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Abstract

Episodic recognition memory is mediated by functionally separable retrieval processes, notably familiarity (a general sense of prior exposure) and recollection (the retrieval of contextual details), whose relative engagement depends partly on the nature of the information being retrieved. Currently, the specific contribution of familiarity to associative recognition memory (where retrieval of the relationships between pairs of stimuli is required) is not clearly understood. Here we test domain dichotomy theory, which predicts that familiarity should contribute more to associative memory when stimuli are similar (within-domain) than when they are distinct (between-domain). Participants studied stimulus pairs, and at test, discriminated intact from rearranged pairs. Stimuli were either within-domain (name-name or image-image pairs) or between-domain (name-image pairs). Across experiments we employed two different behavioural measures of familiarity, based on ROC curves and a Modified Remember-Know procedure. Both experiments provided evidence that familiarity can contribute to associative recognition; however familiarity was stronger for between-domain pairs - in direct contrast to the domain dichotomy prediction.

Familiarity for Associations? A Test of the Domain Dichotomy Theory

Dual-process theory posits the existence of familiarity and recollection, two functionally and neurally separable processes underlying episodic memory retrieval (for a review see Yonelinas, 2002). An item is familiar if it simply engenders a sense of having been encountered before, whereas recollection provides additional contextual details about a previous episode. The two processes have been repeatedly dissociated, using a wide range of encoding conditions (e.g., Jacoby, 1998), retrieval tasks (e.g., Lecompte, 1995), and stimuli (e.g., Ratcliff, McKoon & Tindall, 1994), providing strong support for the dual-process distinction. Despite this, many substantive issues remain unresolved, including the relationship between the processes (Jacoby, 1991; Joordens & Merikle, 1993) and how they interact with other memory systems (Greve, van Rossum & Donaldson, 2007; Yovel & Paller, 2004). Here we focus on a related question: under what circumstances can familiarity contribute to successful recognition?

Familiarity is generally agreed to play an important role in standard item recognition memory tests, which assess memory for individual stimuli. Even when recollection is clearly impaired, for example in amnesic patients (Holdstock et al., 2002; Mayes, Holdstock, Isaac, Hunkin & Roberts, 2002), familiarity provides a strong basis for accurate performance. In contrast, in tests requiring memory for relationships between items, familiarity has traditionally been thought to play a less prominent role (Hockley & Consoli, 1999). Indeed, associative recognition tasks have been used to isolate recollection (e.g., Donaldson & Rugg, 1998), consistent with the belief that memory for such relationships should be supported exclusively by recollection (Yonelinas, 1997).

**Does familiarity support associative recognition?**

More recently, episodic memory theorists have begun to consider circumstances under which familiarity might contribute to associative recognition. In particular, a growing body of evidence suggests that when distinct stimuli are unitized (encoded and retrieved as a single unit) familiarity does contribute to associative recognition (Rhodes & Donaldson, 2007; Quamme, Yonelinas & Norman, 2007; Haskins, Yonelinas, Quamme & Ranganath, 2008). For example, behavioural and imaging data suggest that pairs of linguistically associated words, like “traffic-jam”, evoke more familiarity at retrieval than semantically related word pairs, like “cereal-bread” (Rhodes & Donaldson, 2008). Accordingly, some models of episodic memory propose that familiarity can support associative recognition, but only when to-be-remembered pairs are unitized (Eichenbaum, Yonelinas & Ranganath, 2007; Diana, Yonelinas & Ranganath, 2007).

Whilst unitization has received substantial empirical support, the ‘domain dichotomy’ theory (Mayes, Montaldi & Migo, 2007) provides an alternative account of why familiarity might sometimes contribute to associative recognition. According to this view, familiarity can support successful associative recognition even when stimuli are not unitized; instead, the contribution of familiarity is driven primarily by overlapping component representations in the medial temporal lobes. It is important to note that while item familiarity can support associative recognition indirectly (e.g., by providing a cue for recollection), both the unitization and domain dichotomy accounts propose and refer to a separate global familiarity for the associated pair. Here we provide a brief overview of domain dichotomy and its empirical predictions, before presenting two experiments that directly test the domain dichotomy view.

**The Domain Dichotomy Theory**

Domain dichotomy is based on a neuroanatomical account of medial temporal lobe function. At the heart of the theory is the separation of 'within-domain' and 'between-domain' associations. Within-domain associations (e.g., between two images or two words) occur between pairs of items that share some characteristics (e.g., modality; semantic category; component features) and are therefore likely to be represented by activity in overlapping populations of neurons in the perirhinal cortex. Between-domain associations (e.g., between an image and a word) conversely share fewer characteristics and so their representations are expected to be more distal and weakly connected.

This neuroanatomical account is itself derived in part from neural network models, which provide specific predictions about the role of familiarity. Computational models of familiarity typically invoke Hebbian type learning rules, causing similar inputs to be stored as similar patterns of activation and strengthening the overlap of these representations through repeated activation (Norman & O'Reilly, 2003; but see Greve, Donaldson & van Rossum, 2010). This view implies that similar items should interact strongly, leading to better support from familiarity (Mayes et al., 2007). Consistent with this, some studies have shown patients with hippocampal lesions to be more strongly impaired at recognising between-domain than within-domain pairs (Vargha-Khadem et al., 1997; Mayes et al., 2004). Here we use healthy participants to test a prediction that domain dichotomy derives from lesion data, namely that within-domain pairs should be better supported by familiarity than between-domain pairs.

**Testing Domain Dichotomy**

We assess the predictions of domain dichotomy by examining associative recognition memory using two different measures of familiarity – safeguarding against the particular assumptions associated with each. First, we use confidence judgments made at test to form receiver-operator characteristic (ROC) curves; this allows estimates of familiarity and recollection to be derived using mathematical memory models (see Yonelinas, 2002). Second, we use phenomenological data, asking participants directly about their memory experience. In the original remember-know procedure (Tulving, 1985) participants were required to identify if they recollected some aspect of the original experience (remember), or if they simply found the test stimulus familiar (know). Given recent criticism of this method, in particular by proponents of domain dichotomy (Montaldi, Spencer, Roberts & Mayes, 2006; Mayes et al., 2007), here we use their modified procedure - making the terms familiarity and recollection explicit, training participants to distinguish recollection from high-confidence familiarity, and examining familiarity and recollection in separate tasks.

To examine memory we use a standard associative recognition task, presenting pairs of stimuli at study, and requiring participants to distinguish intact from rearranged pairs at test. If familiarity does contribute to successful associative recognition, both ROC analysis and the modified remember-know procedure should find evidence of it. Importantly, if the domain dichotomy view is correct, both methods should find greater estimates of familiarity for within-domain than between-domain pairs. As we explain below, both experiments found evidence of familiarity, but in stark contrast to the predictions of domain dichotomy theory it contributed more when pairs were between-domain.

