Prior Experience Alters the Appearance of Blurry Object Borders

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Abstract
Object memories activated by borders serve as priors for figure assignment: figures are more likely to be perceived on the side of a border where a well-known object is sketched. Do object memories also affect the *appearance* of object borders? Memories represent past experience with objects; memories of well-known objects include many with sharp borders because they are often fixated. We investigated whether object memories affect appearance by testing whether blurry borders appear sharper when they are contours of well-known objects versus matched novel objects. Participants viewed blurry versions of one familiar and one novel stimulus simultaneously for 180ms; then made comparative (Exp. 1) or equality judgments regarding perceived blur (Exps. 2-4). For equivalent levels of blur, the borders of well-known objects appeared sharper than those of novel objects. These results extend evidence for the influence of past experience to object *appearance,* consistent with dynamic interactive models of perception.

Studies of vision demonstrate that bottom-up processes are not sufficient for understanding how the brain constructs our percept of the external world; instead, they reveal that higher factors such as attention, expectation, and memory also influence visual processing[1-5]. While attention facilitates processing of visual stimuli by granting priority to the more relevant aspects of the scene, memory and expectation do so by constraining possible interpretations of visual input and predicting what is likely to occur in the sensory environment based on prior experience; all result in improved perceptual performance[3,6-8].

In addition to behavioural effects, Carrasco and colleagues showed that spatial attention can increase the subjective *appearance* of contrast[9]. Their participants viewed two Gabor patches shown to the left and right of fixation; their task was to report the orientation of the higher contrast patch. Before the Gabor patches were shown, participants were cued to allocate attention to either the left or right location. They found that the stimulus shown in the location to which attention was allocated appeared higher in contrast than the unattended stimulus. This approach was criticized for the possibility of response bias in that, when uncertain regarding which patch was higher in contrast, participants may have simply reported the one on the pre-cued side; as a remedy, an equality judgement, which is resistant to this kind of bias, was suggested.[10]. This criticism was countered by a study showing that (a) equality judgements were less sensitive than comparative judgements to both physical stimulus differences and attention-dependent differences in appearance, and (b) the effect of attention on perceived contrast could nevertheless be replicated using equality judgements[11]. Additional experiments revealed that the influence of attention on stimulus appearance extends to other attributes, such as spatial resolution[12], spatial frequency and gap size[13], colour saturation[14], and motion coherence[15].

The results described above raise the question of whether other high-level factors, such as expectation and prior experience, can modulate stimulus appearance, in particular the perceived sharpness of blurry object borders[16-18]. Like contrast and spatial frequency, blur is a fundamental feature in vision. Blur is present in a scene in varying degrees due to changes in the environment (distance or depth) or the observer (pupil diameter or refractive errors), yet the visual system compensates for blur to allow us to see the world 'in focus'[19]. While previous research provides evidence that observers' sensitivity to stimulus attributes like contrast and spatial frequency can be increased by spatial attention, blur detection thresholds have been shown to be unaffected by manipulations of attention via cognitive load[20].

A previous study investigating the effects of prior knowledge on the perceived blur of words showed that in order to match the apparent blur of a real word, a comparison pseudo-word had to be sharper, suggesting an effect of prior experience in sharpening the perception of blurry stimuli[17]. The stimuli in that experiment were displayed indefinitely, however; hence, observers could have adjusted their focus differently when looking at real versus pseudo-words, in which case the results would indicate that prior experience alters behaviour (which leads to a change in perceived blur) but would not indicate that prior experience directly alters appearance. Here, we report six experiments investigating whether the integration of memory representations with sensory input can sharpen the appearance of blurry borders of a well-known object versus a matched novel object when both objects were briefly presented simultaneously, eliminating the possibility of differential accommodation for the two types of stimuli.

A well-known object is one that has been encountered often in daily life (henceforth, referred to as a *familiar* object). Therefore, memories of familiar objects probably span a range of blur levels. Many of these memories are likely to be sharp given that people fixate on objects

with which they interact[21]. Thus, if percepts are generated by combining bottom-up input with higher-level object memories activated by a stimulus, then for a given level of blur, the borders of familiar objects should appear sharper than those of novel objects. We tested this hypothesis and also examined whether predictions generated from a word prime can sharpen the perception of the blurry borders of a well-known object. The presentation of a prime typically improves performance, most likely because the word activates a target-related concept before the stimulus[22-24]. We used a masked prime to attempt to manipulate expectations before the silhouettes appeared.

Summary of experiments

In all experiments participants completed 864 trials, each of which contained one familiar and one novel object located to the left and right of fixation. The novel object was matched to the familiar object by rearranging the parts of the familiar object into a novel configuration. The objects were blurred using Gaussian smoothing kernels spanning 9 standard deviations (σ), to which we refer as "blur levels," varying from 3σ to 11σ (see Methods). In half the trials, the familiar object was the *Standard*, set at an intermediate blur level of 7σ and the novel object was the *Test*, presented at blur levels ranging from 3σ (least blurry) to 11σ (blurriest); in the other half of the trials, these roles were reversed. These trial types were randomly intermixed. In Experiments 1A and 1B participants were instructed to report whether the object on the left or on the right appeared blurrier. If object memories sharpen the appearance of blurry borders, the point at which *Test* objects appear equal to *Standard* objects will be shifted toward the blurrier end of the blur continuum for familiar compared to novel *Test* objects, indicating that for a given level of blur, the borders of familiar object appear sharper than those of novel objects. To address the possibility that response bias could account for results consistent with this prediction, we

assessed equality judgements in Experiments 2 – 4: On each trial, participants reported whether the two objects appeared to be the same or different levels of blur. If object memories influence the appearance of blurry borders, we expect participants will be more likely to respond that the two objects appear equal in blur when the familiar object is blurrier than the novel object, suggesting that long term object memories activated by familiar but not novel objects, sharpen the perception of blurry borders. In Experiments 1A, 1B, and 2, masked word primes preceded the stimulus presentation. These primes denoted either the familiar object, an unrelated object, or had no semantic value (a string of x's). As will be discussed in Experiment 1, our manipulation of expectation was not effective. Therefore, we do not dwell on our test of whether expectation affects perceived blur. Primes were not used in Experiments 3 and 4.

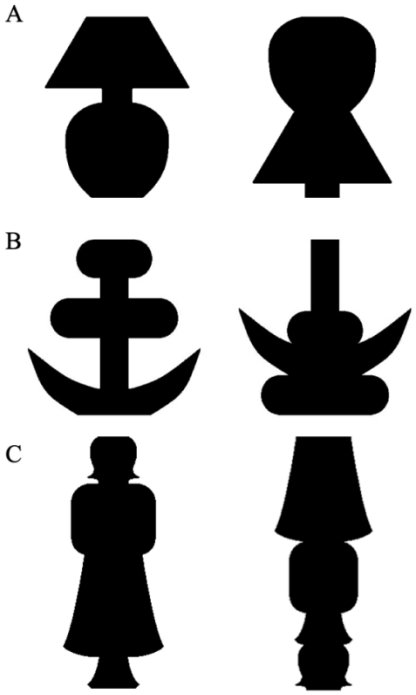

Figure 1 - Stimuli used in Experiments 1-4

The familiar object is on the left and the novel object on the right. The novel stimulus was an object created by rearranging the parts of the familiar object into a different, novel, configuration, where parts were delimited by successive minima of curvature. The two types of objects appeared equally often to the left and right of fixation. The stimuli are shown here without blur. A) Stimuli used in Experiments 1-3; the familiar object is a table lamp. B)

Stimuli used in Experiment 4A; the familiar object is an anchor. C) Stimuli used in Experiment 4B; the familiar object is a standing woman.

