Perceptual blurring and recognition memory: A desirable difficulty effect revealed

Published in Acta Psychologica September 2015

doi: 10.1016/j.actpsy.2015.06.006

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Abstract

Recent research in the area of desirable difficulty—defined as processing difficulty at either encoding or retrieval that improves long-term retention—has demonstrated that perceptually blurring an item makes processing less fluent, but does not improve remembering (Yue et al., 2013). This result led us to examine more closely perceptual blurring as a potential desirable difficulty. In Experiment 1, better recognition of blurry than clear words was observed, a result that contrasts with those reported by Yue et al. This result was replicated in Experiment 2, in which both mixed-list and pure-list designs were used. The following experiments were conducted to determine when blurring does and does not result in enhanced remembering. The desirable difficulty effect observed in Experiments 1 and 2 was replicated in Experiments 3A, 3B, and 3C, despite varying encoding intent during study, context reinstatement at the time of test, study list length, and the nature of the distractor task between study and test phases. It was only in Experiments 4A and 4B that a null effect of perceptual blurring on remembering was found. These experiments demonstrated that (1) the level of blurring used is critical, with a lower blurring level producing results similar to Yue et al. (2013), and (2) the introduction of judgments of learning at the time of study eliminated the benefit of blurring on remembering. These results extend the desirable difficulty principle to encoding manipulations involving perceptual blurring, and identify judgments of learning at encoding as a powerful moderator of this particular desirable difficulty effect.

Keywords: desirable difficulty, recognition, metamemory, perceptual disfluency

1. Introduction

This article focuses on the relation between ease of encoding and the efficiency of long-term remembering. R. A. Bjork (1994; E. L. Bjork & Bjork, 2011) pointed to a host of human learning and memory effects that suggest that difficulties in encoding or retrieval of information are often accompanied by improved long-term retention of that same information at a later point in time. The spacing effect offers one example of this relation; increasing the temporal spacing between repeated encodings of an item increases encoding difficulty of the repetitions, but improves final retention (R. A. Bjork & Allen, 1970; Cuddy & Jacoby, 1982). Variation in the context associated with encoding, interleaved rather than blocked learning, and generation (or testing) rather than mere reading (or studying) at the time of encoding also increase both encoding difficulty and subsequent retention. Given the benefits to memory performance produced by these and other manipulations, R. A. Bjork (1994) referred to them as “desirable difficulties”.

Although the desirable difficulty principle is sufficiently broad to capture just about any situation in which additional processing benefits remembering (e.g., the elaboration associated with semantic orienting tasks; Craik & Lockhart, 1972), there has been particular interest in studies that have shown memory to benefit from subtle manipulations of perceptual encoding difficulty. For example, Diemand-Yauman, Oppenheimer, and Vaughan (2011) demonstrated better retention for information presented in difficult-to-read fonts than clear fonts, both in the laboratory and in a classroom setting. This result suggests that direct manipulation of the fluency of perceptual processing is sufficient to produce better remembering for more difficult to encode items. Another finding that may be captured by the desirable difficulty principle was first reported by Nairne (1988). In this study, words presented relatively briefly and masked were remembered better than words presented for a longer duration and left unmasked at encoding (see also Hirshman & Mulligan, 1991; Hirshman, Trembath & Mulligan, 1994; Mulligan, 1996, 1999). More recently, two studies have reported that congruency between targets and distractors in a selective attention task can impact later recognition, with better recognition at test for items that were incongruent (i.e., target and distractor information mismatched) than for items that were congruent (i.e., target and distractor information matched) at study (Krebs, Boehler, De Belder, & Egner, 2013; Rosner, D'Angelo, MacLellan, & Milliken, 2014).[1] Once again, these effects fit with the general idea that processing difficulty during encoding, in this case elicited by competing target and distractor items, results in better remembering. Finally, Besken and Mulligan (2014) reported a recent study in which participants listened to intact words and words that had segments replaced by silence. In both recall and recognition memory tests, better remembering was observed for the fragmented than intact words, a result that again fits with the idea of desirable difficulty.

Given the wide array of procedures that produce better remembering for stimuli that are relatively difficult to encode due to perceptual manipulations, the desirable difficulty principle appears to have broad empirical support. A compelling possibility is that a common underlying mechanism that responds to difficulty mediates all of these effects. Such a mechanism could play an important role in a wide range of task contexts that require flexible adaptation to encoding demands, perhaps up-regulating attention under conditions in which encoding processes are disfluent (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001). At the same time, there have

[1] Specifically, Krebs et al. (2013) had participants complete a face-word Stroop-like task, in which they observed faces with the words "man" or "woman" superimposed on top of them. The gender of the face and the word either matched (congruent) or mismatched (incongruent), and participants were to indicate the gender of the face while ignoring the word. Alternatively, in our previous study (Rosner et al., 2014), participants were presented with red and green spatially interleaved words, and were asked to read the red word aloud. The two words were either the same (congruent) or different (incongruent).

been failures to observe desirable difficulty effects that raise questions about the ubiquity of the mechanism responsible for such effects. In the following section, two notable failures to observe desirable difficulty effects are described.

1.1. Challenges to the Desirable Difficulty Principle

The first of the problematic results was reported by Hirshman et al. (1994). As noted above, Nairne (1988) reported that memory performance is better for words presented briefly and pattern masked than for words presented for a longer duration and left unmasked at the time of encoding. In addition to replicating this result several times, Hirshman et al. (1994) examined whether memory performance would be affected by a manipulation of stimulus contrast at the time of encoding. During an incidental study phase, participants identified words that were perceptually high contrast (i.e., white words on a black background) or low contrast (i.e., dark grey words on a black background). Indeed, naming times in this study phase were about 30 ms faster for high contrast than for low contrast words. Yet, in a following test of free recall, there was no difference in remembering between the high contrast and low contrast items.

A second problematic result was reported recently by Yue, Castel, and Bjork (2013). These researchers reported five experiments that examined memory performance for words that were either perceptually clear or perceptually blurry at the time of encoding. Yue et al. were particularly interested in the relation between judgments of learning (JOLs) at study and memory performance at test. JOLs were collected at study for each word by asking participants to indicate, on a scale of 1-100, how likely they believed they would remember the word later on. The desirable difficulty principle suggests that participants might well produce a counter-intuitive result, with participants' JOLs indicating that they expect to be able to remember better the items that are easier to process during the study phase, whereas actual remembering may show the opposite pattern. Across five experiments, Yue et al. found that participants' JOLs were indeed higher for clear than blurry words, but that memory performance (both recall and recognition) was no better for blurry than for clear words; in fact, there was a consistent trend across the experiments in the direction of better memory for clear than blurry words.

1.2. The Present Study

For the desirable difficulty principle to be useful to researchers, it is important to note and understand both its successes and its failures. To this end, the empirical work described in the present article focused on the method used by Yue et al. (2013), and aimed to identify why this procedure failed to produce a pattern of results consistent with the desirable difficulty principle. The implications of the Yue et al. study for the desirable difficulty principle hinge closely on why ease of processing was not inversely related to efficiency of remembering in their study. In particular, we aimed to discriminate among three possibilities. First, the results of Yue et al. could imply that desirable difficulty effects simply cannot be demonstrated when encoding difficulty is induced with perceptual blurring at the time of encoding. A second possibility is that perceptual blurring can produce desirable difficulty effects, but that such effects may hinge on the specific parameters used to implement the blurring manipulation. A third possibility assumes again that perceptual blurring can produce desirable difficulty effects, but that these effects can be overridden by other memory influences that make the desirable difficulty component of memory performance difficult to observe in some empirical contexts.

2. Experiment 1

The first of the experiments reported here was in fact conducted in our lab prior to publication of the Yue et al. (2013) study, and was motivated by our earlier study of the relation between selective attention at encoding and remembering (Rosner et al., 2014). In that study, participants named one of two interleaved words that were either identical (congruent) or different (incongruent) in an incidental study phase. Naming times were about 100 ms slower for the incongruent items than for the congruent items. In a following surprise test phase, recognition memory was more accurate for items that were incongruent than for items that were congruent at study. One interpretation of these results focuses specifically on mechanisms that resolve competition between targets and distractors at the time of study (see also Krebs et al., 2013). By this view, specific cognitive control processes used to resolve distractor interference could incidentally strengthen memory representations, resulting in better memory for incongruent than congruent items. However, as noted above, the same results could as easily be captured by the much broader desirable difficulty principle, according to which encoding difficulty across a wide range of methods improves remembering. To address this issue, we conducted Experiment 1 of the current study. The aim of this experiment was to examine whether degrading perception of a single word, by blurring its presentation, produces a parallel result to our earlier study that varied selective attention demands at encoding (Rosner et al., 2014).

2.1. Method

2.1.1. Participants. Twenty-four participants (20 females, mean age = 19 years, standard deviation age = 1.4 years) from the McMaster University student pool completed the experiment in exchange for course credit or $10. All participants spoke English fluently, and had normal or corrected-to-normal vision.

2.1.2. Apparatus and stimuli. The experiment was run using PsychoPy (Peirce, 2007, 2009) on a Dell computer. Stimuli were presented on a BENQ LED monitor, and consisted of five letter high-frequency nouns (Kučera & Francis, 1967) presented in white on a black background. The words subtended 4.01 degrees of visual angle horizontally and 0.92 degrees vertically. Clear stimuli were presented as text stimuli using the visual module in PsychoPy. Blurred stimuli were created by applying a Gaussian blur of 15 to each word using GNU Image Manipulation Program (GIMP; see Figure 1). These pictures were then imported into PsychoPy as picture files.