## Experiment 1

We employed names and abstract images as stimuli; because they differ both conceptually and perceptually they should occupy different ‘domains’. In particular, each class of stimulus was chosen so that individual exemplars shared many features (e.g., size and shape), whilst still being individually distinguishable. Given these constraints, on average a name-image pair should be more between-domain than either a name-name pair or image-image pair. We also considered that one class of stimulus might be inherently more recognisable than another. To isolate relationship-driven memory differences, name-name and image-image pairs were collapsed to form a general within-domain condition, hence the relationship between items differed across conditions (within-domain; between-domain) but the items did not.

It has also been suggested that two representations must be directly encoded for overlap to occur (Mayes et al., 2007). We encouraged direct encoding in two ways. First, the items comprising each pair were presented simultaneously at study. Second, participants were instructed to judge how well the two items went together, without linking them via additional self-generated cues.

**Methods**

In Experiment 1 we examined memory using 9-point ROC curves, constructed separately for each participant. We estimated the contribution of familiarity and recollection using the Dual-Process Signal Detection (DPSD) model (Yonelinas, 1997), characterising recollection as a probabilistic process and familiarity as a continuous signal.

**Participants.** Thirty right-handed participants completed the Experiment; 1 data set was excluded due to non-compliance. The remaining 29 participants (11 female; mean age 22.8, range 18-31) all had normal or corrected-to-normal vision and no known neurological problems. Participants gave informed consent (approved by the University of Stirling Department of Psychology Ethics Committee) and either received course credits or were compensated for their time at a rate of £5 per hour.

**Stimuli.** Each stimulus comprised a pair of items presented above and below central fixation, as illustrated in Figure 1. We employed three stimulus conditions. Within-domain conditions comprised pairs of either Christian names (WD-Names) or abstract images (WD-Images); a between-domain (BD) condition comprised equal proportions of image-name and name-image pairs. Names were screened for length (4-7 letters) and frequency in the adult population (derived from names in the top 1000 US male or female names between 1950 and 1990, see www.ssa.gov). Common shortenings of the same name were used if they were easily distinguishable from each other (e.g., Tony/Anthony). A separate group of participants (N=9) rated 575 images for abstractness (nameable; slightly nameable; abstract) and the most abstract were selected for use in this study. The selected images were rated "abstract" 93% of the time. In total 324 names and 324 images were used.

**Procedure.** The experiment was implemented using E-Prime (www.pstnet.com) and responses collected using a 5-button PST Serial Response Box. Instructions and lexical stimuli were presented in bold white 18-point Courier New typeface against a black background. At a viewing distance of approximately 1 metre the items in each stimulus pair together subtended a maximum visual angle of $3.7^{o}$ vertically and $3.4^{o}$ horizontally.

The experiment was divided into 12 blocks, 4 for each stimulus condition, ordered randomly. Each block was further divided into a 27-trial study phase and an 18-trial test phase. At test, 9 pairs of items were intact (appeared together in the preceding study phase) and 9 were rearranged (appeared in separate study trials). For example, given three pairs A-B, C-D and E-F at study, an intact test pair would be A-B and a rearranged test pair C-F (discarding items D and E). Thus, every item shown at test had been encountered exactly once at study and successful performance required participants to remember the relationships between items.

Figure 1 shows the procedure for Experiment 1. Each study trial began with a blank screen for 500ms, followed by a central fixation cross for 1000ms, and a second blank screen for 100ms. The to-be-remembered pair was then presented for 3000ms. Following a 500ms blank screen participants were required to indicate on a scale from 1-5 how well the two items went together; this response initiated the beginning of the next trial.

Test trials were identical to study trials except that each pair was presented for 1000ms, and the response screen asked participants to judge whether the items were intact or rearranged. Following the *intact/rearranged* response participants indicated how confident they were that they were correct, again using a scale of 1-5. This confidence response initiated the beginning of the next trial.

At both study and test the mapping of left and right buttons to (*intact/rearranged*) and (*1-5*) responses was fully counterbalanced across blocks of 4 participants; the stimulus condition (*WD/WD/BD*) and test condition (*intact/rearranged/not shown*) of each item was fully counterbalanced across blocks of 9. On average the procedure took 1.5 hrs to complete, including a practice block and debriefing.

**Results**

Mean ROC curves for each condition are presented in Figure 2; each exhibits clear curvilinearity, consistent with a contribution of familiarity to performance. Below we explicitly assess whether the contribution of familiarity varies across conditions, as predicted by the domain dichotomy theory.

As a more informative measure of performance than accuracy, discrimination $d_a$ was calculated directly from participant confidence judgments. Where $\mu_i$ and $\mu_r$ denote the mean confidence rating to intact and rearranged pairs respectively, and $\sigma_i$ and $\sigma_r$ denote their standard deviations, $d_a$ is calculated by:

$$d_a = \frac{\mu_i - \mu_r}{\sqrt{(\sigma_i^2 + \sigma_r^2)/2}}$$

We also fit individual subjects' ROC curves to the associative DPSD model, which yields three parameters: recall-to-accept (rate of recollection to intact pairs), recall-to-reject (rate of recollection to rearranged pairs) and familiarity. All estimates were computed separately for each participant and condition.

Overall task performance is summarised in Figure 3A. Paired t-tests revealed significantly lower discrimination in the WD-Image condition (0.86) than either the BD (1.91; $t(28) = 6.62$, $p = .001$) or WD-Name (1.86; $t(28) = 6.19$, $p = .001$) conditions. No difference in discrimination was found between the BD and WD-name conditions ($p = .766$).

Mean familiarity estimates for each condition are presented in Figure 3B. Paired t-tests showed significantly lower familiarity estimates for the WD-Image condition (0.44) than either the BD (1.15; $t(28) = 4.00$, $p = .001$) or WD-Name (1.08; $t(28) = 3.69$, $p = .001$) conditions; WD-Name and BD did not reliably differ ($p = .658$). Crucially, and inconsistent with domain dichotomy, neither WD condition had higher familiarity than the BD condition.