Results

Experiment 1 – Comparative Judgements

In Experiment 1A we presented two objects, one familiar and one novel, preceded by masked word primes; the familiar object was the silhouette of a lamp (see Fig. 1A). A sample trial is shown in Fig 2. Participants were asked to report whether the left or right object appeared blurrier.

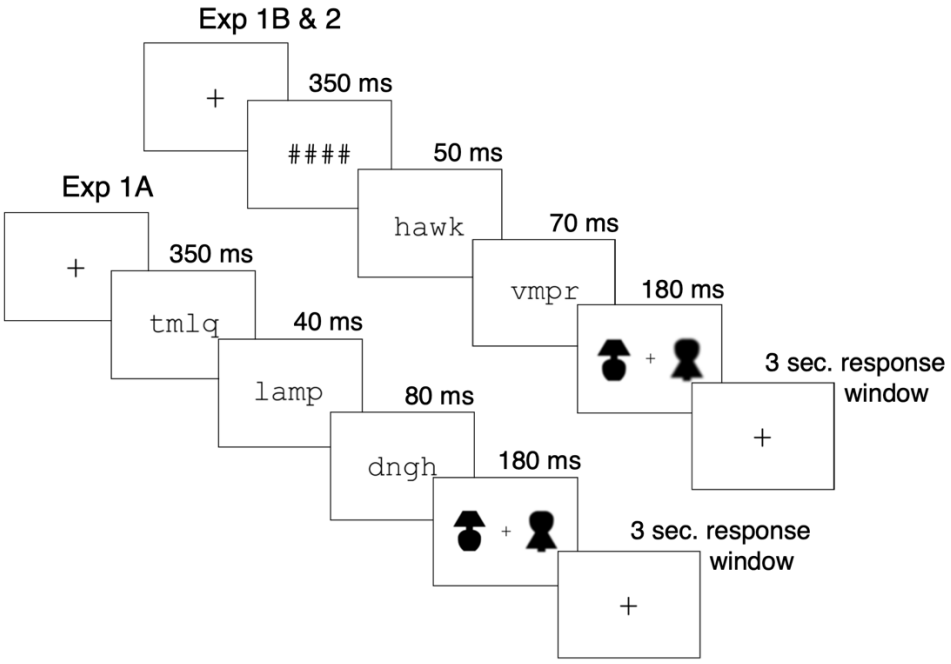

Figure 2 - Sample trials for Experiments 1A, and Experiments 1B and 2
Experiments 1A, and 1B and 2 used the same word primes, post-masks and stimuli, but differed in timing and pre-masks. In the sample trial sequence for Experiment 1A, the *Standard* was the novel object presented to the right of fixation, and the *Test* was the familiar object, presented here at 3σ. In the sample trial sequence for Experiments 1B and 2, the *Standard* was the familiar object to the left of fixation, and the *Test* was the novel object, presented here at 11σ. The word primes in this figure are enlarged for visibility.

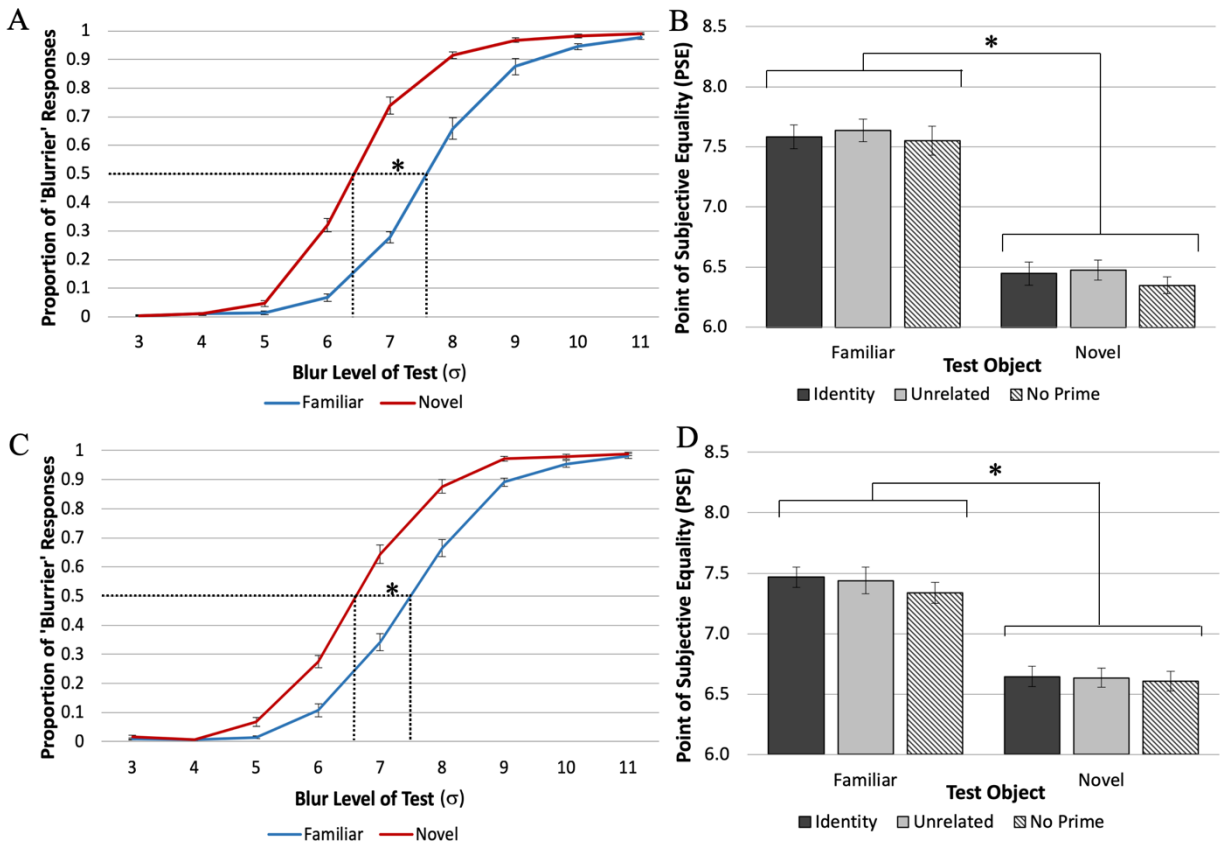

Figure 2 Results of Experiments 1A and 1B

A & C) The mean proportion of trials on which that the *Test* object was perceived as blurrier than the *Standard* as a function of the blur level of the *Test* object for Exp. 1A (A) and Exp. 1B (C). B & D) PSE estimates for each priming condition for each *Test* Object type for Exp. 1A (B) and for Exp. 1B. The dotted lines indicate the PSE (D) The PSE values for familiar and novel *Test* objects as a function of Prime type. For familiar *Test* objects a blurrier stimulus was subjectively equal to a *Standard* (7σ) novel stimulus and for novel *Test* objects a sharper stimulus was subjectively equal to a *Standard* (7σ) familiar stimulus. This is consistent with the hypothesis that for a given level of blur, familiar objects appear sharper than novel objects. No effects of Prime type were obtained. Errors bars represent the Standard Error.