Figure 1. Examples of experimental stimuli. An example of a clear word is presented at the very top (used in all reported experiments). An example of a 10% blurred word is presented on the bottom left (used in Experiments 4A and 4B); an example of a 15% blurred word is presented on the bottom right (used in all reported experiments). Blurry words were created by applying a Gaussian blur of 10 or 15 to clear words using GIMP.

2.1.3. Procedure. The experimental session had three parts: a study phase, a distractor task, and a surprise recognition memory test. Participants were seated 50 cm away from the monitor with a standing microphone placed in front of them. For the study phase, participants were required to read the word they saw on the screen aloud as quickly and accurately as they could. They were not informed that they would be asked to remember the words later on. Each trial began with the presentation of a fixation cross for 2000 ms, followed by a word for 1000 ms. The microphone recorded participants' response times from the onset of the stimulus to the onset of their naming response as detected by the microphone. Following the word stimulus, a blank screen was presented while an experimenter coded participants' responses as a "1" (correct), "2" (incorrect), or "3" (spoil) using the keyboard. Responses were considered incorrect if a participant named the wrong word, if they began to name the wrong word but corrected to the right one, or if they failed to make a response. Spoils were coded if a spurious noise (e.g., coughing) was suspected to have set off the microphone.

Following the study phase, participants completed math problems for 10 minutes. Afterward, participants were provided with instructions for the memory test both verbally and written on screen. The memory task was a recognition memory test with a remember/know distinction, which was employed to determine the contributions of recollection and familiarity to performance (Rajaram, 1993; Yonelinas & Jacoby, 1995; Yonelinas, 2002). Based on the findings of McCabe and Geraci (2009), the labels "Type A" for remember (the recollection of a word from the study phase) and "Type B" for know (a feeling that the word was in the study phase) were used, as these labels have been shown to reduce the level of remember false alarm rates obtained. Participants were told that their task was to determine whether or not the words presented to them were seen in the study phase. If they believed they had seen the word, they were to indicate the word was old, and then to specify if the word evoked a Type A or Type B memory; otherwise, they would classify the word as new. For every trial, a fixation cross was presented for 2000 ms, followed by a word in the middle of the screen and the words "OLD" and "NEW" on the bottom left and right of the screen, respectively. These stimuli stayed on screen until response to serve as a reminder for which key corresponded to which response. If participants believed the word was new, they were to press the L key, which would initiate the next trial. If they thought the word was old, they were to press the A key. At this point, the word stimulus would stay on screen, and “OLD” and “NEW” would be replaced by “TYPE A” and “TYPE B”, respectively. If the word evoked a Type A memory, participants were to press the A key; otherwise, they would press the L key to indicate a Type B memory.

2.1.4. Design. Four lists of 60 words each were used to create the stimuli for a total of 240 words (see Appendix A). One hundred twenty words from two of the lists were presented in both the study and test phases and were considered “old”, while the 120 words from the other two lists were presented only in the test phase, and were considered “new”. For both the old and new words, one list was used to create clear words, and the other list was used to create blurry words, so that there were 60 clear and 60 blurry old words, and 60 clear and 60 blurry new words. The four word lists were counterbalanced across participants, so that each list was assigned to each role (old/new, clear/blurry) an equal number of times.

Word order was completely randomized, such that clear and blurry words were randomly intermixed in the study phase, and clear and blurry old and new words were randomly intermixed in the test phase. All old words were presented at test in the same manner in which they were presented at study; that is, clear words during study were clear at test, and blurry words during study were blurry at test.

2.2. Results

2.2.1. Study phase. Correct response times (RTs) from the study phase were submitted to the non-recursive moving criterion outlier analysis of Van Selst and Jolicoeur (1994). This analysis establishes a criterion for outlier exclusion that varies with the number of observations per condition, thus ensuring that different percentages of observations are not systematically excluded from cells of different sizes. In the present experiment, this method resulted in the exclusion of 3.3% of observations from further analysis. Mean RTs were computed from the remaining observations, and were submitted to a one-tailed paired sample t-test that revealed faster RTs for clear words (611 ms) than blurry words (680 ms), $t(23) = 8.60$, $p < .001$, $d = 2.48$. An analysis was not conducted on the error rates, as participants made no errors for the clear words, and the error rate was also very low for the blurry words (.014). Mean RTs and error rates can be seen in Table 1.

Table 1
Mean Response Times (ms) and Error Rates for the Study Phase

Experiment	Clear	Blurry
1	611 (.000)	680 (.014)
2		
Mixed	623 (.002)	678 (.012)
Blocked	595 (.003)	642 (.017)
3A		
Incidental	652 (.001)	725 (.020)
Intentional	638 (.003)	705 (.013)
3B	562 (.002)	629 (.014)
3C	641 (.002)	723 (.005)
4A		
10% blur	689 (.000)	720 (.002)
15% blur	697 (.002)	753 (.005)
4B		
10% blur	616 (.004)	621 (.015)
15% blur	622 (.003)	698 (.021)

Note: Table displays response times with error rates in parentheses.

2.2.2. Test phase. For this and all subsequent test phase analyses, words that were responded to incorrectly during study were excluded from further analysis. The proportions of “old” responses for each item type, collapsed across participants, are displayed in Figure 2. To examine differences in remembering, *d’* values (Table 2) for blurry and clear words were compared using a two-tailed paired sample t-test. The difference in *d’* values for blurry (1.43) and clear words (1.25) approached significance, $t(23) = 2.02$, $p = .055$, $d = 0.58$, in line with better recognition sensitivity for blurry than clear words. A corresponding analysis of beta was not significant, $t(23) = 0.84$, $p = .411$, $d = 0.12$ indicating that bias to respond "old" did not differ for clear and blurry items.

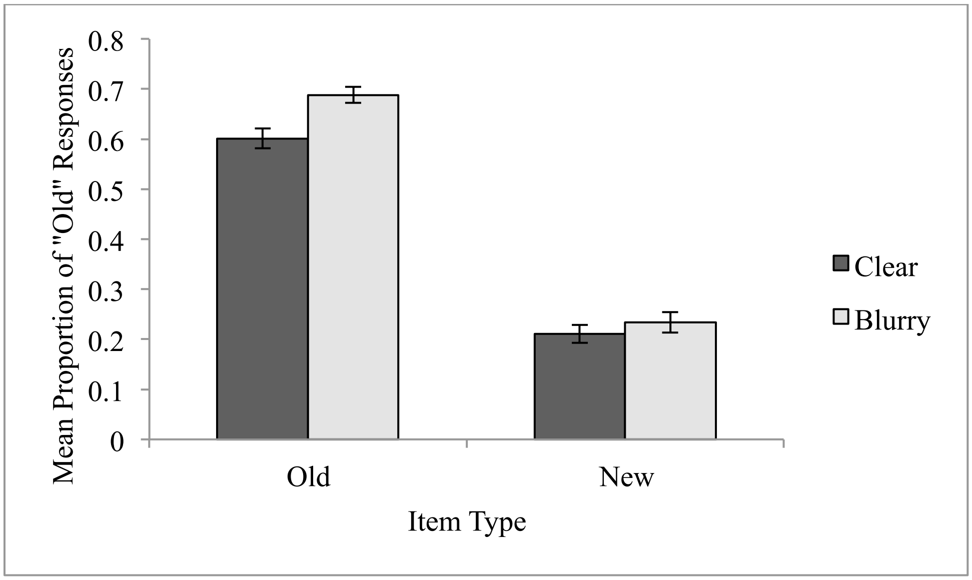

Figure 2. Mean proportions of "old" responses for Experiment 1. Error bars reflect the standard error of the mean, corrected for between-subject variability (Morey, 2008).

Table 2

d' Values for the Test Phase

Experiment	Clear	Blurry
1	1.25 (2.48)	1.43 (2.19)
2		
Mixed	1.43 (1.03)	1.61 (1.01)
Blocked	1.45 (1.03)	1.60 (1.04)
3A		
Incidental	0.98 (1.92)	1.11 (1.74)
Intentional	1.15 (2.00)	1.32 (2.04)
3B	0.94 (1.91)	1.09 (2.03)
3C	1.65 (1.92)	1.89 (1.96)
4A		
10% blur	2.31 (0.13)	2.21 (0.12)
15% blur	2.18 (0.18)	2.06 (0.19)
4B		
10% blur	1.74 (2.26)	1.62 (2.47)
15% blur	1.69 (2.35)	1.79 (2.39)

Note: Table displays *d'* values with beta in parentheses.

Using the independence remember-know procedure, the separate contributions of recollection and familiarity to recognition were evaluated for this and all following experiments (Yonelinas & Jacoby, 1995; Yonelinas, 2002). The contribution of recollection to recognition is estimated by the proportion of "remember" (or Type A) responses (R); going forward, this will be referred to as a recollection estimate. The contribution of familiarity to recognition is estimated based on the proportion of "know" (or Type B) responses given that a remember response was not made (1-R); going forward, this will be referred to as a familiarity estimate. Estimates for recollection and familiarity were determined separately for hits and false alarms, and analyses were conducted on the hit minus false alarm difference scores (see Table 3). These difference scores were analysed for the clear and blurry conditions using two-tailed paired sample t-tests. The analyses revealed a significant effect of perceptual clarity on both recollection, $t(23) = 2.83$, $p = .010$, $d = 0.81$, and familiarity, $t(23) = 2.26$, $p = .034$, $d = 0.65$. Both recollection and familiarity were higher for blurry (.349; .295) than clear items (.278; .234).

