich, 2010). On this end, so to speak, there also exists a correspondence challenge, but only when more than one item is present. After drawing a sample with some feature content, an observer needs to assign a correspondence between the feature and one of the objects believed to be in the image. But because the samples are noisy —because an observer should possess uncertainty about where exactly in time and space a sample came from— there is a risk of correspondence errors. Indeed, this exact explanation has recently been offered to account for well-known feature binding challenges (Treisman & Schmidt, 1982; Vul & Rich, 2010**)**. Of course, there is no feature binding challenge in one item displays. Thus typical costs associated with remembering two items compared to one may reflect correspondence errors during encoding, instances during which stray samples influence the inferred properties of an object. And in turn, integral feature differences in the current experiments may have prevented such sampling-related correspondence errors by making it more clear when pairs of samples arose from independent sources in the world.

Neurally, explaining the reported results in terms of how integral features may prevent correspondence errors requires mechanisms that represent integral feature combinations. Recent fMRI research suggests one such potential mechanism, that neurons can be tuned to conjunctions of features. Integral features then, are those for which neurons reflect joint preferences, while separable features are those for which pairs of neurons represent conjunctions (Drucker, Kerr, & Aguire, 2009). In the related experiments, changing an object along only one integral feature dimension evoked a smaller, and non-linear recovery from adaptation relative to changing two integral feature dimensions. This supplies evidence of signals in the brain that could support the identification of correspondences between probe objects and memory representations on the basis of integral feature relationships.

Finally, we emphasize that what is perhaps most surprising about the reported results is that memory performance *improved* when memory displays were made *more complicated*, when *more information* was added. In Experiment 4, memory performance was better when displays included a triangle and a circle, for example, as opposed to two triangles. Yet, one could more efficiently summarize the contents of two triangle displays. Redundancy in these scenes should have drawn down less memory resources than the varied displays. We therefore accounted for the performance observed not in terms of memory resources and storage, but instead, in terms of correspondence computations that must be involved in encoding and retrieving contents to and from memory. In general, research has focused almost exclusively on the nature of VWM resources and storage, to the exclusion of the computations that must be involved in acquiring and using information. As we have shown here, accounting for such computations —and the errors that they may induce— can lead to the realization that storage limitations are less severe than they may initially seem. VWM resources appear at least ample enough to afford as precise representations of two items as of just one. But computations deciding between multiple options naturally become more error prone as the number of options increases (see also, Duncan, 1980; Navon, 1984).

References

Alvarez, G. A., & Cavanagh, P. (2004). The capacity of visual short-term memory is set both by visual information load and by number of objects. *Psychological Science*, *15*, 106-111.

Anderson,D.E., Vogel,E.K.,& Awh, E. (2011). Precision in visual working memory reaches a plateau when individual item-limits are exceeded.*Journal of Neuroscience*, *31*, 1128-1138.

Bae, G.Y. & Flombum, J. (2012). Close encounters of the distracting kind: Identifying the cause of visual tracking errors. *Attention, Perception, & Psychophysics*, *74*, 703-715.

Bae, G.Y., Wilson, C., Holland, P.C., & Flombaum, J. (under review). Correspondence computations limit spatial working memory.

Bays, P. M. & Husain, M. (2008). Dynamic shifts of limited working memory resources in human vision. *Science*, *321*, 851-854

Bays, P. M., Catalo, R. F. G. & Husain, M. (2009). The precision of visual working memory is set by allocation of a shared resource. *Journal of Vision*, *9*, 1-11.

Brady, T. F., Konkle, T, and Alvarez, G.A. (2011). A review of visual memory capacity: Beyond individual items and towards structured representations. *Journal of Vision*, *11*, 1-34.

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, *24*, 87-185.

Drucker, D.M., Kerr, W.T., & Aguirre, G.K. (2009). Distinguishing conjoint and independent neural tuning for stimulus features with fMRI adaptation. *Journal of Neurophysiology*, *101*, 3310-3324.

Duncan, J. (1980). The demonstration of capacity limitation. *Cognitive Psychology, 12,* 75-96.

Fukuda, K., Awh, E., & Vogel, E.K. (2010). Discrete capacity limits in visual working memory.*Current Opinion in Neurobiology*, *20*,177-182.

Garner, W.R. (1974). *The processing of information and structure*, Wiley, New

York.

Garner, W.R. (1976). Interaction of stimulus dimensions in concepts and choice processes. *Cognitive Psychology*, *8*, 98-123.

Garner, W.R, & Felfoldy, G.L. (1970). Integrality of stimulus dimensions in various types of information processing. *Cognitive Psychology*, *1*, 225-241.

Girshick, A.R., Landy, M.S., Simoncelli, E.P. (2011). Cardinal rules: visual orientation perception reflects knowledge of environmental statistics. *Nature Neuroscience*, *14*, 926-932.

Levillain, F. & Flombaum, J. (2012). Correspondence problems cause repositioning costs in visual working memory. *Visual Cognition*, *20*, 669-695.

Luck, S.J., & Vogel, E.K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*, 279-281.

Navon, D. (1984). Resources-A theoretical soup stone? *Psychological Review*,*91*, 216-234

Palmer, J. (1990). Attentional limits on the perception and memory of visual information. *Journal of Experimental Psychology: Human Perception and Performance*, *16*, 332-350.

Spering, G. (1960). The information available in brief visual presentations. *Psychological Monographs*, *74*,1-29

Treisman, A. & Schmidt, H. (1982). Illusory conjunctions in the perception of objects. *Cognitive Psychology*, *14*, 107-141.

Wood, C.C. (1975). Auditory and phonetic levels of processing in speech perception: neurophysiological and information-processing analyses. *Journal of Experimental Psychology: Human Perception and Performance*, *104*, 3-20.

Wheeler, M.E. & Treisman, A.M. (2002). Binding in short-term memory. *Journal of Experimental Psychology: General*, *131*,48-64.

Wilken, P. & Ma, W. J. (2004). A detection theory of change detection. *Journal of*

Vision, *4*, 1120-1135.

Van den Berg, R., Shin, H., Chou, W., George, R., & Ma, W.J. (2012). Variability in encoding precision accounts for visual short-term memory limitations. *Proceedings of the National Academy of Sciences*, *109*, 8780-8785.

Vul, E., Hanus, D., & Kanwisher, N. (2009). Attention as inference: Selection is probabilistic; Responses are all-or-none samples. Journal of Experimental Psychology: General, 138, 546-560.

Vul, E. & Rich, A.N. (2010). Independent sampling of feature enables conscious perception of bound objects. *Psychological Sciences*, *21*, 1168-1175.

Zhang, W. & Luck, S. J.(2008). Discrete fixed-resolution representations in visual working memory. *Nature*, *453*, 233-235.