Recollection rates were analysed using an ANOVA with factors of type (*recall-to-accept/recall-to-reject*) and condition (*BD/WD-Name/WD-Image*). A main effect of condition ($F(2,56) = 4.50$, $p = .015$) reflected lower recollection for WD-Image (0.15) than BD (0.24; $t(28) = 2.24$, $p = .033$) or WD-Name (0.26; $t(28) = 2.70$, *p* = .012) conditions, but WD-Name and BD conditions did not differ (*p* = .517). A main effect of type (*F*(1,28) = 12.08, *p* = .002) reflected higher rates of recall-to-accept (0.27) than recall-to-reject (0.17); this did not interact with condition (*p* = .661). Overall recollection rates are illustrated in Figure 3C, collapsed across type. We assessed relationship-driven effects in two ways. First, items were matched across conditions by collapsing WD pairs together for each participant. Paired t-tests revealed stronger discrimination for BD than WD pairs (1.91 vs 1.22; *t*(28) = 4.83, *p* = .001; Cohen's *d* = 1.096); driven by greater familiarity (1.15 vs 0.75; *t*(28) = 2.46, *p* = .021; Cohen's *d* = 0.711), but not recollection (0.24 vs 0.21, *p* = .337). Second, we controlled for item effects by regressing discrimination, familiarity and recollection separately against factors of item (*two/one/zero names*) and relationship (*WD/BD*); full details are given in the online supplementary material. Item type was significant for all three dependent variables: names led to better discrimination (*B* = 0.991; *p* = .001), familiarity (*B* = 0.636; *p* = .001) and recollection (*B* = 0.112; *p* = .010) than images. Relationship had a significant effect (BD>WD) on discrimination (*B* = 0.547; *p* = .002) and familiarity (*B* = 0.392; *p* = .016) but not recollection (*p* = .391). All reported effect sizes are unstandardized. Importantly, both methods reveal *greater* familiarity for BD than WD pairs, independent of item effects: the opposite pattern to that predicted by domain dichotomy.

**Discussion**

Familiarity estimates from a DPSD model were significantly greater than zero for all pair types, consistent with a contribution of familiarity to associative recognition. Contrary to the prediction of domain dichotomy however, we observed greater familiarity for between-domain than within-domain pairs. Most importantly, this difference was present when controlling for stimulus class: analysis revealed independent effects of item type (stimulus class) and relationship (within/between-domain), and critically, when directly compared between-domain pairs were more familiar than within-domain pairs of the same items.

In examining the effect of relationship type we have used the familiarity estimate from the DPSD model. This provides a stronger test of the domain dichotomy prediction than familiarity as a proportion of overall recognition, which is as likely to reflect differences in recollection as familiarity. Nonetheless, others argue that a greater ratio of familiarity to accuracy for within-domain pairs may constitute evidence for domain dichotomy (Bastin, Van der Linden, Schnakers, Montaldi & Mayes, 2009). We therefore also compared proportional familiarity across conditions; this did not provide an alternative basis for supporting the domain dichotomy view (full details available online). Finally, we also re-examined the data using an alternative Unequal-Variance Signal Detection (UVSD) model (Wixted, 2007) to reinforce the conclusion that discrimination was greater for between-domain than within-domain pairs (1.83 vs 1.31; $t(28) = 3.83$; $p = .001$). In short, regardless of the approach taken to estimate memory processes, the ROC data are inconsistent with domain dichotomy theory.

## Experiment 2

The DPSD model used to obtain process estimates in Experiment 1 is well suited to this purpose for two reasons: it generally gives a close fit to the ROC data, and it explicitly distinguishes between recollection and familiarity. Nonetheless, the model relies on a number of assumptions; consequently parameter estimates should be interpreted with caution, and preferably corroborated with other measures. In particular, the DPSD model assumes that familiarity and recollection are functionally independent. However if the processes are correlated, as in a redundancy view

(Joordens & Merikle, 1993; and see Greve et al., 2010), both the DPSD model and the traditional remember-know paradigm would underestimate the true strength of familiarity for conditions eliciting high recollection.

To minimise the impact of this (unknown) statistical relationship on parameter estimates Mayes and colleagues suggest a modified remember-know procedure, whereby familiarity and recollection measures are obtained separately. Participants are trained to distinguish between familiarity and recollection (rather than the potentially misleading terms “knowing” and “remembering”). In a “familiarity-only” procedure participants are asked not to actively recollect, but report recollection when it occurs. This measure of familiarity ought to be more reliable because the recollection rate is low and therefore the relationship between the two processes should have a small effect. In a “recollection-only” procedure recall of some specific aspect of an original presentation is required for an old/new judgment, regardless of confidence. Making the distinction between strongly familiar and recollected trials explicit should result in more reliable estimates of recollection. Thus, Experiment 2 replicates Experiment 1, replacing ROC curves with the modified remember-know procedure.

**Method**

**Participants.** An additional 18 (10 female) participants (mean age 19.1, range 17-25) completed a modified remember-know procedure. The exclusion criteria, consent, ethics and payment rates were identical to those in Experiment 1.

**Procedure.** Each participant performed the familiarity-only task of the modified remember-know procedure for 6 consecutive blocks (2 of each condition) and the recollection-only task for another 6 blocks; task order was counterbalanced across participants. In the familiarity-only task the “*intact/rearranged*” and confidence judgments at test were replaced with a single "*familiar-intact/unfamiliar-rearranged/recollected*" judgment. Participants responded intact or rearranged on the basis of familiarity only; when involuntary recollection occurred (of any aspect of an original study episode) they were required to respond "*recollected*".

In the recollection-only task participants made a single "*recollected-intact/recollected-rearranged/no recollection*" judgment. Here participants responded intact only if they recalled some aspect of the original study presentation, and rearranged if they recalled one of the items being paired with another at study. In the absence of explicit recollection they were required to respond "*no recollection*", regardless of confidence. With the exception of these procedural differences Experiment 2 was identical to Experiment 1.

**Results**

Non-recollected trials (of unknown accuracy) in the recollection-only experiment were assigned the (known) accuracy for non-recollected trials in the familiarity-only procedure, giving an overall accuracy for each participant and condition. Mean accuracy for each condition (BD = 0.81; WD-Name = 0.81; WD-Image = 0.66) did not reliably differ across Experiments 1 and 2 (BD: $p$ = .423; WD-Name: $p$ = .441; WD-Image: $p$ = .338), suggesting that the change in retrieval task did not significantly alter performance. Familiarity was assessed by examining discrimination (false alarm corrected hits) in the familiarity-only procedure after discarding recollected trials[1]. Paired t-tests revealed lower familiarity for the WD-Image (0.24) than BD condition (0.38; $t(17) = 2.83$, $p$ = .011), but the WD-Name condition (0.33) did not reliably differ from either WD-Image ($p$ = .385) or BD ($p$ = .516) conditions. Figure 4A shows familiarity-driven discrimination for each condition.