Table 3

Estimates of recollection and familiarity based on the independence remember-know procedure

	Recollection		Familiarity	
Experiment	Clear	Blurry	Clear	Blurry
1	.278	.349	.234	.295
2				
Mixed	.399	.394	.279	.363
Blocked	.367	.396	.279	.349
3A				
Incidental	.214	.287	.190	.207
Intentional	.239	.300	.252	.291
3B	.172	.223	.166	.187
3C	.325	.307	.403	.482
4A				
10% Blur	.450	.392	.553	.545
15% Blur	.457	.418	.432	.419
4B				
10% Blur	.377	.286	.338	.351
15% Blur	.366	.389	.348	.378

2.3. Discussion

The results of Experiment 1 contrast with those reported in the study of Yue et al. (2013). Consistent with the desirable difficulty principle, recognition memory was more sensitive for words that were blurry at encoding than for words that were clear at encoding. This conclusion is supported by effects of perceptual clarity on *d'*, recollection, and familiarity, although the effect on *d'* only approached significance. These results contrast with the non-significant trend toward better recognition for clear than blurry words reported by Yue et al. (2013).

3. Experiment 2

Experiment 1 provides preliminary evidence that recognition memory can be better for blurry than clear words. Experiment 2 addresses whether this result requires the mixed-list presentation method used in Experiment 1. We addressed this issue because a range of effects, such as the production effect (better memory for items read aloud than silently; MacLeod, Gopie, Hourihan, Neary, & Ozubko, 2010), the generation effect (better memory for items produced by the participants than items read; Slamecka & Graf, 1989), and the bizarreness effect (items leading to bizarre imagery are better remembered than items that produce a common image; Einstein & McDaniel, 1987) all tend to occur in mixed-list designs but not pure-list designs (e.g., MacLeod et al., 2010; see McDaniel & Bugg, 2008 for a review). These results have led researchers to conclude that each of these effects hinges on distinctiveness differences between item types that occur only for mixed lists, or alternatively to relational and item-specific encoding factors that differ for item types across mixed- and pure-list designs (McDaniel & Bugg, 2008). We were interested in learning whether the effect observed in Experiment 1 might also belong to this family of effects.

In Experiment 2, there were two groups of participants: one group completed an experimental session in which clear and blurry items were manipulated within-list, as in Experiment 1, whereas the other group was presented with pure-lists of clear and blurry items at both study and test. Better recognition for blurry than clear items in the mixed-list group but not the pure-list group would suggest that the recognition advantage for blurry over clear items has the same cause as the other effects described above. Alternatively, better recognition for blurry than clear items in both mixed-list and pure-list designs would point to some other cause.

3.1. Method

3.1.1. Participants. Forty-eight participants (32 females, mean age = 20 years, standard deviation = 1.8 years) from the McMaster University student pool were recruited in exchange for course credit or $12. All participants spoke English fluently, and had normal or corrected-to-normal vision. Twenty-four participants were randomly assigned to each of the mixed-list and pure-list conditions.

3.1.2. Apparatus, stimuli, and procedure. The apparatus, stimuli, and procedure of Experiment 2 were identical to Experiment 1 with the following exceptions. Items were presented in two study-test iterations; as such, participants were aware from the beginning of the experiment that they were to remember the words presented to them at study. Additionally, the detailed instructions for the remember/know task were provided at the beginning of the experiment, before the first study phase. Following the first study phase, participants completed math problems as a distractor task for four minutes, and then completed the first recognition memory task. Participants then did another four-minute math distractor task followed by a second study phase, another four-minute math distractor task, and a second test phase.

3.1.3. Design. The design of Experiment 2 was identical to that of Experiment 1 with the following exceptions. For the mixed-list group, clear and blurry words were randomly intermixed for the study and test phases, as in Experiment 1. However, rather than a single study-test iteration with 60 clear and 60 blurry words intermixed at study, there were two study-test iterations in each of which 30 clear and 30 blurry words were intermixed at study. In each of the two test phases, equal numbers of new clear and blurry items were intermixed with the old clear and blurry items.

For the pure-list group, participants were presented with items of one item type in the first study-test iteration (e.g., all clear words) and presented with the other item type in the second study-test iteration (e.g., all blurry words). Aside from this constraint, word order was completely randomized within each study and test block. Block order was counterbalanced across participants, such that half completed the blurry study-test block first and the clear study-test block second, and half completed the study-test blocks in the opposite order.

3.2. Results

3.2.1. Study phase. Correct RTs were submitted to the same outlier analysis as in Experiment 1, which removed 2.7% of observations from further analysis. Mean RTs (see Table 1) were computed from the remaining observations and, along with the error rates, were submitted to 2 x 2 mixed-factor ANOVAs, with perceptual clarity (clear versus blurry) as a within-subject factor and group (mixed-list versus pure-list) as a between-subjects factor. These analyses revealed a main effect of perceptual clarity for both RTs, $F(1,46) = 23.47$, $p < .001$, $\eta_p^2 = .338$, and error rates, $F(1,46) = 21.56$, $p < .001$, $\eta_p^2 = .320$, with faster RTs and lower error rates for clear (609 ms; .002) than blurry words (660 ms; .014). No other effects were significant, all *p*'s > .10.

3.2.2. Test phase. The mean proportions of "old" responses across item type are presented in Figure 3. An analysis of *d'* (see Table 2) was conducted using the same mixed-factor ANOVA described above, with perceptual clarity as a within-subject factor and group as a between-subjects factor. This analysis revealed a main effect of perceptual clarity that approached significance, $F(1,46) = 3.46$, $p = .069$, $\eta_p^2 = .070$, with higher values of *d'* for blurry (1.60) than clear words (1.44). The interaction between perceptual clarity and group was clearly not significant, $F(1,46) = 0.02$, $p = .894$, $\eta_p^2 < .001$. A corresponding analysis of beta revealed no significant effects, all *p*'s > .10.

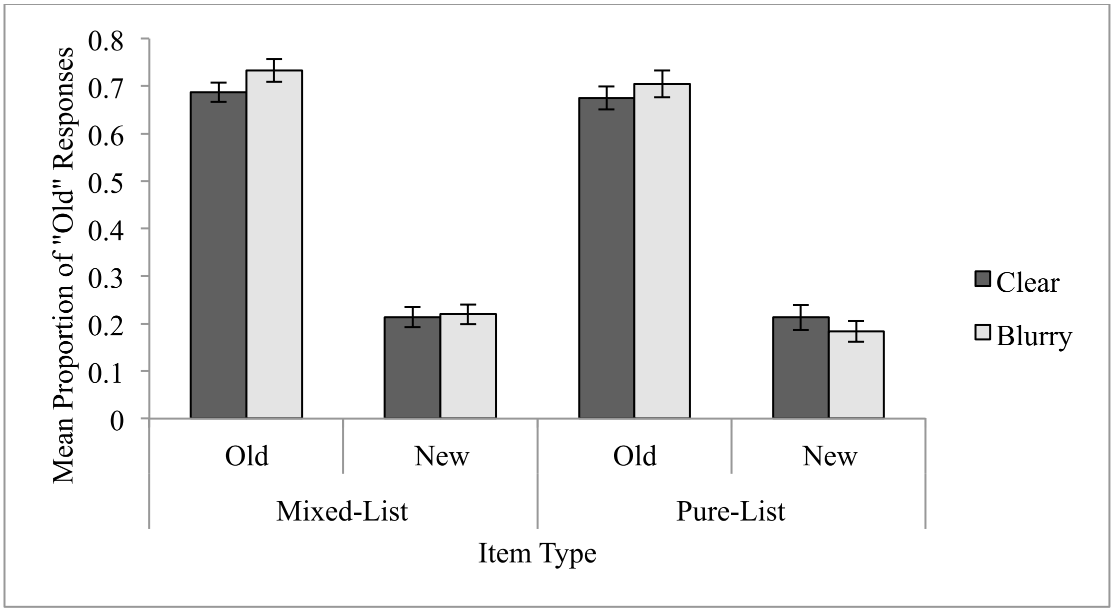

Figure 3. Mean proportions of "old" responses for Experiment 2. Error bars reflect the standard error of the mean, corrected for between-subject variability (Morey, 2008).

Estimates of recollection and familiarity were analysed using the previously described mixed-factor ANOVA. Results similar to the *d'* analysis were obtained in the analysis of familiarity, with higher familiarity estimates for blurry (.355) than clear items (.279), $F(1,46) = 8.34$, $p = .006$, $\eta_p^2 = .154$, and no evidence of an interaction, $F(1,46) = 0.91$, $p = .764$, $\eta_p^2 =.002$. There were no significant effects in the analysis of recollection estimates (see Table 3).[2]

[2] Preliminary analyses were conducted to examine whether the effect of the key variable of interest (i.e., perceptual clarity) was affected by block (in the mixed-list group), or by block order (in the pure-list group) for each of the six dependent variables of interest: naming RTs and error rates in the study phase, and *d'*, beta, recollection estimates, and familiarity estimates in the recognition test phase. In the analysis of the within-list group, in which block served as a within-subject factor, block interacted significantly with perceptual clarity only in the analysis of error rates, $F(1,23) = 5.36$, $p = .030$, $\eta_p^2 = .189$, reflecting a higher error rate for blurry than clear words for block one, $t(23) = 2.94$, $p = .004$, $d = 0.85$, but not block two, $t(23) = 0.81$, $p = .212$, $d = 0.23$. In the analysis of the pure-list group, in which block order served as a between-subjects factor, block order interacted significantly with perceptual clarity only in the analyses of *d'*, $F(1,22) = 3.38$, $p = .043$, $\eta_p^2 = .131$, and familiarity estimates, $F(1,22) = 17.24$, $p < .001$, $\eta_p^2 = .439$. Although these result were of potential interest, they were found to be driven primarily by better memory performance and higher familiarity estimates generally in the first block than in the second block (which meant that performance in the clear-blurry group was numerically better for clear words than blurry words, and performance in the blurry-clear group was numerically better for blurry words than clear words). As none of these effects involving block or block order were deemed relevant, the data were collapsed across these variables in all of the analyses reported.