Fig. 3A shows the average proportion of trials on which participants reported the *Test* object was blurrier as a function of the *Test* object blur level. We fit these averages to a logistic function using a non-linear least squares method to obtain the point of subjective equality (PSE). Fig. 3B shows the PSE for each of the priming conditions and each stimulus condition. In Experiment 1A a blurrier familiar *Test* object (*PSE* = 7.59σ, *SE* = 0.091) was subjectively equal to a *Standard* novel stimulus, and a sharper novel *Test* object (*PSE* = 6.42σ, *SE* = 0.069) was

subjectively equal to a *Standard* familiar stimulus. This difference was expected if perception results from the integration of the current sensory information with long-term memory (LTM) representations of objects that on average are sharper than the blurry versions of familiar objects presented in the experiment. Averaging over the PSE differences found in the two *Test* object conditions, the results show that the familiar object appeared sharper than the matched novel object by 0.59σ in Experiment 1A. A 2 X 3 ANOVA (with the factors of *Test* Object type: familiar vs. novel, and Prime type: identity, unrelated, and control), showed this main effect of *Test* object type to be statistically significant, $F_{1,13} = 70.9$, $p < .00001$, $\eta_p^2 = 0.85$. There was no effect of Prime type, $F_{2, 26} = 1.57$, $p = 0.23$, $\eta_p^2 = 0.11$; nor was there an interaction between Prime type and *Test* Object type, $F_{2, 26} = 0.14$, $p = .87$, $\eta_p^2 = 0.010$.

We hypothesized that the absence of a priming effect might occur because the masks interfered with the effectiveness of the word prime. Accordingly, we changed the masking conditions in Experiment 1B, such that the pre- and post-masks were shorter in duration, whereas the prime was longer (see Fig. 2 for sample trial). To further reduce the interference of the pre-mask with the prime, on each trial, we substituted a string of pound signs ("####") for the random string of consonants used in Experiment 1A.

Fig. 3C shows the proportion of 'Blurrier' responses as a function of *Test* object blur level for Experiment 1B. Replicating Experiment 1A, the curve-fitting data showed that blurrier familiar *Test* objects appeared subjectively equal to *Standard* novel objects (*PSE* = 7.41σ, *SE* = 0.068) and sharper novel *Test* objects appeared equal to *Standard* familiar objects (*PSE* = 6.63σ, *SE* = 0.060; Fig 3D). Thus, overall familiar objects appeared sharper by 0.39σ. An ANOVA showed this effect to be statistically significant by a main effect of *Test* Object type, $F_{1,13} = 46.5$, $p < .00001$, $\eta_p^2 = 0.78$. Again, we observed no main effect of Prime type, $F_{2, 26} = 0.56$, $p = 0.58$,

142 $\eta_p^2 = 0.041$, and no significant interaction between Prime type and *Test* Object type, $F_{2, 26} = 0.30$,
143 $p = 0.75$, $\eta_p^2 = 0.022$.

144 The lack of priming effects may be due to the low predictive relationship of the identity
145 prime to the stimuli: Both the familiar and the novel stimulus were shown on each trial; subjects
146 were unaware of which was the *Test* and which was the *Standard*. The prime conditions referred
147 only to the *Test* object; hence, the prime denoted the familiar *Test* stimulus on only 16.7% of
148 trials; 33.3% of the trials were unprimed (control) trials, and 50% of the trials were preceded by
149 a prime that was unrelated to the familiar object (see Methods). A low predictive relationship
150 was used so that the primes did not lead participants to expect the familiar stimulus on each trial,
151 but it may have reduced the likelihood of observing a priming effect. It is clear that even for
152 familiar *Test* objects, the primes had no effect.

153 In order to verify that we manipulated familiarity effectively, participants completed a
154 post-experiment questionnaire where they were asked to name the two objects that were
155 presented during the experiment. In Experiment 1A, 76% of participants named the familiar
156 object as a lamp. The most common interpretation for the novel object was 'ghost' with 32%
157 agreement. In Experiment 1B, 66% of participants named the familiar object. The most common
158 interpretation for the novel object was again 'ghost' with 25% agreement. Thus, participants
159 were more likely to perceive one of the stimuli as denoting a well-known "familiar" object than
160 the other.

161 **Experiment 2 – Equality Judgements**

162 In Experiment 2, participants were instructed to report whether the two objects presented
163 on each trial were the same or different levels of blur. We averaged the proportion of 'Same'
164 responses for each *Test* blur level (Fig. 4A). We then fit these averages to a normal Gaussian

distribution using a non-linear least squares method to obtain a centroid value (*b*), which corresponds to the location of the peak of the distribution (where the probability of a 'Same' response is highest). Fig. 4B shows the centroid value for each *Test* Object type and each Prime type in Experiment 2. Replicating the effect of Experiment 1, this time assessed by equality judgements rather than comparative judgements, the familiar object was perceived as sharper than the novel object ($b_{familiar} = 8.02\sigma$, $SE = 0.085$; $b_{novel} = 7.56\sigma$, $SE = 0.078$; Fig. 4A). The ANOVA showed a significant main effect of *Test* Object type, $F_{1,22} = 34.1$, $p < .0001$, $\eta_p^2 = 0.61$. These results support the hypothesis that, for familiar objects, perceived sharpness is a joint function of the current stimulus and LTM representations of familiar objects that are on average sharper than the *Standard* stimulus in the current experiment. No such LTM representations exist for the novel object.