We similarly examined discrimination in the recollection-only procedure, after discarding non-recollected trials. Paired t-tests revealed poorer recollection for WD-Image (0.42) than BD (0.70; $t(17) = 4.52$, $p = .001$), or WD-Name (0.71; $t(17) = 5.84$, $p = .001$) conditions, but BD and WD-Name pairs showed no difference ($p = .875$). Figure 4B shows recollection-driven discrimination for each condition.

As for Experiment 1, familiarity, recollection and accuracy were regressed against item and relationship type. All trends were in the same direction as Experiment 1 and were significant for accuracy (items: $B = 0.125$; $p = .001$ and relationship: $B = 0.064$; $p = .031$) and recollection (items: $B = 0.293$; $p = .001$ and, marginally, relationship: $B = 0.136$; $p = .059$). While the familiarity regression lacked sufficient power (items: $B = 0.088$; $p = .314$ and relationship: $B = 0.101$; $p = .183$), when compared directly BD pairs did exhibit greater familiarity (0.38 vs 0.28; $t(17) = 2.13$, $p = .048$; Cohen's $d = 0.549$) as well as accuracy (0.81 vs 0.75; $t(17) = 3.30$, $p = .004$; Cohen's $d = 0.679$) and recollection (0.70 vs 0.57; $t(17) = 2.17$, $p = .044$; Cohen's $d = 0.516$) than WD pairs of the same items.

**Discussion**

The results from Experiment 2 closely match those from Experiment 1: familiarity appears to support performance in all three conditions, but in contrast to a domain dichotomy view the contribution was greater for between-domain than within-domain pairs. Of particular importance is the demonstration of phenomenological evidence for familiarity, given that familiarity estimates from the DPSD model rely upon an assumption that recollection is thresholded. If recollection is graded (Wixted 2007), the curvilinearity that is interpreted as reflecting familiarity could be accounted for by weaker recollection. While possible, this explanation is inconsistent with above-chance performance in the familiarity-only procedure. In addition, participants all reported themselves well able to distinguish between familiar and recollected trials, both during the practice phase and at the end of the study. Thus, together our results suggest that performance is being supported by a process that both looks (Experiment 1), and feels (Experiment 2), like familiarity.

## Discussion

The results presented here provide evidence that familiarity can contribute to the retrieval of novel associations. Our data suggest that familiarity supported performance in an associative recognition task, regardless of pair type (names, images, mixed pairs) or how performance was assessed (ROC analysis, modified RK procedure). As illustrated in Figure 5, however, familiarity was consistently greater for between-domain pairs. These results therefore present a fundamental challenge to domain dichotomy theory, raising questions about how familiarity should best be characterised and what role it plays in associative recognition.

The results of any study evidently rely to some extent on the stimuli used, and at present there is no precise definition of a domain to guide this choice. Perhaps, therefore, our particular stimuli simply do not give rise to overlapping representations as predicted. Data from neuroimaging may be important in this regard: future studies should demonstrate whether individual classes of stimuli are indeed represented in separate domains and whether item representations converge spatially (using fMRI) and temporally (using EEG). More broadly, in functional terms, perhaps familiarity is not well characterised by the kinds of ‘tuning’ mechanisms and overlapping representations that are proposed by the models that motivate domain dichotomy theory (for further discussion see Greve et al., 2010).

Although our findings are clear, they stand in contrast with a study that claims support for domain dichotomy (Bastin et al., 2009), in which face-face pairs were shown to elicit more proportional familiarity than face-name pairs. These data are strikingly consistent with the lesion data reported by Mayes and colleagues, and the use of forced-choice procedures may account for some differences with our study. However, we have reservations about the strength of evidence they provide for domain dichotomy: face-name pairs actually gave rise to better associative recognition during pilot testing (familiarity was not reported) and face-face pairs were therefore presented for longer at study to equate performance. Given this manipulation it is possible that familiarity, like overall recognition, may have originally been matched or greater for face-name pairs – unfortunately the design of the experiment makes this impossible to determine. Even more importantly, between-domain pairs were not compared to within-domain pairs from both domains, making it mathematically impossible to disentangle (or characterise their result in terms of) item and relationship effects.

In our findings the relationship effect is demonstrably independent of item effects. Proponents of domain dichotomy might argue that the predicted effect is still present, masked by a larger effect in the opposite direction – a possibility that is, of course, impossible to rule out. Thus here we focus on the key finding that between-domain pairs were recognised more easily than within-domain pairs: why might this be? In both experiments between-domain pairs elicited greater estimates of familiarity. This raises the possibility that they might be more robustly unitized than within-domain pairs, given that unitization has been implicated in familiarity for associations (Rhodes & Donaldson, 2007; 2008; Quamme et al., 2007). It is however circular to categorise stimuli as unitized (or not) based on differences in familiarity alone, emphasising the need for independent means of assessing unitization. Memory for unitized pairs might be more strongly impaired by manipulations that introduce perceptual differences between study and test (e.g., switching the positions of items, or presenting them separately), or, as suggested by Mayes et al. (2007), recognition or perception of the individual components might be reduced following unitization.

One aspect of the current findings is not predicted by unitization: in Experiment 2 between-domain pairs elicited higher levels of recollection compared to within-domain pairings of the same items. Given that unitization is primarily an account of familiarity, it is compatible with this change in recollection, but does not readily explain it. Instead, better memory for individual items might assist recollection and thereby support stronger associative recognition. For example, items might be more distinctive when presented as part of a between-domain pair, and therefore better recognised (Curran, Tanaka & Weiskopf, 2002). Results from Criss and Shiffrin (2004) also suggest that increasing the number of similar items in a list impairs memory, predicting poorer item recognition for within-domain conditions. Intriguingly however, the same study suggested that associative recognition performance was dependent on the similarity of pairs rather than items, posing a challenge for a purely item-level explanation.

Finally, our data also demonstrate that the nature of the stimuli is important for remembering: names were generally better remembered than images. The relationship-driven difference we report here is, however, statistically independent of this item type effect. Interestingly, a previous study using faces and words (Criss & Shiffrin, 2004: Experiment 1, Group A) finds a similar effect of relationship, also independent of stimulus type effects. An important aim for future research will be to establish whether, in broader terms, relationship effects are influenced by the nature of stimuli (e.g., Rhodes & Donaldson, 2007), or exist generally for certain types of association (e.g., within- or between-domain).

We began this study in search of evidence for domain dichotomy in one area where it has been notably lacking: psychological studies of normal subjects. While our results do not support domain dichotomy, they are consistent with a role for familiarity alongside recollection in associative recognition. Interestingly, they also suggest that the way items are combined might change the contribution of each process to retrieval - characterising these relationship effects remains an important goal for future research.