3.3. Discussion

One important result in this experiment was that recognition memory was again more sensitive for blurry words than for clear words. In this case, the analysis of *d'* again revealed an effect favouring blurry words that approached significance, while estimates of familiarity were significantly higher for blurry than clear words. The consistently higher sensitivity for blurry than clear words across Experiments 1 and 2, together with similar results reported later in this article, suggest strongly that this effect is a reliable one.

A second important result in this experiment is that the effect of perceptual clarity was not affected by whether clear and blurry items were presented in mixed or pure lists. Indeed, the differences in the *d'* values for clear and blurry words across the two groups were near identical (see Table 2). This result suggests that the effect of perceptual clarity on recognition observed here is not restricted to mixed-list presentations. As such, the underlying cause of the perceptual clarity effect discussed here may well differ from that of the production, generation, and bizarreness effects (MacLeod et al., 2010; McDaniel & Bugg, 2008).

4. Experiments 3A, 3B, and 3C

Having established the reliability of the perceptual clarity effect on recognition in Experiments 1 and 2, we turned to the issue of why this result was not observed by Yue et al. (2013). Recall that in the Yue et al. study, memory performance was found to be no better for blurry than clear items; indeed memory was consistently superior for clear than blurry words, and this difference was significant in one of five experiments. Across the five experiments, four tested memory using a free recall task (Experiments 1a, 1b, 2a, and 3), while one tested memory using a recognition task (Experiment 2b) at the time of test. Given our use of a recognition test, we focused primarily on differences between our method and Experiment 2b of the Yue et al. study.

One procedural difference between Experiment 1 of the present study and the method used by Yue et al. (2013) concerns encoding intent. In our Experiment 1, participants were instructed only to name the items as they appeared in the study phase and were not informed of a test phase. As such, encoding was incidental. In contrast, in the Yue et al. study encoding was intentional. Although encoding was also intentional in our Experiment 2, what was lacking across all of these separate experiments was a careful manipulation of encoding intent within a single experiment. We addressed this issue in Experiment 3A.

Another procedural difference between the two studies concerned the reinstatement of context at test. In Experiments 1 and 2 of the present study, context was fully reinstated, with blurry items at study presented blurry at test, and clear items at study presented clear at test. In contrast, Yue et al. (2013) did not reinstate context, instead presenting visual items (clear or blurry) at study and auditory items at test. Given the importance of context reinstatement to remembering (e.g., Godden & Baddeley, 1975; Tulving & Thomson, 1973), and in particular the possibility that benefits of context reinstatement may be pronounced for unique and perhaps difficult encoding contexts (Kolers, 1976), it seemed plausible that this difference across the two studies could be critical. This difference in methodology was addressed in Experiment 3B by replicating Experiment 1 with the exception of the use of auditory probes at test.

The method used in the present study also differed from that in the Yue et al. (2013) study in terms of study list length and the nature of the distractor task. For example, in Experiments 1 and 2 of the present study, 120 items were studied (across either one or two study lists), whereas Yue et al. used a single study list with only 52 items. Additionally, both

Experiments 1 and 2 of the present study employed a math distractor task between the study and test phases that was minutes in duration; in contrast, Yue et al. had participants count backward by multiples of three for ten seconds. These procedural differences, together with those addressed in Experiments 3A and 3B, were examined in Experiment 3C. In this experiment, participants were given intentional encoding instructions, and the test items were presented auditorily. Moreover, the study list was reduced from a single list of 120 items to a single list of 60 items, and participants completed a ten second distractor task between study and test.

4.1. Method

4.1.1. Participants. One hundred and eight participants were recruited from the McMaster University student pool and e-mail advertising, and completed Experiments 3A, 3B, and 3C in exchange for course credit or $5 cash per half hour spent participating in the study. All participants had normal or corrected-to-normal vision and spoke English fluently. The 48 participants (38 females) in Experiment 3A had a mean age of 19 years (standard deviation = 1.9 years); 24 participants were randomly assigned to each of the incidental and intentional encoding conditions. The 36 participants (24 females) who completed Experiment 3B had a mean age of 19 years (standard deviation = 2.2 years). The 24 participants (17 females) in Experiment 3C had a mean age of 24 years (standard deviation = 7.0 years).

4.1.2. Apparatus, stimuli, procedure, and design. The apparatus, stimuli, procedure, and design of Experiments 3A, 3B, and 3C were similar to those in Experiment 1, with exceptions noted separately for each experiment below.

4.1.2.1. Experiment 3A. The method for the incidental encoding group was identical to Experiment 1, and for the intentional encoding group was identical to Experiment 1 with one exception. Participants were told in the study phase that they were to read the words aloud as quickly and accurately as possible, *and* that they would be asked to remember the words later on.

4.1.2.2. Experiment 3B. The method of Experiment 3B was identical to Experiment 1 with the following exceptions. For the test phase, all stimuli were presented using auditory probes by importing sound files with the PsychoPy audio module; sound files were created using Audacity 2.0.5. To serve as reminders for which response corresponded to which key, the words “OLD” and “TYPE A” were presented on the left side of the screen, and the words “NEW” and “TYPE B” were presented in the right side of the screen. These reminders were centred vertically on the screen.

4.1.2.3. Experiment 3C. The method of Experiment 3C was identical to Experiment 3B with the following exceptions. Participants were informed that they would be asked to remember the words from the study phase in a later recognition memory test phase. To minimize the amount of time between the study and test phases, detailed instructions for the test phase (including remember/know instructions) were provided prior to the study phase. Additionally, the number of words used in the experiment was reduced by half, so that there were 60 words presented during study (30 clear and 30 blurry) and 120 words presented at test (60 old and 60 new). Word lists were constructed by taking a random half of the words from Experiments 1, 2, 3A, and 3B (see Appendix B). Finally, the distractor task lasted 10 seconds as opposed to 10 minutes, and required participants to count backward from 567 by multiples of 3 out loud.

4.2. Results

4.2.1. Study phase. Correct RTs were submitted to the same outlier analysis as Experiment 1, which resulted in the exclusion of 3.2%, 3.0%, and 3.1% of the RTs for

Experiments 3A, 3B, and 3C, respectively. Mean RTs were computed from the remaining observations, and were analyzed along with the corresponding error rates (see Table 1).

4.2.1.1. Experiment 3A. Mean RTs and error rates were analyzed using 2 x 2 mixed factor ANOVAs that treated perceptual clarity (blurry versus clear) as a within-subject factor, and group (incidental versus intentional encoding) as a between-subjects factor. As the study phase was the same for the two groups, the main effect of group and the interaction between group and perceptual clarity were not significant, *p*'s > .10. However, the main effect of perceptual clarity was significant for both RTs, $F(1,46) = 52.04$, $p < .001$, $\eta_p^2 = .531$, and error rates, $F(1,46) = 24.24$, $p < .001$, $\eta_p^2 = .345$. Consistent with Experiment 1, clear words were responded to faster (645 ms) and produced a smaller error rate (.002) than blurry words (715 ms; .016).

4.2.1.2. Experiment 3B. A one-tailed paired sample t-test revealed slower RTs for blurry (629 ms) than clear words (562 ms), $t(35) = 11.86$, $p < .001$, $d = 2.79$. A similar analysis of error rates indicated a higher error rate for blurry (.014) than clear words (.002), $t(35) = 5.07$, $p < .001$, $d = 1.19$.

4.2.1.3. Experiment 3C. A one-tailed paired sample t-test revealed slower RTs for blurry (723 ms) than for clear words (641 ms) $t(23) = 5.90$, $p < .001$, $d = 1.70$, while error rates did not differ significantly for clear (.002) and blurry words (.005), $t(23) = 1.16$, $p = .128$, $d = 0.34$.

4.2.2. Test phase. The proportions of "old" responses for each condition in Experiments 3A, 3B, and 3C, collapsed across participants, can be observed in Figure 4. For each of the experiments, the dependent measure of recognition memory sensitivity submitted to analysis was *d'*, with beta serving as a measure of response bias (see Table 2). The contributions of recollection and familiarity to recognition were also examined (see Table 3).