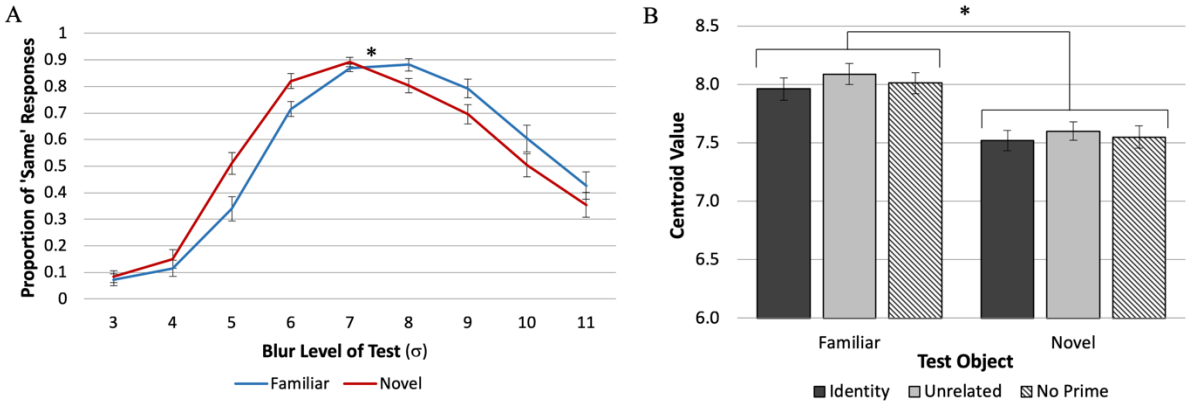

Figure 3 Results of Experiment 2
A) The mean proportion of 'Same' responses as a function of the blur level of the *Test* object. B) Centroid value estimates separated by *Test* object type and Prime type. The centroid values show that for familiar *Test* objects a blurrier stimulus was subjectively equal to a *Standard* (7σ) novel stimulus. This is consistent with the hypothesis that for a given level of blur, familiar objects appear sharper than novel objects. Errors bars represent the Standard Error.

We also observed a main effect of Prime type, $F_{2,44} = 3.65$, $p < 0.04$, $\eta_p^2 = 0.14$: The centroid values for both familiar and novel *Test* objects were significantly higher when they were

preceded by an unrelated prime (b = 7.85, SE = 0.068) rather than an identity prime (b = 7.74, SE = 0.078). It is difficult to interpret this main effect because neither "unrelated" nor "identity" primes had any relationship to the novel object; they were dummy primes from the same categories as the primes for the familiar object – an artificial object in the identity condition (i.e., "pole") and a natural object in the unrelated condition (i.e., "hawk), yet the effect was present, $p < 0.02$. Moreover, the mean centroids in the "no prime" condition did not differ significantly from those in the other two priming conditions, $p > 0.28$ for the identity prime and $p > 0.13$ for the unrelated prime, so the results can't be interpreted as a systematic response to the category of the prime (e.g., systematically inhibiting expectations based on artificial primes but not natural primes). Finally, Prime type and *Test* Object type did not interact, $F_{2, 44} = 0.15$, $p = 0.87$, $\eta_p^2 = 0.007$, as would be expected if the identity prime induced an expectation that modulated the perceived blur of the familiar object but not the novel object.

In Experiment 2, the centroid for both the familiar and novel *Test* objects corresponded to a blurrier object than the *Standard*. This finding was unexpected because in Experiment 1, when the familiar object was the *Standard*, participants' PSEs for the novel *Test* object were less blurry than the *Standard* blur value of 7σ, as expected if they perceived the familiar object as sharper both when it was the *Test* and when it was the *Standard*. The centroid shift in Experiment 2 may be due to a bias to say 'Same' for both *Test* Object types that may have emerged due to a disproportionate number of 'Different' versus 'Same' trials: Of the 864 trials, 756 were 'Different' and only 108 were 'Same'. This is because the same trials were used in Experiment 2 as in Experiment 1. A 'Same' bias has been observed previously with equality judgements under similar conditions of more 'Different' trials than 'Same' trials[11]. To estimate any perceived increase in sharpness due to familiarity in light of this response bias, we divided the difference

between the centroids for the familiar versus novel objects by two to account for the fact that any difference observed assays the perceived sharpening of the familiar object both when it was the *Test* object and when it was the *Standard* object, as in Experiments 1A and 1B. Using this method, the familiarity-dependent sharpening step was estimated to be 0.23σ (SE = 0.040). This estimated sharpening step was smaller than in Experiments 1A and 1B, perhaps because equality judgements are less sensitive than comparative judgements. Nevertheless, this difference was statistically greater than 0, $t_{22} = 5.84$, $p < 0.00001$, *Cohen's d* = 1.22.

Most participants in Experiment 2 were able to name the familiar object as a lamp with 59% agreement. The most common interpretation for the novel object was again 'ghost' with 21% agreement. Thus, participants were more likely to perceive one of the stimuli as denoting a well-known "familiar" object than the other.

Experiment 3 – Equality Judgements without Priming

In Experiment 3, participants again reported whether the two objects presented on each trial were the same or different levels or blur. Because of the absence of systematic effects of priming in the previous experiments, the stimuli were not preceded by primes or pre- and post-masks.

The distribution of 'Same' responses is shown in Fig. 5A. Once again, the centroid value was significantly higher for the familiar object ($b = 7.93\sigma$, $SE = 0.11$) than for the novel object ($b = 7.43\sigma$, $SE = 0.083$; Fig. 5B), indicating that the familiar object was perceived as sharper than the novel object at an equivalent level of blur, $t_{24} = 5.69$, $p < 0.00001$, $SE = 0.087$, *Cohen's d* = 1.138. As in Experiment 2, the centroids for both *Test* Object types were greater than the value of the *Standard*, suggesting that a bias to say 'Same' played a role in this experiment as well. Using

the same method as before, the familiar object was perceived as shaper than the novel object by 0.25σ (*SE* = 0.044), which was statistically greater than 0, $t_{24} = 5.69$, $p < 0.00001$, *Cohen's d* = 1.14, thereby replicating the results of Experiment 2 without word primes before the displays.

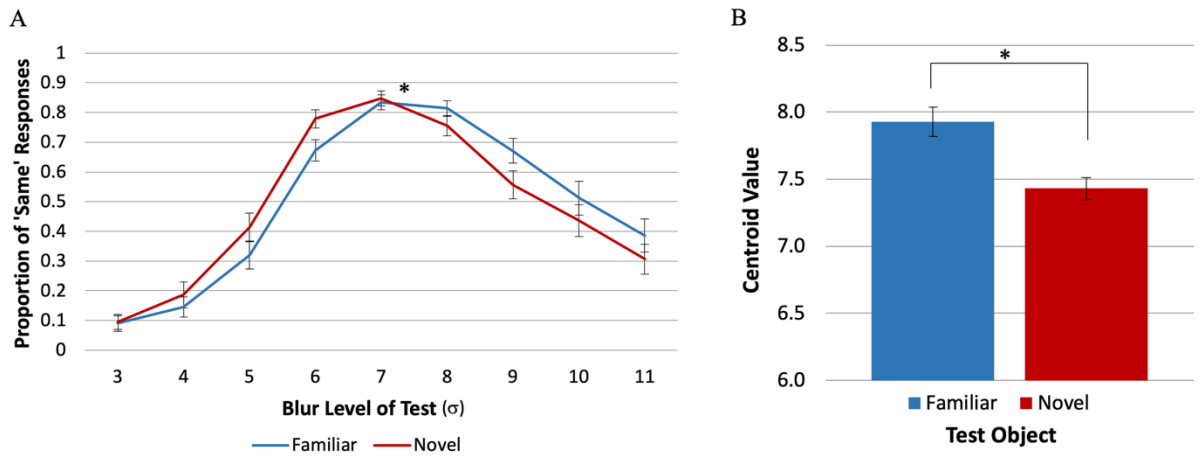

Figure 4 Results of Experiment 3
A) The mean proportion of 'Same' responses as a function of the blur level of the *Test* object. B) Centroid value estimates show a main effect of *Test* Object type. For familiar *Test* objects a blurrier stimulus was subjectively equal to a *Standard* (7σ) novel stimulus. This is consistent with the hypothesis that for a given level of blur, familiar objects appear sharper than novel objects. Error bars represent Standard Error.