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Footnote

[1]This estimate of familiarity is accurate under an assumption of stochastic independence (recollected trials are on average no more or less familiar than non-recollected trials). We also assessed familiarity under the alternative statistical assumptions of redundancy (recollected trials are more familiar) and exclusion (less familiar). The results are qualitatively similar, and are included as supplementary material online.

Figure Captions

*Figure 1.* Procedure for Experiment 1. At study, participants were presented with a pair of items and given a direct encoding task. At test, participants were presented with two items from the study phase and asked to judge whether they were originally presented together (intact) or in different pairs (rearranged), then indicate how confident they were of their answer on a five-point scale. Participants performed the task separately for pairs of names, pairs of images and mixed pairs.

*Figure 2.* Group ROC curves for each condition from Experiment 1. Datapoints show mean hits and false alarms for each decision criterion; curves are from the best-fitting DPSD model in each case. Note that reported parameter estimates were obtained by fitting the DPSD model to individual participant data; these group ROCs provide a visual comparison between conditions. All three show clear curvilinearity.

*Figure 3.* Mean (**A**) discrimination, (**B**) familiarity and (**C**) recollection rate from Experiment 1 for each condition, measured by fitting individual participant data to a DPSD model of associative recognition. Contrary to the domain dichotomy prediction, the BD condition exhibits just as much familiarity as the performance-matched WD-Name condition.

*Figure 4.* Mean (**A**) familiarity-driven and (**B**) recollection-driven discrimination for each condition in Experiment 2. The BD and WD-Name conditions did not differ for either process, matching the pattern observed in Experiment 1.

*Figure 5.* Familiarity for within-domain and between-domain pairs of the same items as predicted by the domain dichotomy view; and as observed in Experiments 1 and 2. Between-domain pairs elicited greater estimates of familiarity in both experiments, clearly contradicting the predictions of domain dichotomy theory.

Figure 1

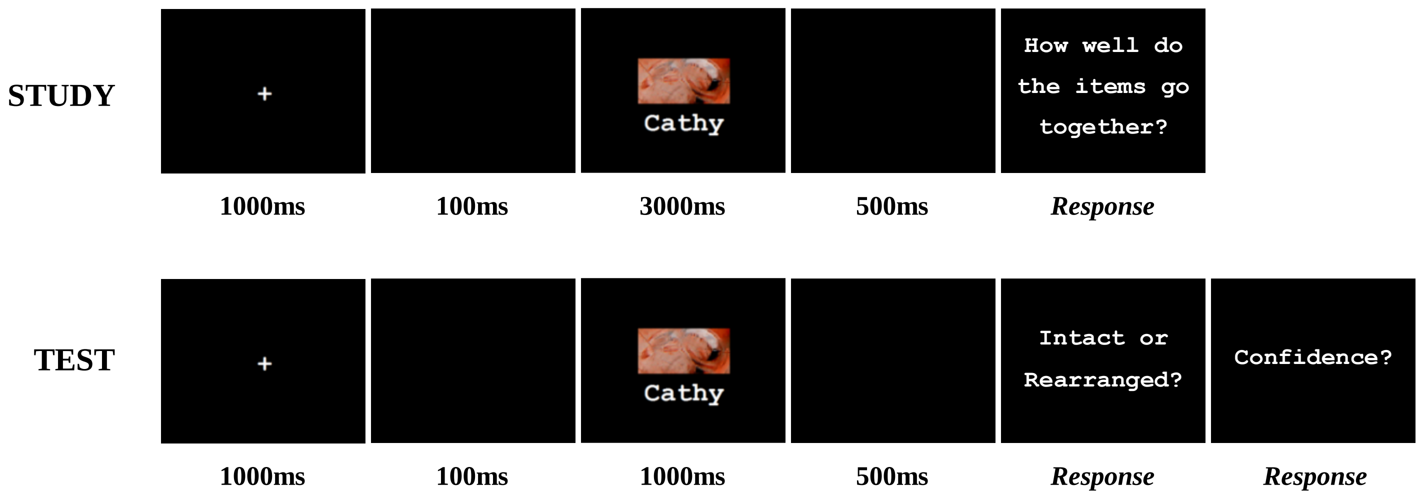
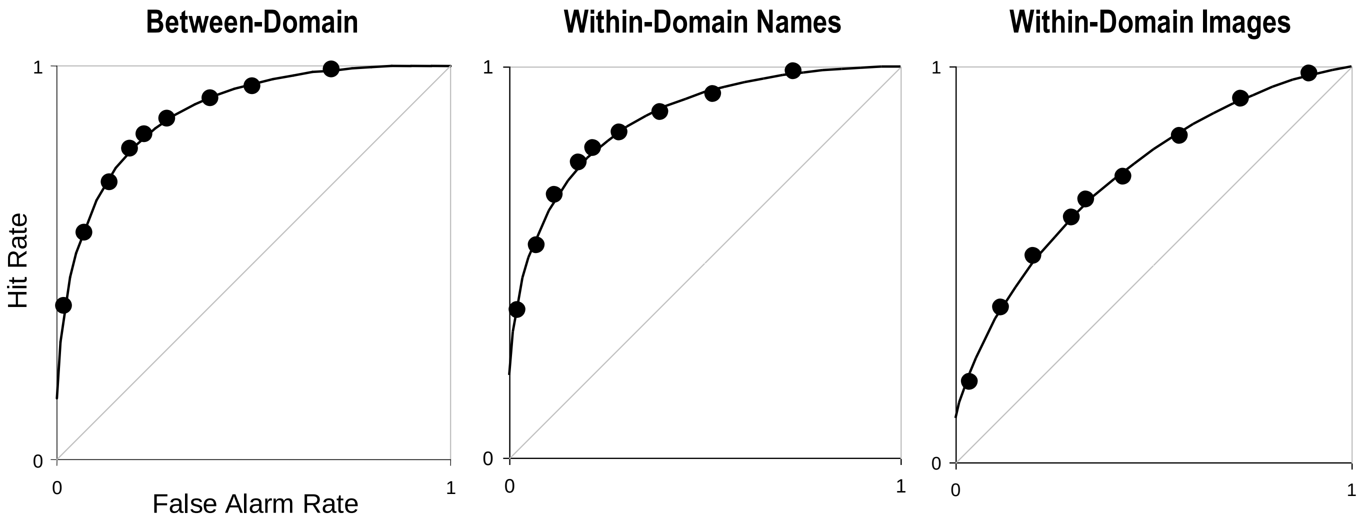
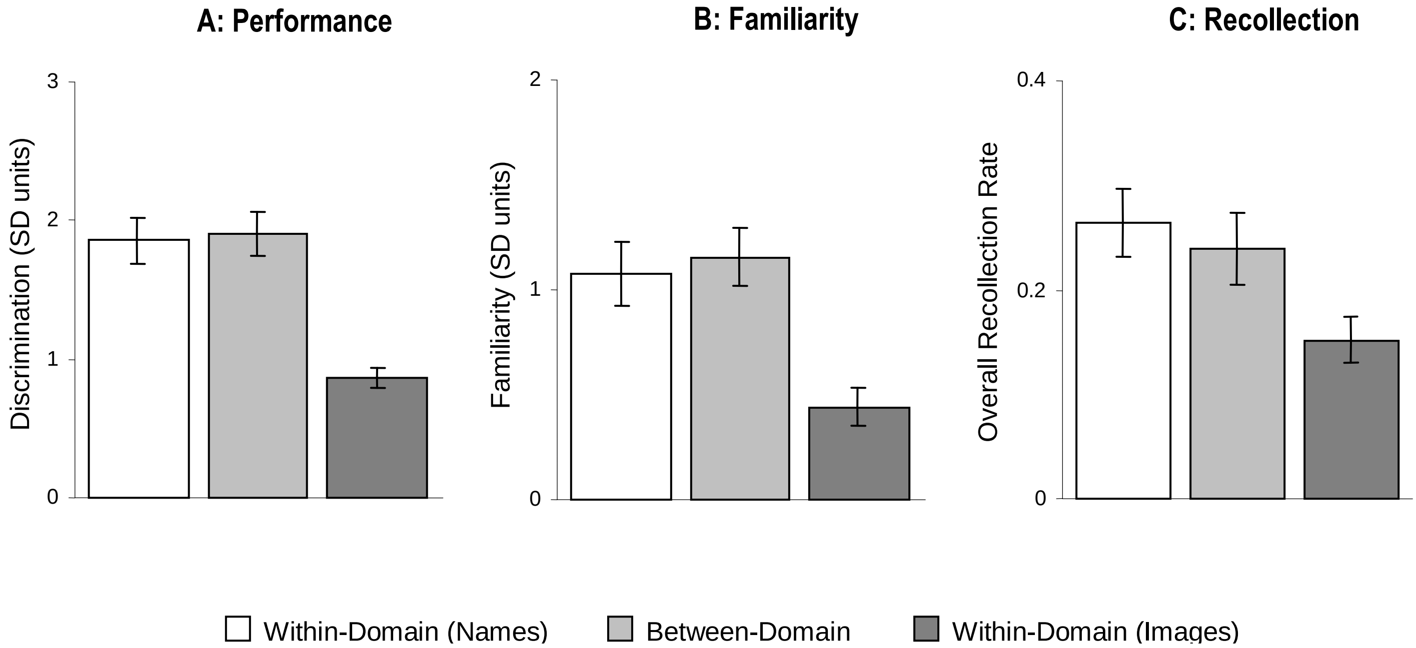