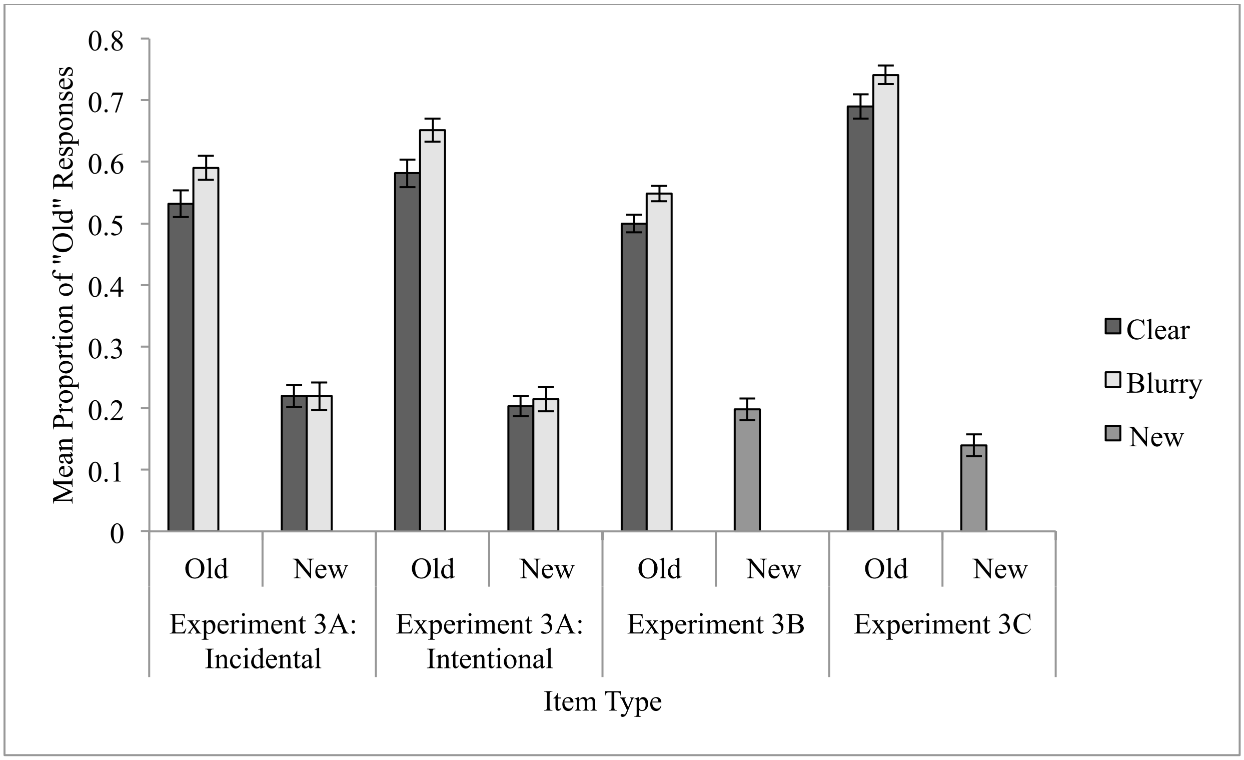

Figure 4. Mean proportion of “old” responses for Experiments 3A, 3B, and 3C. Error bars reflect the standard error of the mean, corrected for between-subject variability (Morey, 2008). As all items were presented as auditory probes at test for Experiments 3B and 3C, “old” responses to new items could not be classified as “clear” or “blurry” and are therefore presented as one overall false alarm rate.

4.2.2.1. Experiment 3A. The *d'* and beta values, as well as recollection and familiarity estimates for each condition were submitted to 2 x 2 mixed factor ANOVAs that treated perceptual clarity (blurry versus clear) as a within-subject factor, and group (incidental versus intentional encoding) as a between-subjects factor. The analysis of *d'* revealed a significant main effect of perceptual clarity, $F(1,46) = 9.06$, $p = .004$, $\eta_p^2 = .164$, indicating higher values of *d'* for blurry (1.21) than clear words (1.07). The perceptual clarity by group interaction was not significant, $F(1,46) = 0.20$, $p = .659$, $\eta_p^2 = .004$, indicating no difference in recognition sensitivity across the two groups. The analysis of beta revealed no significant effects, all *p*’s > .10.

In the analysis of recollection estimates, there was a significant main effect of perceptual clarity, $F(1,46) = 28.31$, $p < .001$, $\eta_p^2 = .381$, with higher estimates of recollection for blurry (.294) than for clear words (.226). This result was not obtained in the analysis of familiarity, though the main effect of group was significant, $F(1,46) = 5.41$, $p = .024$, $\eta_p^2 = .105$, with higher familiarity estimates for the intentional group (.272) than the incidental group (.199). All other effects were not significant, all *p*’s > .10.

4.2.2.2. Experiment 3B. Both *d’* and beta were submitted to two-tailed paired sample t-tests. The analysis of *d’* revealed greater sensitivity for blurry (1.09) than clear words (0.94), $t(35) = 2.90$, $p = .006$, $d = 0.68$, while the analysis of beta revealed no difference between blurry and clear words, $t(35) = 0.37$, $p = .713$, $d = 0.09$. A corresponding analysis of recollection estimates revealed significantly higher recollection estimates for blurry (.223) than clear words (.172), $t(35) = 2.90$, $p = .006$, $d = 0.68$. The analysis of familiarity estimates revealed no significant difference between blurry (.187) and clear words (.166), $t(35) = 1.35$, $p = .186$, $d = 0.32$ (see Table 3).

4.2.2.3. Experiment 3C. Again, *d’*, beta, recollection estimates, and familiarity estimates were submitted to two-tailed paired sample t-tests. The analysis of *d’* revealed an effect that approached significance, $t(23) = 1.92$, $p = .067$, $d = 0.55$, with higher *d’* values for blurry (1.89) than for clear words (1.65). The analyses of beta values and recollection estimates were not significant, all *p*’s > .10. The analysis of familiarity estimates revealed a greater contribution of familiarity to recognition of blurry (.482) than clear words (.403), $t(23) = 2.73$, $p = .012$, $d = 0.79$.

4.3. Discussion

The results of these experiments offer a clear picture. Together with the results of Experiments 1 and 2, they show that perceptual blurring at encoding can indeed produce a desirable difficulty effect. Across all of these experiments, recognition sensitivity was greater for blurry than clear items, and a corresponding difference was observed in either recollection or familiarity estimates in each experiment. At the same time, these experiments fail to identify why a desirable difficulty effect was not observed in Yue et al.'s (2013) study. None of the procedural differences that were examined in Experiments 3A (intentionality of encoding), 3B (context reinstatement), or 3C (study list length and distractor task) account for the different results observed here and in the Yue et al. study.

5. Experiments 4A and 4B

Two additional differences between our method and that of Yue et al. (2013) were the focus of the final two experiments. One difference that had yet to be explored was the level of blurring used. Although both studies used clear and Gaussian-blurred words as visual stimuli, Yue et al. (2013) blurred their words by 10%, whereas the words in all of the preceding experiments in this study were blurred by 15%. It seemed plausible that our 15% blurring manipulation increased encoding difficulty sufficiently to produce a desirable difficulty effect, whereas Yue et al.'s 10% blurring manipulation failed to do so. A second methodological difference examined in Experiment 4A concerned the task participants completed during the study phase. The participants in the preceding experiments of the present study were asked to read the words presented to them aloud as quickly and accurately as they could. In contrast, Yue et al. (2013) asked their participants to provide a JOL for every item presented in the study phase, indicating on a scale of 1-100 how likely they believed they would remember the word in a later memory test.

In each of Experiments 4A and 4B, we tested two groups of participants. For one group in each experiment, we used a Gaussian blur of 10% for the blurry words, and for the other group we used a Gaussian blur of 15% for the blurry words. In Experiment 4A, participants in both groups were asked to read each word aloud as quickly and accurately as possible, and were also asked to provide a JOL for each word. In Experiment 4B, participants in both groups were asked only to read each word aloud, as in the preceding experiments reported here (i.e., no JOL was required in Experiment 4B). If the use of a JOL task at encoding prevented Yue et al. (2013) from observing a desirable difficulty effect, then a desirable difficulty effect should not be observed for either of the two groups in Experiment 4A, but could well be observed for both groups in Experiment 4B. Together with the results of the preceding experiments, this result would imply that a JOL task promotes additional processing of items that makes it difficult to observe a desirable difficulty effect with a perceptual blurring manipulation. If the use of a more subtle blurring manipulation (i.e., 10% rather than 15% blur) contributed to Yue et al. not observing a desirable difficulty effect, then we may observe better remembering for blurry than clear words in the 15% blur condition but not for the 10% blur condition for both Experiments 4A and 4B. This result would suggest that encoding difficulty must reach some threshold level to trigger the mechanisms responsible for the desirable difficulty effect. Finally, if the use of JOLs and the more subtle blurring manipulation both contributed to the different results observed here and in the Yue et al. study, then we might well observe a combination of the two predicted patterns of results described above.

5.1. Method

5.1.1. Participants. Ninety-six undergraduate students were recruited from the McMaster University student pool and participated in Experiments 4A and 4B in exchange for course credit. Forty-eight of these participants (40 females, mean age = 20.0, standard deviation = 2.9 years) completed Experiment 4A. The other 48 participants (39 females, mean age = 19.6 years, standard deviation = 3.7 years) completed Experiment 4B. All participants in both experiments had normal or corrected-to-normal vision and spoke English fluently. Participants were randomly assigned either to the 10% blur or 15% blur conditions, with 24 participants assigned to each of these conditions in both experiments.

5.1.2. Stimuli, apparatus, procedure, and design. The stimuli, apparatus, procedure, and design were identical to Experiment 3C with the following exceptions.

5.1.2.1. Experiment 4A. A between-subjects factor that varied the degree of blurring for blurred words was added to the design. For one group of participants a 10% Gaussian blur was used, whereas for the other group of participants a 15% Gaussian blur was used (see Figure 1). During the study phase, as in prior experiments, participants were asked to name each word aloud as quickly and accurately as possible. Following the naming response, instructions appeared in the middle of the screen prompting participants to provide a JOL from 1-100 to indicate how likely they believed they would remember the word in the upcoming memory test. The instructions specified that 1 should be considered “least likely” and 100 should be considered “most likely”. Their responses were provided verbally, and entered by the experimenter via a keyboard response. Following the JOL being entered, the next trial began.

5.1.2.2. Experiment 4B. A between-subjects factor that varied the degree of blurring for blurred words was also added to the design of Experiment 4B. However, for this experiment, during the study phase participants were asked only to name each word aloud as quickly and accurately as possible. As such, the only difference in method between Experiments 4A and 4B was the inclusion of JOLs in Experiment 4A but not in Experiment 4B.