The responses collected in the post-experiment questionnaire revealed that most participants were able to name the familiar object, with 70% reporting it was a lamp. The most common interpretations for the novel object were 'Vase' and 'Octopus', with 13% agreement each. Thus, participants were substantially more likely to perceive one of the stimuli as denoting a well-known "familiar" object than the other.

Experiment 4 – Equality Judgements with Different Stimuli

In Experiment 4, to examine whether this effect generalizes beyond the stimuli used in Experiments 1 - 3, we assessed equality judgements with two new sets of stimuli: An anchor and a matched part-rearranged novel stimulus (Fig. 1B; Experiment 4A) and a woman and a matched part-rearranged novel stimulus (Fig. 1C; Experiment 4B).

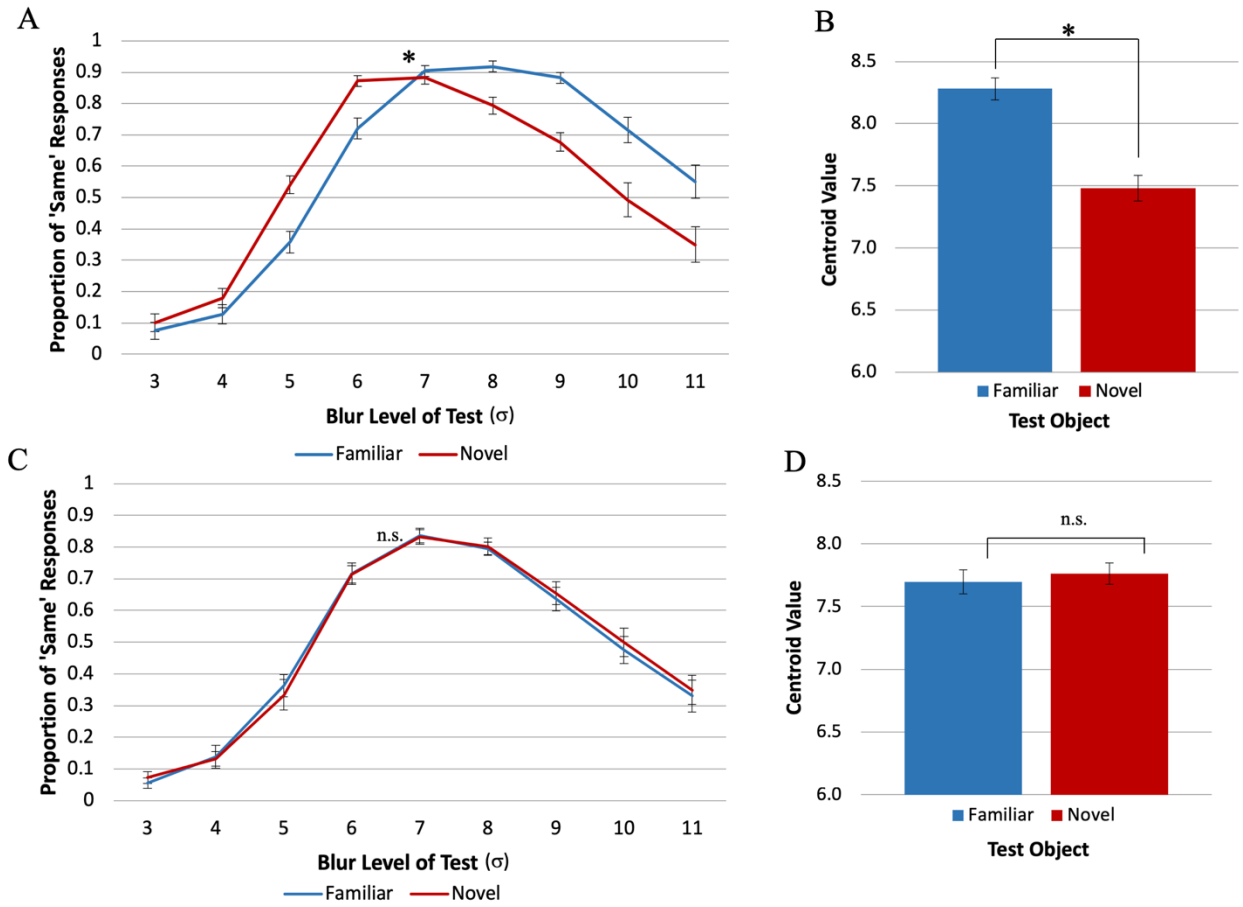

Figure 5 Results of Experiment 4
A&C) The mean proportion of reports that the objects were the same level of blur as a function of the blur level of the *Test* object A) for Exp. 4A and C) for Exp. 4B. B&D) Centroid value estimates for each *Test* Object type B) for Exp. 4A and D) for Exp. 4B. For familiar *Test* objects a blurrier stimulus is subjectively equal to a *Standard* (7σ) novel stimulus, consistent with the hypothesis that for a given level of blur, familiar objects appear sharper than novel objects. Error bars represent Standard Error.

The distribution of 'Same' responses in Experiment 4A is shown in Fig. 6A. A shift in the distributions of 'Same' responses is evident again, indicating that blurrier borders of familiar *Test* objects were perceived as equal to those of the *Standard* novel object. The centroid value was statistically higher for the familiar object than for the novel object (Fig. 6B; $b_{\text{familiar}} = 8.28\sigma$, $SE = 0.090$; $b_{\text{novel}} = 7.48\sigma$, $SE = 0.10$), $t_{16} = 7.06$, $p < 0.00001$, *Cohen's d* = 1.71. These results replicate the effects obtained in the previous experiments where observers reported perceiving

the two objects as equal in blur when the familiar *Test* object was at a higher blur level than the novel *Standard* object. As in Experiments 2-3, however, the centroid values for the novel object was also higher than the *Standard* blur level of 7σ, indicating a bias to respond 'Same' may have been present in both *Test* stimulus conditions. We estimated the familiarity-dependent sharpening step to be 0.40σ (SE = 0.056), or 40% of a blur level. As in the previous experiments, the perceived sharpening due to familiarity was statistically greater than 0, $t_{16} = 7.06$, $p <$ 0.00001, *Cohen's d* = 1.71.In Experiment 4A, 90% of participants identified the familiar object as an anchor correctly. Only one interpretation of the novel object was mentioned by more than one participant: "Yoda" (a "Star Wars" film character), with 15% agreement. Thus, participants were substantially more likely to perceive one of the stimuli as denoting a well-known "familiar" object than the other.