STUDY
+
Cathy
How well do the items go together?
1000ms
100ms
3000ms
500ms
Response
TEST
+
Cathy
Intact or Rearranged?
Confidence?
1000ms
100ms
1000ms
500ms
Response
Response

Figure 2



Between-Domain
Within-Domain Names
Within-Domain Images
Hit Rate
False Alarm Rate
1
0
0
1

Figure 3



A: Performance
B: Familiarity
C: Recollection
Discrimination (SD units)
Familiarity (SD units)
Overall Recollection Rate
3
2
1
0
2
1
0
0.4
0.2
0
Within-Domain (Names)
Between-Domain
Within-Domain (Images)

Figure 4

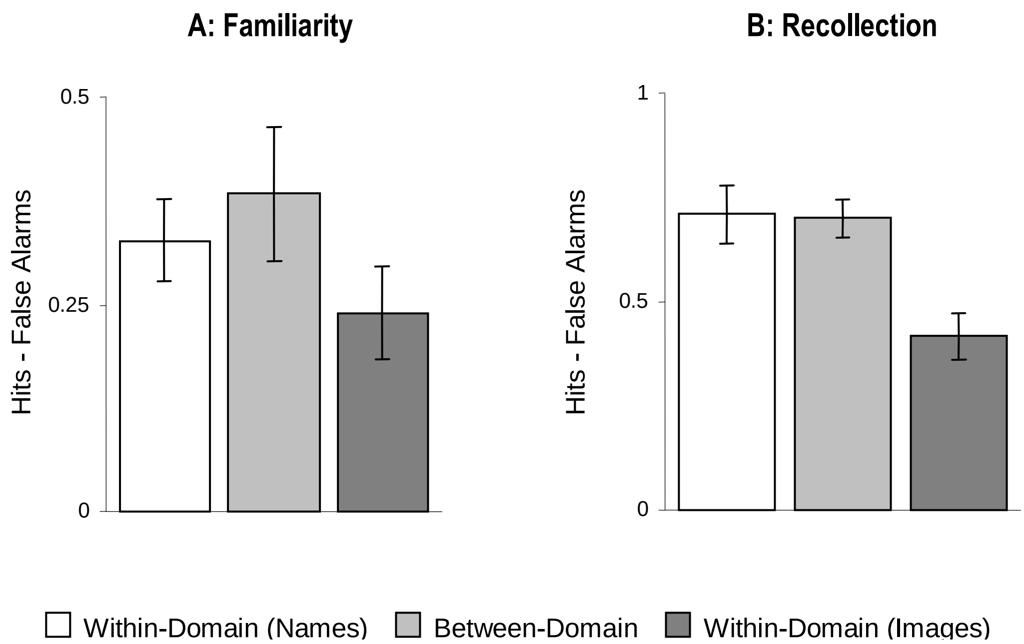
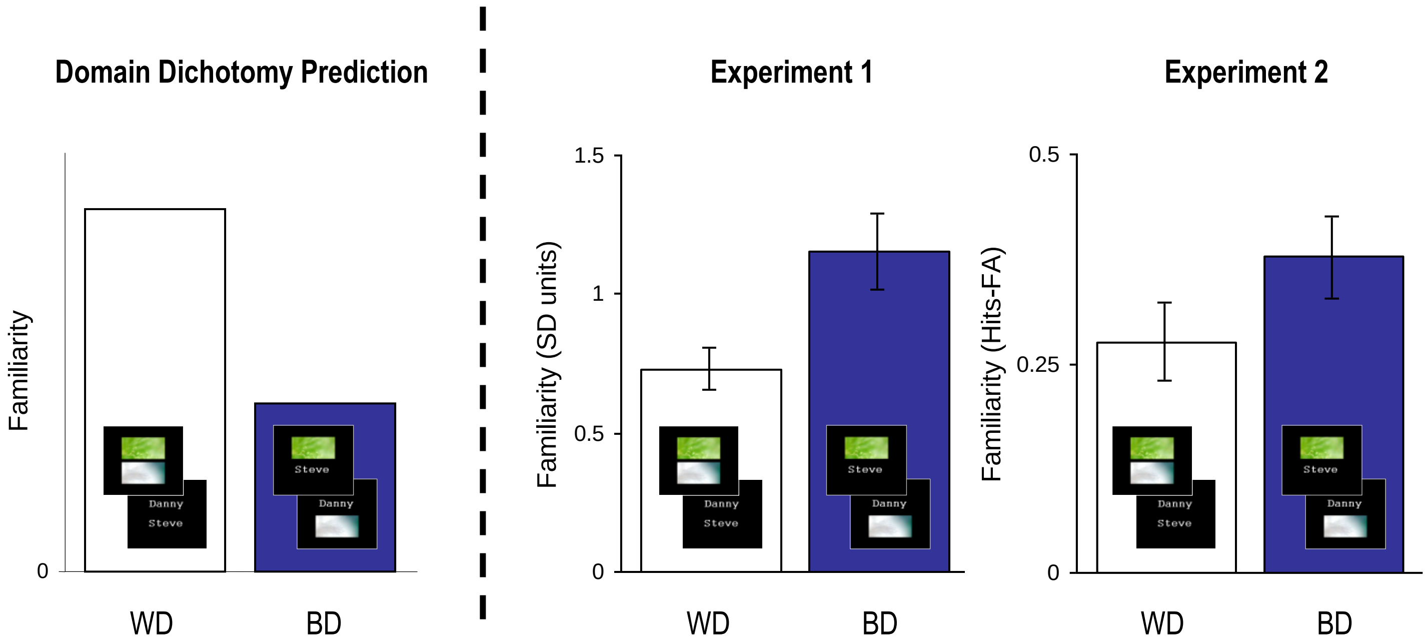