5.2. Results

5.2.1. Study phase. Correct RTs were submitted to the same outlier analysis used in Experiment 1, resulting in the exclusion of 2.0% and 3.0% of the RTs from further analyses in Experiments 4A and 4B, respectively. Mean RTs were computed from the remaining observations. In Experiment 4A, JOLs from trials in which the target word was named incorrectly were discarded, and mean JOLs were computed from the remaining observations.

5.2.1.1. Experiment 4A. Mean RTs, error rates, and mean JOLs were submitted to 2 x 2 mixed factor ANOVAs that treated perceptual clarity (clear versus blurry) as a within-subject factor, and group (10% blur versus 15% blur) as a between-subjects factor. Mean RTs and error rates can be observed in Table 1; JOLs can be observed in Table 3.

Table 3
Mean Judgments of Learning from Experiment 4

Group	Clear	Blurry	Mean
10% blur	51.6	50.7	51.1
15% blur	59.2	57.7	58.7
Mean	55.4	54.2	

The analysis of RTs revealed a significant main effect of perceptual clarity, $F(1,46) = 34.30$, $p < .001$, $\eta_p^2 = .427$, indicating faster responses for clear (693 ms) than blurry words (737 ms). The interaction between perceptual clarity and group approached significance, $F(1,46) = 2.83$, $p = .099$, $\eta_p^2 = .058$, with a larger difference between blurry and clear RTs in the 15% blur than the 10% blur group.

The analysis of error rates revealed an effect of perceptual clarity that approached significance, $F(1,46) = 3.36$, $p = .073$, $\eta_p^2 = .068$, with slightly higher error rates for blurry (.003) than clear words (.001). The main effect of group was significant, $F(1,46) = 4.49$, $p = .039$, $\eta_p^2 = .088$, indicating that participants in the 15% blur condition had an overall higher error rate (.003) than participants in the 10% blur condition (.001).

The analysis of JOLs revealed an effect of group that approached significance, $F(1,46) = 2.83$, $p = .099$, $\eta_p^2 = .058$, with overall higher JOLs in the 15% blur condition (58.7) than the 10% blur condition (51.1). The main effect of perceptual clarity was not significant, $F(1,46) = 1.30$, $p = .261$, $\eta_p^2 = .027$, indicating no difference between JOLs for clear (55.4) and blurry words (54.2). All other effects were not significant, all *p*'s > .10.

5.2.1.2. Experiment 4B. Mean RTs and error rates were submitted to the same 2 x 2 mixed factor ANOVAs as in Experiment 4A, with perceptual clarity as a within-subject factor, and group as a between-subjects factor. Mean RTs and error rates are listed in Table 1.

The analysis of RTs revealed a significant main effect of perceptual clarity, $F(1,46) = 41.17$, $p < .001$, $\eta_p^2 = .472$, with faster responses for clear (619 ms) than blurry words (660 ms). The interaction between perceptual clarity and group was significant, $F(1,46) = 31.69$, $p < .001$, $\eta_p^2 = .408$. To examine this interaction, the effect of perceptual clarity was analyzed separately for the two groups. In the 15% blur condition, the effect of perceptual clarity was significant, $t(23) = 8.09$, $p < .001$, $d = 2.34$, with faster responses for clear (622 ms) than for blurry words (698 ms). In contrast, in the 10% blur condition, the effect of perceptual clarity was not significant, $t(23) = 0.59$, $p = .281$, $d = 0.17$.

The analysis of error rates revealed a significant main effect of perceptual clarity, $F(1,46) = 7.93$, $p = .007$, $\eta_p^2 = .147$, with higher error rates for blurry (.018) than clear words (.003). Neither the main effect of group nor its interaction with perceptual clarity were significant, both *p's* >.10.

5.2.2. Test phase. The proportions of "old" responses, collapsed across participants, are displayed in Figure 5. Values of *d'* and beta (Table 2), as well as recollection and familiarity estimates (Table 3) were submitted to the same 2 x 2 mixed factor ANOVAs as described above for the study phase data.

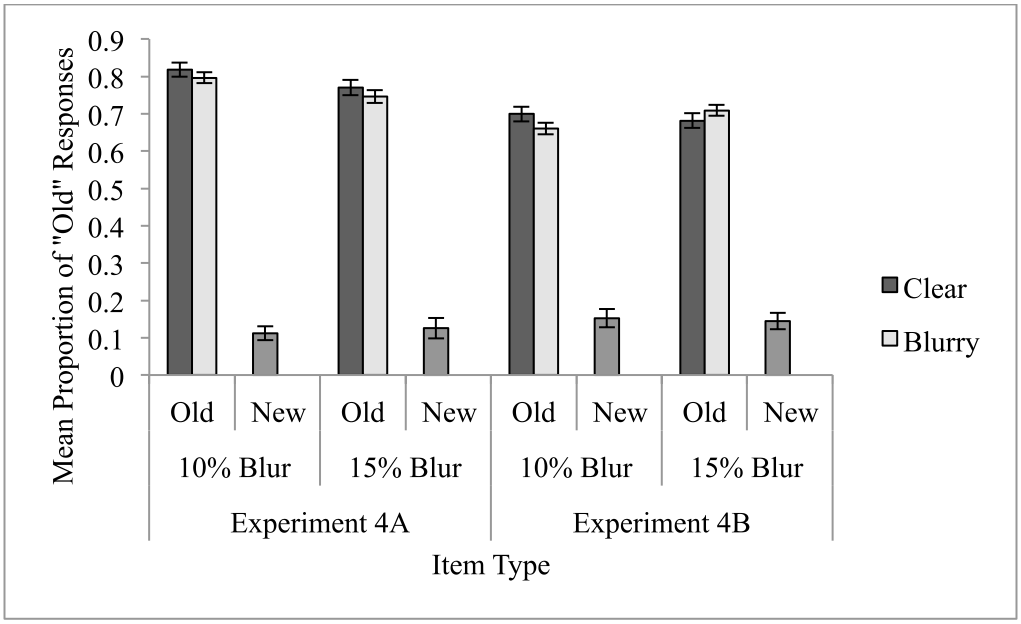

Figure 5. Mean proportion of "old" responses for Experiments 4A and 4B. Error bars reflect the standard error of the mean, corrected for between-subject variability (Morey, 2008). As all items were presented as auditory probes at test, "old" responses to new items could not be classified as "clear" or "blurry" and are therefore presented as one overall false alarm rate.

5.2.2.1. Experiment 4A. In the analysis of *d'*, the main effect of perceptual clarity was not significant, $F(1,46) = 2.80$, $p = .101$, $\eta_p^2 = .058$. Indeed, and in contrast to all previous experiments reported here, recognition sensitivity was numerically lower for blurry (2.13) than for clear words (2.24). None of the other effects in either the analysis of *d'* or beta reached significance, all *p*'s > .10.

The analysis of recollection estimates revealed a main effect of perceptual clarity, $F(1,46) = 8.96$, $p = .004$, $\eta_p^2 = .163$, with higher estimates of recollection for clear (.453) than blurry words (.405). In the analysis of familiarity estimates, a main effect of group was observed, $F(1,46) = 6.64$, $p = .013$, $\eta_p^2 = .126$, with a higher contribution of familiarity to recognition for the 10% blur group (.549) than 15% blur group (.425). All other effects in the analyses of recollection and familiarity estimates were not significant, all *p*'s > .10.

5.2.2.2. Experiment 4B. In the analysis of *d'*, the main effects of perceptual clarity and group were not significant, all *p*'s > .10. However, there was a significant interaction between perceptual clarity and group, $F(1,46) = 4.75$, $p = .034$, $\eta_p^2 = .094$, indicating that the effect of perceptual clarity did indeed depend on the level of blurring used. To examine this interaction further, the effect of perceptual clarity was examined separately for the two groups. In the 10% blur condition, the difference in *d'* between clear (1.74) and blurry words (1.62) approached significance, $t(23) = 1.74$, $p = .095$, $\eta_p^2 = .502$, with the numerical trend being opposite that observed in Experiments 1, 2, 3A, 3B, and 3C, and in line with the result reported above for Experiment 4A—that is, lower sensitivity for blurry than clear words. In contrast, for the 15% blur condition, the trend was opposite that observed for the 10% blur condition, and consistent with that observed in Experiments 1, 2, 3A, 3B, and 3C: higher sensitivity for blurry (1.79) than for clear (1.69) words, although in this case the effect was not statistically significant, $t(23) = 1.35$, $p = .190$, $d = 0.39$.

In the analysis of beta, the main effect of perceptual clarity approached significance, $F(1,46) = 3.02$, $p = .089$, $\eta_p^2 = .061$, indicating that the bias to respond “old” was slightly higher for blurry (2.43) compared to clear items (2.30) regardless of old/new status. All other effects were not significant, $p > .10$.

The analysis of recollection estimates revealed a main effect of perceptual clarity that approached significance, $F(1,46) = 3.96$, $p = .052$, $\eta_p^2 = .079$, with higher recollection estimates for clear (.371) than blurry words (.337). However, this main effect was qualified by a significant interaction, $F(1,46) = 10.95$, $p = .002$, $\eta_p^2 = .192$, that was examined further by analyzing the simple main effect of perceptual clarity for the two groups separately. For the 10% blur group, recollection estimates were significantly higher for clear (.377) than for blurry words (.286), $t(23) = 3.80$, $p < .001$, $d = 1.10$. In contrast, for the 15% blur group, there was a non-significant trend in the opposite direction, with lower recollection estimates for clear (.366) than for blurry words (.389), $t(23) = 0.92$, $p = .367$, $\eta_p^2 = .265$. None of the effects in the analysis of familiarity estimates were significant, all *p*'s > .10.