In Experiment 4B, we did not obtain the previously-seen shift in perceived blur between the familiar and novel conditions (Fig. 6C). The centroid values obtained for the familiar and the novel objects (Fig. 6D; $b_{\text{familiar}} = 7.70\sigma$, $SE = 0.095$; $b_{\text{novel}} = 7.76\sigma$, $SE = 0.085$) did not differ statistically, $t_{15} = -0.83$, $p = 0.42$, *Cohen's d* = 0.21 The responses to the post-experiment questionnaire for Experiment 4B reveal the reason: while 80% of participants were able to correctly name the familiar object as a woman, there was high agreement that the putatively novel object depicted a familiar object: 45% agreed that the novel object resembled a lamp, and 20% agreed it represented a male figure, producing a combined index of 65% familiar object interpretations for the novel stimulus. Thus, in Experiment 4B, we did not succeed in presenting objects that differed substantially in the degree to which they depicted a familiar object. For this reason, we determined that Experiment 4B does not serve as a good test of our hypothesis,

287 although it does establish that differences between conditions are not necessarily obtained using
288 this method.
289

290 Discussion

291 In Experiment 1 participants made comparative judgements, indicating which of two
292 simultaneously displayed objects with blurry borders was 'Blurrier'; PSEs indicated that for
293 equivalent levels of blur, a well-known "familiar" object appeared sharper than a novel object,
294 both when it was the *Standard* and when it was the *Test* object. These results were consistent
295 with the hypothesis that object perception in general and object appearance in particular result
296 from the integration of memory representations with the input. For well-known objects, these
297 include many instances in which the objects were fixated and attended outside the laboratory[21],
298 thus these representations are sharper than the blurry images used in these experiments. The
299 (sharper) activated memory representations of the known object are integrated with the (blurry)
300 sensory input, and this will produce a percept that is sharper than the displayed object. Note that
301 we conceive of object memories as dynamic representations that are updated with each exposure
302 to an object. Nonetheless, experience with novel objects accrued during the experiment cannot
303 produce equivalent results because only blurry versions of the objects were shown during the
304 experiment. Likewise, we found no evidence that experience with blurry versions of the familiar
305 object during the experiment caused it to appear less sharp in the second half of trials.

306 Might a response bias interpretation fit our results? Suppose, for instance, that there was a
307 bias to pair "novel" with "blurry;" could it be argued that the results of Experiments 1A and B
308 index response bias rather than appearance? (Note that no such bias is known.) In order to

309 eliminate any potential response bias, participants in Experiments 2, 3, and 4A made equality
310 judgements. These experiments showed that blurry familiar objects appeared sharper than
311 equivalently blurry matched novel objects, thereby ruling out a response bias interpretation and
312 showing that the familiarity-dependent effects are sufficiently robust to be observed with a less-
313 sensitive response[11]. Experiment 4B did not show the same pattern of results, but responses to a
314 post-experiment questionnaire revealed that participants interpreted both the familiar and the
315 putatively novel stimulus as depicting familiar objects. Thus, when participants instead saw two
316 seemingly familiar objects the difference in perceived sharpness disappeared, suggesting that the
317 effects obtained in the previous two experiments are indeed mediated by activation of familiar
318 objects memories.

319 In Experiments 2, 3 and 4A the centroid value for the novel stimulus deviated from the
320 *Standard* in the same direction, albeit to a lesser degree, as that for the familiar stimulus. This
321 pattern was attributed to a different type of response bias – a bias to say 'Same'. This 'Same'
322 bias may arise because the adaptation of the design of Experiment 1 for equality judgements led
323 to many more 'Different' trials than 'Same' trials. Together with a 2AFC response, this may
324 have led participants to produce more 'Same' responses[11]. Why would a 'Same' bias operate
325 systematically to increase the centroid value? It is known that sensitivity to differences in blur
326 decreases with increasing blur levels[25]. Perhaps a stronger 'Same' bias emerged when
327 discrimination was harder. A 'Same' bias should operate equally for familiar and novel *Test*
328 objects, however. Accordingly, the difference between the centroids for the familiar and novel
329 objects can still estimate familiarity-dependent differences in perceived sharpness of object
330 borders. Indeed, despite the 'Same' bias, Experiments 2, 3 and 4A showed that blurry familiar
331 objects appear significantly sharper than blurry novel objects.

332 Might our results be explained by attention rather than by the integration of incoming
333 information with memories of familiar objects? Some have claimed that attention is
334 automatically allocated to familiar over novel objects[26]. Yet a recent study[27] showed that
335 previous results taken to support this claim were replicated only under conditions of target search
336 involving spatiotemporal uncertainty and concluded that figural properties (e.g., familiarity,
337 convexity, etc.) can be entered into a task-dependent attentional priority map[28,29]. Our
338 experiments did not involve search nor was spatiotemporal uncertainty present: each stimulus
339 was shown in one of only two locations (left or right of the fixation cross) at a fixed interval after
340 trial onset; hence it is unlikely that familiarity was entered into an attentional priority map in the
341 current experiments. Is it possible that when participants found the blur comparison difficult,
342 their uncertainty was high such that familiarity was prioritized for attentional allocation, thereby
343 causing the perceived sharpening of the borders of the familiar objects? Given that the only
344 uncertainty in the experiment was whether the two objects were the same or different levels of
345 blur, we find this explanation unlikely. Finally, there is some evidence that novel objects are
346 more likely than familiar objects to attract attention[30-32].

347 Could claims that attention is attracted by blur explain our results? Both novel and
348 familiar stimuli were presented an equal number of times in all blur levels, so this explanation
349 cannot account for our data. Moreover, blur detection has been shown to occur pre-attentively[20].
350 Object memories have also been shown to operate pre-attentively to influence figure
351 assignment[33-39]. Consequently, the explanation in terms of the integration of object memory and
352 current stimulation better fits the data than an explanation in terms of attention. Previous studies
353 have shown that borders of stimuli such as those tested here can access memory representations
354 of familiar objects very early in processing and serve as priors for figural assignment[4-5, 33, 35-39].

355 The present experiments show that the influence of past experiences transcends the effect seen
356 on figural assignment and extends to the subjective appearance of stimuli.

357 Higher-level influences on the perception of stimuli have also been observed in studies
358 on perceived sharpness of objects in peripheral vision[40-42, cf. 43,44]. Objects in the periphery tend to
359 appear sharper than an equally-blurry object presented foveally. This "sharpness overconstancy"
360 is thought to arise from a default assumption of sharpness caused by a prevalence of sharp
361 borders in the visual world. Our results may relate to sharpness overconstancy because our
362 stimuli were presented in the near retinal periphery. However, sharpness overconstancy cannot
363 account for the differential sharpening of the familiar relative to the novel objects because both
364 were equidistant from fixation; participants were comparing two peripheral stimuli to each other.
365 Thus, our results add to the literature by showing that this phenomenon varies as a function of
366 the familiarity of the object.