A: Familiarity
B: Recollection
Hits - False Alarms
0.5
0.25
0
1
0.5
0
Within-Domain (Names)
Between-Domain
Within-Domain (Images)

Figure 5



Domain Dichotomy Prediction
Familiarity
0
Steve
Danny
Steve
Danny
WD
BD
Experiment 1
1.5
1
0.5
0
Familiarity (SD units)
WD
BD
Experiment 2
0.5
0.25
0
Familiarity (Hits-FA)
WD
BD

Appendix: Online Supplementary Material

**Separating item and relationship effects**

We used linear regression to establish whether associative relationship (i.e. within/between-domain) has an effect on familiarity, recollection or overall performance independent of item type (names/images). Each participant provided three observations, one for each condition (WD-Names, WD-Images, BD). For each experiment we fit a regression of the form:

$$P = x_I I + x_R R + c$$

Here the dependent variable P denotes overall performance (we also carried out the analysis separately for recollection and familiarity), *I* denotes item type (the proportion of items in each pair that are names, 0,0.5 or 1), *R* denotes relationship type (WD = 0, BD = 1), $x_I$ and $x_R$ are their respective coefficients (calculated by the model) and *c* is a constant. A coefficient that is significantly greater than zero indicates that its respective factor does contribute to the dependent variable. The results of these analyses are summarised in the main paper (Experiment 1 results; Experiment 2 results) and Tables 1 and 2 below. Non-significant results ($p > .050$) are marked by parentheses.

**Familiarity as a proportion of overall performance**

We also analysed proportional familiarity, as suggested in Bastin et al., (2009). For Experiment 1, we calculated the proportion of total discrimination in the DPSD model accounted for by familiarity (rather than recollection). This value was numerically highest for between-domain pairs, but the only comparison that approached significance was between-domain vs image-image pairs ($p = .055$). For Experiment 2, we calculated the ratio of accuracy on the familiarity-only procedure to an overall measure of accuracy estimated from both procedures, similar to the approach taken by Bastin et al., (2009). There were no significant differences in this value across conditions. Results from both experiments are summarised in Figure 6. Bastin and colleagues argue that proportional familiarity should be greater for within-domain than between-domain pairs; our data clearly do not support domain dichotomy using this alternative measure.

**The statistical relationship between familiarity and recollection**

The estimates of familiarity in both experiments are affected by the statistical relationship between familiarity and recollection. For the results reported in the main paper we assumed independence, by which recollected trials are no more familiar on average than non-recollected trials. We also calculated familiarity under two alternative assumptions: redundancy (recollected trials are strongly familiar) and exclusion (recollected trials are not familiar). The results of these calculations for each experiment are summarised in Table 3 and Table 4 below.

**Comparison of ROC and modified-RK conclusions**

From the previous tables it is clear that the familiarity estimates from both processes are quantitatively, as well as qualitatively, similar when compared using the same units (false alarm corrected hits, after removing recollected trials). We also calculated recollection rates in Experiment 2 as the probability of accurate recollection in the recollection-only procedure. This was done separately for intact and rearranged pairs, correcting for false alarms and misses respectively, giving estimates comparable to the recall-to-accept and recall-to-reject parameters of the DPSD model. These results are summarised in Tables 5 and 6 below: they show generally higher estimates of recollection for Experiment 2 than Experiment 1. There are at least two possible reasons for the difference, both of which may play a role. First, participants may have made greater effort to recollect trials during the recollection-only procedure, because their response was dependent upon it. Second, Experiment 1 has a stricter criterion for identifying recollected trials (maximal confidence) than Experiment 2 (respond “recalled”), leading to lower estimates of recollection. In this case recollection might be more graded than the DPSD model predicts, and thus be underestimated by it.

**Stimuli**

Table 7 lists the 324 names used as stimuli in these experiments.