5.3. Discussion

In Experiments 4A and 4B, two different levels of blurring were used across groups within experiment to examine whether a certain level of blurring is required to observe a desirable difficulty effect. Additionally, the influence of task during study on later remembering was examined by requiring participants to name and provide a JOL for every word at the time of study in Experiment 4A only.

The results of the two experiments were very clear. First, recognition sensitivity did not differ significantly for clear and blurry words in either group in Experiment 4A; in fact, the trend in the analysis of *d'* favoured higher sensitivity for clear than for blurry words. Moreover, this trend was accompanied by higher estimates of recollection for clear than blurry words. These results nicely replicate the findings of Yue et al. (2013), in which they also observed a trend favouring better memory for clear over blurry words in all five experiments (this trend being statistically significant in one of the five experiments). The contrast between the results of

Experiment 4A and those of all preceding experiments in this study suggest strongly that introduction of a JOL task at the time of study modulates the influence of perceptual clarity on recognition. Specifically, it seems that the JOL task used by Yue et al. but not used in Experiments 1, 2, 3A, 3B, and 3C of the present study contributed to the different results observed across the two studies.

Remarkably, the results of Experiment 4B demonstrate that another of the methodological differences between our study and that of Yue et al. (2013) may also have contributed to discrepancies between the results of the two studies. In particular, the effect of perceptual clarity differed significantly for the 10% and 15% blur groups. Whereas for the 10% blur group recognition sensitivity favoured clear over blurry words, the opposite trend was observed for the 15% blur group. This result appeared to be driven by differences in recollection across the two groups. Recollection estimates were significantly higher for clear than blurry words in the 10% blur group, with the opposite trend observed in the 15% blur group. This set of results suggests that whether recognition sensitivity is greater for blurry than for clear words certainly hinges on the use of a level of perceptual blur that meets some criterion level. As such, it seems possible that even if Yue et al. had not included a JOL task at the time of encoding, the level of blurring that they used may not have been sufficient to produce a desirable difficulty effect in recognition memory performance.

6. General Discussion

The series of experiments reported here examined the influence of perceptual blurring on recognition memory, and in particular focused on when blurring does and does not constitute a “desirable difficulty” (R. A. Bjork, 1994). In Experiment 1, recognition memory was better for blurry than clear words, a result that contrasts with the null effect of perceptual blurring reported in a recent study by Yue et al. (2013). In Experiment 2, the same effect was observed, with no evidence that this effect differs for mixed-list and pure-list procedures. The purpose of the remaining experiments was to establish precisely which procedural differences were responsible for the different results across our study and the Yue et al. study.

The results of Experiments 3A, 3B, and 3C ruled out differences in encoding intent, context reinstatement, study list length, and distractor task as the source of the different results. Experiments 4A and 4B were designed to examine two additional methodological differences between the two studies: (1) The degree of perceptual blurring, which was slightly less in Yue et al.'s study than in our study; and (2) the use of a JOL task during encoding, which was used in the Yue et al. study, but not in the first five experiments of our study. To address these differences, the degree of perceptual blurring was manipulated between groups in both Experiments 4A and 4B. In Experiment 4A, both groups were asked to provide a JOL for each word after reading it aloud during the study phase, whereas in Experiment 4B, neither group was required to provide JOLs during the study phase. Importantly, the results for both groups in Experiment 4A were similar to those in Yue et al.'s study, with recognition sensitivity numerically higher for clear than blurry items, and recollection estimates significantly higher for clear than blurry items. In Experiment 4B, the effect of perceptual clarity differed significantly (and qualitatively) between the 10% and 15% blur groups, with trends favouring higher recognition sensitivity for clear than blurry words for the 10% blur group, and the opposite pattern for the 15% blur group. Indeed, recollection estimates were significantly higher for clear than blurry items for the 10% blur group. The results of this experiment imply that differences in the degree of blurring between the Yue et al. study and our study may also have contributed to the different results across the two studies[3].

Three important conclusions can be drawn from these results. First, it is evident that perceptual blurring can constitute a desirable difficulty, in the sense that it can increase the difficulty of encoding but also enhance recognition performance. This result was observed in Experiments 1, 2, 3A, 3B, and 3C with the effect size being moderate in each of these experiments (Cohen, 1977). As such, perceptual blurring adds to a growing list of encoding manipulations that produce such effects (see also Besken & Mulligan, 2014; Diemand-Yauman et al., 2011; Krebs et al., 2013; Nairne, 1988; Rosner et al., 2014). Second, the results of Experiment 4B demonstrate that whether or not a desirable difficulty effect occurs can depend on the degree of perceptual degradation at the time of encoding. Thus, the absence of perceptual degradation effects in the Yue et al. (2013) study, as well as in the earlier study by Hirshman et al. (1994), may both owe to perceptual degradation manipulations that fell short of that required to produce such an effect on remembering. Third, the present results demonstrate the importance of the JOL task at encoding on later remembering. Yue et al. (2013) had participants provide JOLs at encoding across all of their experiments, and in none of their five experiments did they observe superior memory for blurry than clear words. We had participants provide JOLs at encoding only in Experiment 4A, and we also failed to observe superior recognition for blurry

[3] There remain other differences between the Yue et al. (2013) study and ours that went unexplored, and that may also have impacted the results. For example, in the current set of experiments, we asked participants to provide a remember/know judgment for items judged old at test. In contrast, Yue et al. (2013) asked their participants (in Experiment 2b, which also tested recognition memory) to provide a source memory judgment—that is, to indicate whether items judged old at test were clear or blurry at the time of study. However, we view it as unlikely that this difference in method would produce a large difference in results. Although these two types of judgments can both affect recognition memory performance when compared to simple yes/no judgments, remember/know and source memory paradigms often produce very similar results (Mulligan, Besken, & Peterson, 2010). Another difference between studies that went unexplored was stimulus duration in the study phase (1000 ms in the current study, and 2000 ms in the recognition memory experiment conducted by Yue et al., 2013). Whether a longer stimulus duration at study would eliminate the desirable difficulty effect observed in the present study remains an issue for future research.

than clear words in that experiment. Together, these findings support the idea that JOLs at the time of encoding can eliminate the beneficial effect of perceptual blurring on recognition.

Prior studies in which JOLs have been implemented fit well with the impact of JOLs observed in this study. A key issue revealed in these prior studies is that different mechanisms may be involved in making item-by-item JOLs (providing a JOL following every item, as in Experiment 4A) versus aggregate JOLs (an overall estimate for a specific item type following the completion of an encoding phase; Koriat, Bjork, Sheffer, & Bar, 2004). In the case of item-by-item JOLs, it seems possible that processes involved in making JOLs encourage further processing of each item. This additional processing may produce semantic representations for the study items that serve as an alternative basis for recognition memory decisions to those that produce superior recognition for blurry over clear items (see Soderstrom, Clark, Halamish, & Bjork, 2015 for a similar argument). In contrast, aggregate JOLs are less likely to impact processing of individual items, leaving effects of difficulty on remembering intact. Consistent with this view, item-by-item JOLs have been observed to eliminate the well-documented generation effect (Begg, Vinski, Frankovich, & Holgate, 1991; Matvey, Dunlosky, & Guttentag, 2001). Further, item-by-item JOLs, but not aggregate JOLs, have been found to eliminate the perceptual interference effect (Besken & Mulligan, 2013, 2014). Together with the results of the present study, these results make the point that desirable difficulty effects in remembering may be difficult to observe when item-by-item JOLs are made at the time of encoding (see also Rhodes & Castel, 2008, 2009).[4]

[4] It is unclear why the effect of blurring on JOLs was not significant in Experiment 4A, whereas it was significant across the five experiments conducted by Yue et al. (2013). In any case, the mean JOLs were in the predicted direction, and the introduction of the JOL task at encoding clearly produced a different pattern of recognition results than those observed in the experiments without the JOL task. These results indicate that the introduction of JOLs, but not necessarily a difference in metacognitive judgments, is sufficient to eliminate an effect of perceptual blurring on recognition.

6.1. Desirable Difficulty: A Time-on-Task Effect?

The result of primary interest here is that slow naming times for difficult-to-encode items in the study phase were associated with better recognition of those same items in the recognition test phase. Although this result constitutes an example of a desirable difficulty effect, the mechanisms underlying such effects remain an open issue. Our preferred interpretation is that encoding difficulty cues a form of attentional response that in turn leads to better remembering. However, it could be argued that better remembering for more difficult items is simply an artefact of increased time-on-task.[5] Although this time-on-task account does not explain the results of Experiment 4A, in which slower RTs were observed for blurry than clear words and recollection estimates were higher for clear than blurry words, we were interested in assessing whether this account might fit with the results of the other experiments.

Two sets of analyses were conducted on the pooled data from Experiments 1, 2, 3A, 3B, 3C, and the 15% blur group of Experiment 4B to examine this time-on-task explanation. The first analysis involved comparing RTs from the study phase for words that were remembered versus words that were forgotten in the test phase. If time to name an item is invariably linked to how well that item is remembered, slower RTs should be observed for remembered than forgotten items. One-tailed paired sample t-tests revealed that this difference approached significance for blurry items, $p = .071$, but not for clear items, $p = .923$. Thus, although remembered blurry items were responded to more slowly than forgotten blurry items at the time of study, this pattern was not observed for clear items, offering a first indication that processes aside from time-on-task influence later remembering.

[5] A simple time-on-task account also neglects the fact that stimulus durations for the clear and blurry words in the study phase were equated. Only a time-on-task account that focuses on time spent actively encoding for the purpose of responding is at all plausible.