367 The effects seen in this study may be mediated by feedback from high-level brain regions
368 representing object memories. Recently, the perirhinal cortex (PRC) of the medial temporal lobe
369 (MTL), traditionally thought to be exclusively a memory-related structure, has been implicated
370 in object perception[45-51]. Barense and colleagues found that the PRC plays a critical role in
371 border familiarity effects on figure assignment[49] and proposed that the PRC modulates activity in
372 the lower level visual area V2. Subsequent studies reported evidence consistent with this
373 proposal [50-51]; this evidence is consistent with the idea that memory representations of objects are
374 integrated with the input, as we hypothesize here (although we note that there is no evidence that
375 feedback from the PRC in particular mediates the present results).

376 The brain does not produce an exact replica of our surroundings. Instead, via the
377 integration of memory representations from previous experiences, it finds the best interpretation

for the often ambiguous input that it receives, and this may alter object appearance. Here, we have demonstrated that, when objects have blurry borders, well-known ("familiar") objects appear sharper than novel objects. Future experiments should explore whether other visual properties, such as contrast and spatial frequency, are also influenced by prior experience.

The present results showing that memory and perception interact to affect perceived blur should be of interest to a broad range of scientists who seek to understand the brain (e.g., neuroscientists, computational modelers, psychologists), to computer vision scientists, to designers of autonomous vehicles that must operate in less than ideal conditions, and to those who design visual displays. Elucidating the contributions of higher-order regions of the brain to visual perception brings us closer to understanding the intricate processes that give rise to the perceptions that guide our behavior and allow us to interact with our environment.

Methods

The experiments were conducted on a Dell OptiPlex 9020 computer and displayed on a 24-in. AOC monitor at 1920 x 1080 resolution and a 100Hz refresh rate. Participants used a standard keyboard to navigate from trial to trial. In Experiments 1 and 2, the keyboard was used to make responses. In Experiments 3-5, participants used a separate number pad to make responses. The experiment was programmed using MATLAB[52] R2015a and the Psychophysics Toolbox-3.0.12[53-54].

The stimuli were black silhouettes of familiar and novel objects, presented on a medium grey background. In Experiments 1-3 and 5, the familiar stimulus depicted a table lamp (Fig. 1A); in Experiments 4A and 4B the familiar stimuli depicted an anchor (Fig. 1B) and a standing

400 woman (Fig. 1C). To control for differences in low-level features, the novel stimulus was
401 constructed by spatially rearranging the parts of the familiar stimulus, with parts defined as lying
402 between two successive minima of curvature [cf. 55-56]. The number of black pixels in the familiar
403 and novel stimuli was equal.

404 In each trial, a familiar and a novel stimulus were shown to the right and left of fixation.
405 Before each trial, the stimuli were blurred to their assigned blur levels using the *imgaussfilt*
406 function on MATLAB. This function filtered the images using a 2-D Gaussian smoothing kernel.
407 The degree of blurriness depended on the Gaussian distribution that gave its shape to the kernel.
408 We used standard deviations ranging from 3σ (least blurry) to 11σ (blurriest). These standard
409 deviations correspond to the blur levels to which we refer throughout this paper. In each trial,
410 one stimulus was the *Standard* and the other was the *Test*; each served as *Standard* and *Test*
411 equally often. The blur level of the *Standard* was held constant at 7σ. The blur level of the *Test*
412 object varied from 3σ to 11σ. Blur levels varied by intervals of 1σ.

413 We examined whether we manipulated familiarity effectively with a post-experiment
414 questionnaire where participants were asked to name the two objects that were displayed during
415 the experiment. The answers to this question are summarized in the Results sections.
416 Additionally, while this experiment was underway an online Amazon Turk experiment was
417 conducted to determine the familiarity and novelty of a larger set of stimuli [57]. Thirty-two
418 participants viewed half portions of each stimulus (see Fig. 7), and listed the familiar objects
419 resembled by each stimulus. For the stimuli used in our experiments the results obtained in the
420 online experiment corroborate the results we obtained from the participants in our experiments.

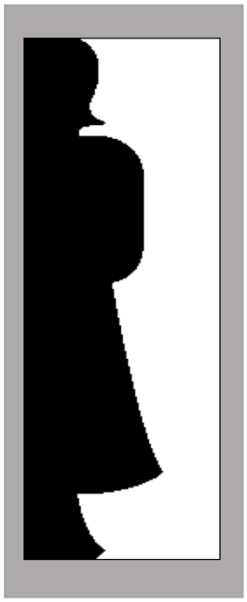

Figure 6 - Example of bipartite display
Bipartite displays were used in online experiment to assess familiarity/novelty of stimuli. In this case, the black region delineates the silhouette of a standing woman.

In Experiments 1A, 1B, and 2, the stimuli were preceded by one of three types of primes: (1) *identity primes*, intended to induce an expectation for the named stimulus, (2) *unrelated* primes (matched for word frequency to the identity primes[59]), intended to induce an expectation for an unrelated object from a different superordinate category, and (3) *control* primes, where no word was presented prior to stimulus presentation. All primes were matched in word length. For those on which the familiar object was the *Test*, the identity prime was "lamp", the unrelated prime was "hawk", and the control prime was "xxxx." For trials on which the novel object was the *Test*, the primes could not be classified as related or unrelated. Accordingly, we chose "dummy" primes from the same categories as the primes for the familiar object. For the novel objects, the dummy primes for the *identity, unrelated*, and *control* conditions were: "pole", "chin", and "xxxx." All Prime types were presented equally often. Word primes were both pre- and post-masked to render them unconscious. In Experiment 1A, the pre-mask and post-mask

were unique strings of random consonants. In Experiments 1B and 2, the pre-mask was changed to a string of #'s. The masks were the same length as the prime words.

Experiments 1A and 1B – Comparative Judgements

Before beginning the experiment, participants viewed the instructions on the computer screen while the experimenter read them aloud. The instructions explained that they would see two objects on each trial, one to the left and one to the right of a fixation cross. Their task was to report which object was blurrier. They were shown examples of the two stimuli and instructed to make their responses with a button press using the left and right arrow keys. They were told they would see the same two objects throughout the experiment. Next, they were guided through a typical trial sequence (Fig. 2). They then completed 3 blocks of 10 practice trials each. Prime type and *Test* blur levels (3σ to 11σ) were balanced in these practice trials. Each stimulus appeared as *Standard* and as *Test* and on each side of the screen an equal number of times. Each block of practice trials was presented in a random order so that each participant completed a different sequence of practice trials. Three practice blocks accustomed participants to viewing short exposure durations: the post-mask for the prime and the experimental stimuli were shown for increasingly shorter exposure durations across the three blocks (twice as long in the first practice block as on experimental trials, $1.5X$ as long in the second practice block, and $1.0X$ as long in the third practice block).