Tables (for Online Supplementary Material)

Table 1

*Results of regression analysis for Experiment 1*

| | **Item** | | | **Relationship** | | | **Constant** |
|---|---|---|---|---|---|---|---|
| Target | p-value | Size | Direction | p-value | Size | Direction | Size |
| F | .001 | .636 | names>images | .016 | .392 | BD>WD | .443 |
| R | .010 | .112 | names>images | (.391) | .032 | (BD>WD) | .151 |
| da | .001 | .991 | names>images | .002 | .547 | BD>WD | .864 |

Table 2

*Results of regression analysis for Experiment 2*

| | **Item** | | | **Relationship** | | | **Constant** |
|---|---|---|---|---|---|---|---|
| Target | p-value | Size | Direction | p-value | Size | Direction | Size |
| F | (.314) | .088 | names>images | (.183) | .101 | BD>WD | .239 |
| R | .001 | .293 | names>images | (.059) | .136 | (BD>WD) | .417 |
| Accuracy | .001 | .125 | names>images | .031 | .064 | BD>WD | .687 |

Table 3

*Familiarity estimates for Experiment 1 under redundancy, independence or exclusion*

| | Mean Familiarity Hits-FA (s.d.) | | | |
|---|---|---|---|---|
| Assumption | BD | Names | Images | WD |
| Redundancy | .51 (.21) | .51 (.17) | .28 (.16) | .40 (.11) |
| Independence | .40 (.25) | .36 (.21) | .17 (.20) | .29 (.15) |
| Exclusion | .24 (.31) | .18 (.27) | .08 (.25) | .14 (.20) |

Table 4

*Familiarity estimates for Experiment 2 under redundancy, independence or exclusion*

| | **Mean Familiarity Hits-FA (s.d.)** | | | |
|---|---|---|---|---|
| Assumption | BD | Names | Images | WD |
| Redundancy | .51 (.16) | .45 (.28) | .35 (.20) | .40 (.15) |
| Independence | .38 (.20) | .33 (.33) | .24 (.22) | .28 (.19) |
| Exclusion | .14 (.27) | .17 (.29) | .13 (.25) | .15 (.20) |

Table 5

*Estimated recollection rates in Experiment 1*

| | Recollection Rate | | | |
|---|---|---|---|---|
| | BD | Names | Images | WD |
| Intact (Ra) | .27 (.26) | .33 (.24) | .20 (.19) | .26 (.16) |
| Rearraged (Rr) | .21 (.21) | .20 (.22) | .10 (.11) | .16 (.14) |

Table 6

*Estimated recollection rates in Experiment 2*

| | Recollection Rate | | | |
|---|---|---|---|---|
| | BD | Names | Images | WD |
| Intact (Ra) | .58 (.24) | .56 (.21) | .28 (.15) | .43 (.16) |
| Rearraged (Rr) | .62 (.15) | .59 (.18) | .42 (.16) | .51 (.15) |

Table 7

*Names used as stimuli in both Experiments 1 and 2*

| | | | | | |
|---|---|---|---|---|---|
| Aaron | Camilla | Frank | Jodie | Mikey | Sally |
| Abby | Carl | Fred | Joel | Miles | Sandra |
| Abigail | Carla | Freddie | Johanna | Miranda | Sandy |
| Adam | Carol | Gabby | Johnny | Miriam | Sarah |
| Adrian | Cassie | Gail | Jolene | Molly | Scott |
| Aimee | Cathy | Gareth | Joseph | Monica | Sean |
| Ainsley | Charlie | Gary | Joshua | Monty | Shane |
| Alan | Cheryl | Gavin | Judith | Nancy | Sharon |
| Albert | Chloe | Geoff | Julia | Naomi | Sheila |
| Alec | Chris | George | Justin | Natalie | Shirley |
| Alex | Cindy | Gerald | Karen | Natasha | Sidney |
| Alfie | Claire | Gillian | Katie | Nathan | Simon |
| Alice | Claude | Gina | Katrina | Neil | Sophie |
| Alison | Claudia | Glenn | Keira | Nelly | Stacy |
| Alvin | Cliff | Gloria | Keith | Nick | Stan |
| Amanda | Colin | Gordon | Kelly | Nicole | Steph |
| Amber | Craig | Grace | Kenny | Nikki | Steve |
| Andrew | Daisy | Graeme | Kevin | Nina | Stuart |
| Andy | Damien | Grant | Kirsty | Noel | Susie |
| Angela | Damon | Greg | Larry | Norm | Suzanne |
| Annabel | Danny | Hannah | Laura | Olivia | Sylvia |
| Annie | Darren | Harriet | Lauren | Ollie | Tammy |
| Anthea | Dave | Harry | Lenny | Oscar | Tania |
| Anthony | Dawn | Hayley | Liam | Pamela | Teddy |
| Anya | Dean | Hazel | Lily | Patsy | Teri |
| April | Debbie | Heather | Linda | Paul | Tessa |
| Archie | Denise | Helen | Lindsey | Pauline | Theresa |
| Arnie | Dennis | Henry | Lizzy | Peggy | Thomas |
| Arthur | Derek | Holly | Lloyd | Penny | Tiffany |
| Ashley | Diana | Horace | Lois | Percy | Timothy |
| Audrey | Dominic | Imogen | Louis | Peter | Tina |
| Barbara | Donald | Irene | Louise | Phil | Toby |
| Barney | Donna | Isabel | Lucy | Phoebe | Tommy |
| Barry | Doris | Izzie | Luke | Polly | Tony |
| Becky | Dorothy | Jack | Lynne | Rachel | Tracy |

| | | | | | |
|---|---|---|---|---|---|
| Belinda | Doug | Jaclyn | Maisie | Ralph | Trevor |
| Benny | Duncan | Jake | Mandy | Rebecca | Trish |
| Bernie | Dwain | Jamie | Marcus | Reggie | Valerie |
| Bertie | Ebony | Janet | Margo | Richard | Vanessa |
| Beth | Eddie | Janice | Maria | Richie | Vernon |
| Betty | Edgar | Janine | Mark | Rick | Vicky |
| Beverly | Edith | Jasmine | Martha | Robbie | Victor |
| Bill | Elaine | Jason | Martin | Robin | Vince |
| Bobby | Eleanor | Jayne | Marty | Rodney | Violet |
| Bonnie | Ellie | Jeffrey | Marvin | Roger | Vivian |
| Boris | Elouise | Jemma | Mary | Ronnie | Walter |
| Brenda | Emily | Jenny | Matilda | Rory | Wayne |
| Brett | Emma | Jeremy | Matt | Rosalie | Wendy |
| Brian | Eric | Jerome | Maureen | Ross | Wilbur |
| Bridget | Erin | Jerry | Maxine | Roxanne | Will |
| Bruce | Ernie | Jessica | Megan | Ruby | William |
| Bruno | Ethel | Jill | Melanie | Rupert | Yvonne |
| Caitlin | Faye | Jimmy | Melissa | Ruth | Anita |
| Calum | Fiona | Joan | Mick | Ryan | Selma |

Figure caption (for Online Supplementary Material)

*Figure 6.* Proportional familiarity estimates for (**A**) Experiment 1 and (**B**) Experiment 2 show no evidence of greater familiarity for within-domain pairs, even when measured as a proportion (**A**) or ratio (**B**) of overall recognition.

Figure 6 (for Online Supplementary Material)