The second analysis involved conducting a median split to separate words into "slow" and "fast" groups based on RT during the study phase. From this split, *d'* for slow and fast blurry and clear words could be determined. If time-on-task was the sole determinant of later remembering, higher *d'* values should be observed for slow than fast words within item types. Paired sample t-tests revealed no difference in *d'* between slow and fast clear words; the same was true for blurry words, all *p*'s > .10. However, a more telling analysis comes from the comparison of slow clear and fast blurry words. Although RTs were slower for the slow clear (699 ms) than fast blurry words (580 ms), $p < .001$, *d'* values were still higher for the fast blurry (1.41) than slow clear words (1.30), $p = .002$. In other words, these blurry words were responded to faster and still better remembered than the clear words. These findings demonstrate that a time-on-task explanation falls short of accounting for the desirable difficulty effects observed in the current study.

6.2. Desirable Difficulty: An Attentional-Response-to-Conflict Effect?

As noted above, the present series of experiments was originally motivated by an earlier study in our lab that examined the relation between selective attention processes at encoding and recognition memory (Rosner et al., 2014). In that study, participants identified the red word in a pair of red and green spatially interleaved words that were either the same (congruent) or different (incongruent). The key result in that study was that naming times were faster for congruent than for incongruent items, and performance in a following surprise recognition memory test was better for incongruent than congruent items (see also Krebs et al., 2013). Although this result is unmistakably consistent with the desirable difficulty principle, the study was in fact motivated by theoretical developments in the cognitive control literature.

The conflict monitoring model (Botvinick et al., 2001) is a prominent theory of cognitive control. According to this model, the anterior cingulate cortex detects response conflict (the activation of multiple competing responses), which in turn leads to activation of the dorsolateral prefrontal cortex (DLPFC) and an increase in cognitive control. The specific rationale for our selective attention study derives from the conflict monitoring model, but assumes that conflict on incongruent trials might up-regulate learning and memory processes that have an episodic component (see Crump, Gong, & Milliken, 2006; Egner, Delano, & Hirsch, 2007; Kiesel, Kunde, & Hoffmann, 2006; Spapé & Hommel, 2008; Verguts & Notebaert, 2008), and that might therefore lead to improved remembering (Rosner et al., 2014; see also Krebs et al., 2013). Indeed, Krebs et al. (2013) recorded brain activation during the study phase of their experiment using functional magnetic resonance imaging, and observed higher DLPFC activity for remembered than not-remembered incongruent items, but no such difference for congruent items. These results offer preliminary support for the view that DLPFC activation in response to conflict triggers adjustments in cognitive control that can impact remembering.

In light of these recent findings and their interpretation within the conflict monitoring framework, one of the aims of the present study was to examine whether perceptual blurring of a single word at encoding produces the same effect as congruency between two words at encoding. The results of the present study indicate clearly that this is the case. Of course, these two effects might well have entirely separate causes, in which case the results of the present study would not speak to the notion that conflict up-regulates cognitive control and enhances remembering. On the other hand, it seems worthwhile to at least consider how these two effects might have one and the same cause. Clearly, that cause could not be up-regulated cognitive control in response to conflict triggered by distractor interference, as there were no explicit distractors in the experiments reported in the present study. However, it seems plausible that up-regulated cognitive control could be triggered by the need for additional encoding resources to resolve response *ambiguity*—that is, when a possible response is not readily available based on the perceptual information provided—rather than response conflict, specifically. In addition to offering a plausible account of the desirable difficulty effects observed here, this idea is consistent with the results of Experiment 4B, in which the blurry items in the 10% blur condition may not have been blurry enough to lead to response ambiguity, and thus conferred no benefit of blurring to recognition. More generally, this theoretical view is consistent with one and the same mechanism being responsible for the selective attention results described above and a host of perceptually-based desirable difficulties, such as those produced with perceptual blurring, masking (Nairne, 1988), and fragmented words (Besken & Mulligan, 2013, 2014). Of course, the challenge moving forward is to predict a priori which difficulty manipulations ought to produce the response ambiguity that up-regulates cognitive control and improves remembering.

7. Conclusion

The present study demonstrates that perceptual blurring can produce a desirable difficulty effect, with better recognition memory performance for the less fluently processed blurry items, provided that the blurring manipulation is sufficiently strong. At the same time, and in line with other similar studies reported recently (Besken & Mulligan, 2013, 2014), additional encoding processes associated with item-by-item JOLs appear to eliminate this perceptual blurring effect in our study (Experiment 4A). The relation between this desirable difficulty effect and other effects of encoding difficulty that involve selective attention, pattern masking, and other methods is an issue that merits further study.

Appendix A

Word Lists for Experiments 1, 2, 3A, and 3B

Word List 1:

ACTOR, BIRTH, BLOCK, BRIDE, BRUSH, CHIEF, CHILD, CLASS, CLEAN, CLERK, CROWD, CRUSH, DOUBT, DRINK, EMPTY, EQUAL, FENCE, FROWN, GRANT, GUESS, GUEST, HEART, JUDGE, JUICE, KNOCK, LEAVE, LEMON, LEVEL, LIGHT, LINEN, LUNCH, PIECE, PORCH, PRINT, RADIO, ROUGH, ROUND, SCENE, SCORE, SHAPE, SHOCK, SIGHT, SPACE, SPEED, SPORT, STAMP, STAND, STATE, STONE, STORY, SWEET, TREAT, TRUCK, TRUST, TRUTH, TWIST, UNCLE, VALUE, WASTE, WATER

Word List 2:

ALARM, ASIDE, BOUND, BREAD, BURST, CHAIR, CHARM, CHECK, CHILL, CLAIM, CLOCK, CLOTH, COVER, CRASH, DAILY, DANCE, DREAM, DRIFT, FAINT, FLOOR, FRONT, GLASS, GUIDE, HONEY, HOTEL, MAJOR, MOUTH, MUSIC, NIGHT, OFFER, ONION, ORDER, PLANK, POUND, PRIZE, RANCH, REACH, RIVER, SALAD, SAUCE, SHADE, SHARP, SHEET, SHORT, START, STILL, STOCK, TASTE, TEETH, THROW, TODAY, TRACE, TRAIL, TRICK, VISIT, VOICE, WAGON, WHEEL, WHILE, WORST

Word List 3:

APPLE, BENCH, BLIND, BRAIN, CATCH, CHEST, CLOUD, COAST, CRACK, CROSS, DRESS, EARTH, EVENT, EXTRA, FIELD, FLAME, FORCE, GROUP, GUARD, HORSE, HURRY, IDEAL, LAUGH, LEAST, LIMIT, MATCH, MONTH, NOISE, NURSE, OTHER, OWNER, PAINT, PAPER, PAUSE, QUICK, QUIET, RANGE, SHARE, SHINE, SMALL, SMELL, SMILE, SOUND, SPOIL, STAGE, STARE, STORE, STORM, STRIP, STUDY, STUFF, SWING, TABLE, THING, TRACK, TRAIN, WATCH, WOMAN, WORLD, WOUND

Word List 4:

BATHE, BOARD, BREAK, BRIEF, CABIN, CHEEK, CLIMB, COUNT, COURT, DRIVE, FLASH, FLOUR, FLUSH, FRAME, FRUIT, GRASS, HOUSE, ISSUE, KNIFE, LOCAL, MIGHT, MODEL, MONEY, MORAL, MOTOR, MOVIE, NERVE, PARTY, PHONE, PLANE, PLANT, PLATE, POINT, PRESS, PRICE, PRIDE, RIGHT, SENSE, SERVE, SHELL, SHIRT, SHORE, SHOUT, SKIRT, SLEEP, SLICE, SMART, SMOKE, SPOKE, STEEL, STICK, STYLE, SUGAR, TIMER, TOTAL, TOUCH, TRADE, UNDER, UPPER, YOUTH

Appendix B

Word Lists for Experiments 3C, 4A, and 4B

Word List 1:

BIRTH, BRIDE, CHIEF, CHILD, CLASS, EMPTY, FENCE, GRANT, GUESS, HEART, JUDGE, JUICE, KNOCK, LEMON, LIGHT, LUNCH, PORCH, ROUGH, ROUND, SCENE, SIGHT, SPEED, SPORT, STAMP, STATE, SWEET, TREAT, TRUCK, TRUST, WASTE

Word List 2:

BREAD, CHARM, CHECK, DREAM, DRIFT, GLASS, GUIDE, HONEY, MAJOR, MOUTH, NIGHT, OFFER, ORDER, POUND, PRIZE, RANCH, REACH, SAUCE, SHADE, SHORT, STILL, STOCK, TASTE, TEETH, TODAY, TRACE, TRICK, VISIT, WHEEL, WHILE

Word List 3:

ALARM, ASIDE, BOUND, BURST, CHAIR, CHILL, CLAIM, CLOCK, CLOTH, COVER, CRASH, DAILY, DANCE, FAINT, FLOOR, FRONT, HOTEL, MUSIC, ONION, PLANK, RIVER, SALAD, SHARP, SHEET, START, THROW, TRAIL, VOICE, WAGON, WORST

Word List 4:

ACTOR, BLOCK, BRUSH, CLEAN, CLERK, CROWD, CRUSH, DOUBT, DRINK, EQUAL, FROWN, GUEST, LEAVE, LEVEL, LINEN, PIECE, PRINT, RADIO, SCORE, SHAPE, SHOCK, SPACE, STAND, STONE, STORY, TRUTH, TWIST, UNCLE, VALUE, WATER

Acknowledgments

Financial support for this study was provided in part by a Natural Sciences and Engineering Research Council of Canada Discovery Grant awarded to Bruce Milliken. The funding agreement ensured the authors' independence in designing the study, interpreting the data, writing, and publishing the report. The authors report no conflicts of interest. We would like to thank Stefania Cerisano for lending us her voice for the auditory probes in this study.

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