Participants completed 864 experimental trials. They were instructed to fixate on a cross in the center of the screen throughout the entire trial. They initiated each trial by pressing the space bar. In Experiment 1A, a pre-mask appeared for 350 ms, followed by the prime (40 ms), followed by the post mask (80 ms). In Experiment 1B the pre-mask was a string of #'s instead of a random consonant sequence, the word prime was lengthened to 50 ms, and the post-mask was

shortened to 70 ms. After the post mask, the stimuli were displayed for 180 ms, a duration too short for a saccade to one side or the other. The familiar and novel stimuli occurred equally often on the left and the right of fixation. In each trial, one of the stimuli was the *Standard* (blur level = 7σ); the other, *Test,* stimulus was presented at blur levels 3σ - 11σ equally often. The familiar stimulus was the *Test* on half the trials; the novel stimulus was the *Test* on the other half the trials. There were 16 trials for each combination of stimulus condition (familiar vs novel *Test* stimulus), priming condition (identity, unrelated, control), and *Test* stimulus blur level (3-11). All trial types were randomly intermixed.

After the stimuli disappeared, participants had up to 3 seconds to report whether the object on the right or on the left was 'Blurrier.' Participants were instructed to report which object was blurrier, as opposed to which was sharper in order to reduce the probability that any bias to pair the familiar object with the instructed response would favor our hypothesis[9]. Participants responded using their right hand on the left and right arrow keys, where they pressed the left arrow key for a left response, and the right arrow key for a right response.

Participants viewed the displays from a distance of 98.5 cm. At this distance, the stimuli subtended 2.67° X 2.04° of visual angle in height (H) and width (W), respectively; their innermost borders were located 4.13° from fixation.

Statistical Analysis.

Trials on which a response was not recorded during the 3s response window were excluded. Trials with incorrect display timing were also removed (<1% of trials). This was determined by a MATLAB script written to verify the display timing for each frame in the experiment. For each participant, the data were separated by Prime type (identity, unrelated, control) and *Test* Object type (familiar, novel). For each of these conditions, the number of times

484 the *Test* object was chosen as 'Blurrier' was averaged for each blur level. These averages served
485 as input for the curve-fitting toolbox in MATLAB. Using a Non-Linear Least Squares method,
486 the distribution of each participant's responses was fit to a Logistic Function,

487 $$y = \gamma + (1 - \gamma - \lambda) * \frac{1}{1 + \exp(-\beta * (x - \alpha))}$$

488

489 where λ is the lapse rate, γ is the guess rate, α is the threshold parameter, and β is the slope
490 parameter. The threshold value corresponds to the location of the logistic curve where
491 participants are at chance level reporting either side as the blurrier option, indicating the point of
492 subjective equality (PSE). We obtained the threshold parameter value for each participant's
493 distribution, along with a confidence interval for this value. An outlier removal procedure
494 consisted of removing any participant whose confidence interval for the threshold parameter was
495 lower or higher than two standard deviations from the mean confidence interval for all
496 participants. Three rounds of this procedure were performed. The PSE values were submitted to
497 a 2 X 3 repeated measures ANOVA with *Test* Object type (familiar, novel) and Prime type
498 (identity, unrelated, control) as factors.

499 **Experiments 2-4 Equality Judgements**

500 Participants were instructed to report whether the two objects shown on each trial were
501 the same or different levels of blur. They recorded their responses using a separate number pad
502 rotated 90° to the right, with keys on only the numbers 1 (at the top) and 3 (at the bottom).
503 Participants were instructed to press the top key if the two stimuli were equal in blur or the
504 bottom key if they were different. In other respects, the Experiment 2 procedure was the same as
505 that of Experiment 1B. The procedure for Experiment 3 was the same as Experiment 2, except
506 that no word primes were presented at any point during the experiment. Experiments 4A and 4B

were run interleaved in that when participants entered the laboratory, they were assigned to one of the two experiments using an ABBA procedure. Participants took part in one experiment only. The procedure was the same as in Experiment 3, with the exception of the stimuli. In Experiment 4A the familiar stimulus was the silhouette of an anchor; the stimuli subtended visual angles of 2.67° H X 2.56° W. In Experiment 4B the familiar stimulus was the silhouette of a woman; the stimuli subtended visual angles of 2.67° H X 1.0° W

Statistical Analysis

For each participant, the data were separated by Prime type (identity, unrelated, control) and *Test* Object type (familiar novel), in a manner similar to Experiments 1A and 1B. The distribution of each participant's responses was fit to a normal Gaussian distribution using a Non-Linear Least Squares method,

$$y = \sum_{i=1}^{n} a_i e^{\left[-\left(\frac{x-b_i}{c_i}\right)^2\right]},$$

where a is the amplitude, b is the centroid value, c is related to the width of the peak, and n is the number of peaks to fit (in this case, one peak). The centroid value, b, corresponds to the location of the peak, where the probability of a 'Same' response is highest. A two-way repeated measures ANOVA was performed on the results of Experiment 2 to assess the effect of Prime type and *Test* Object type on the centroid value. A paired-sample, two-tailed t-test was used to compare the centroid values for the familiar and novel *Test* Object types in Experiments 3 and 4.

Participants

All participants were University of Arizona (UA) undergraduate students (ages 17-23) who participated to fulfill a class requirement. Before taking part in the experiments, participants gave informed consent on a form approved by the UA Human Subjects Protection Program.

Participants had normal or corrected to normal vision (at least 20/30) assessed by responses to a Snellen Eye Chart Test. Before beginning data collection, two discard criteria were established for all experiments in this article: Criterion 1 was "failure to follow task instructions" and criterion 2 was "pressing the wrong button in 30% of trials or more" as reported in the post-experiment questionnaire.

Experiment 1A: The data of 14 participants (7 male, 7 female) are reported. Two other participants were discarded based on criterion 1; 8 others were excluded after the outlier removal procedure. Experiment 1B: The data of 14 participants (5 male, 9 female) are reported. Two other participants were discarded based on discard criterion 1; 8 others were excluded after the outlier removal procedure. Experiment 2: The data of 23 participants (11 male, 12 female) are reported. Six other participants were excluded after the outlier removal procedure; none were discarded based on discard criteria. Experiment 3: The data of 25 participants (12 male, 13 female) are reported. Two other participants were discarded based on discard criterion 1; 4 were discarded based on criterion 2; 5 others were excluded after the outlier removal procedure. Experiment 4A: The data of 17 participants (10 male, 7 female) are reported. Four other participants were discarded based on discard criterion 1; 3 others were excluded after the outlier removal procedure. Experiment 4B: The data of 16 participants (9 male, 7 female) are reported. Four other participants were discarded based on discard criterion 1; one was discarded based on criterion 2; 4 others were excluded after the outlier removal procedure.

Data Availability

All data that support these findings are publicly available at https://doi.org/10.5281/zenodo.3325023

Code Availability

The code necessary to reproduce these findings and analyses is available at https://github.com/dianaperez25/BlurPerception

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Author Contributions

S.M.C. and M.A.P. conceived the study. S.M.C., D.C.P. and M.A.P. designed the experiments. S.M.C. and D.C.P. collected and analyzed the data. D.C.P. wrote the manuscript. M.A.P. provided direct supervision and feedback during study design, data collection, data analysis and interpretation, and manuscript preparation stages. All authors approved the final version of the manuscript.