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# A Meta-analysis of Memory Abilty in Synaesthesia

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**Abstract**

People with synaesthesia have often been reported to possess enhanced memory relative to the general population and, in some cases, exceptional memory ability. However, there are also inconsistencies in this literature and it is unclear whether this reflects sampling error (exacerbated by low Ns) or more meaningful differences that arise because synaesthesia relates to some aspects of memory more than others. To this end, a multi-level meta-analysis was conducted. Synaesthetes have enhanced episodic memory with a medium population effect size estimate ($\hat{d}$ = 0.61), whereas the effects on working memory were significantly smaller ($\hat{d}$ = 0.36) but still exceeded that of controls. Moderation analyses suggested that, aside from the division between long term versus working memory, the effects of synaesthesia are pervasive i.e. they extend to all kinds of stimuli, and extend to all kinds of test formats. This pattern is hard to reconcile with the view that synaesthetic experiences directly support memory ability: for instance, digit span (where synaesthesia could be helpful) showed a small effect whereas episodic memory for abstract images (where synaesthesia is irrelevant) yielded larger effects. Synaesthesia may be the only known neurodevelopmental condition linked to a pervasive enhancement of long-term memory.

Keywords:

Episodic memory; working-memory; synaesthesia/synesthesia; meta-analysis; superior ability.

People with synaesthesia experience the world in remarkable ways: music may trigger colourful moving shapes, words may have tastes, and numbers may be visualised as 3D spatial landscapes (e.g. Ward, 2013). But are these people remarkable in other ways, beyond their synaesthesia? This paper evaluates, through a meta-analysis, the claim that people with synaesthesia have enhanced memory abilities. Several well-known case studies of exceptional memory are known to have had synaesthesia. Shereshevskii had multiple forms of synaesthesia and could recall meaningless lists of syllables decades after first learning them (Luria, 1968). Daniel Tammet was able to learn Icelandic in a week and holds the European record for reciting the mathematical constant, pi (Tammet, 2006). However, both of these cases explicitly also trained themselves with mnemonic devices. The first group study of memory ability in synaesthetes versus controls showed that synaesthetes outperformed controls on several tests (Yaro & Ward, 2007), although synaesthetes generally do not have exceptional memory (i.e. $z$-scores > 2 relative to the neurotypical distribution). Although this finding has been replicated (see Rothen, Meier, & Ward, 2012), the results tend to be variable in magnitude and statistical significance. It is uncertain whether this variability reflects random sampling error (exacerbated by the use of small samples) or more theoretically interesting possibilities such as synaesthesia being linked to some memory processes more than others. These possibilities can be dissociated through a formal meta-analysis. The purpose of this research is to use meta-analysis to clearly define the memory constructs (if any) that are enhanced in synaesthesia with a view to informing both theories of memory and theories of synaesthesia.

Synaesthesia is a developmental condition that emerges in childhood (Simner & Bain, 2013), if not before. It has a heritable component (Barnett et al., 2008) and, in adults, is linked to structural brain differences including increases in both grey matter density and white matter organisation in a number of regions including those implicated in memory (e.g. medial temporal lobes and parietal cortex) (Romke Rouw & Scholte, 2010). The term 'condition' is used with clarification because it is not a pathology, but can plausibly be considered a trait that is part of a wider constellation of neurocognitive differences with a genetic component (Ward, in press; for a different view see Hupe

& Dojat, 2015). If anything, synaesthesia appears to be linked to enhanced cognitive ability (e.g. R. Rouw & Scholte, 2016). However, it may also be linked to certain clinical vulnerabilities. For instance, having grapheme-colour synaesthesia (colours for letters and/or numbers) is a possible risk factor for developing PTSD (post-traumatic stress disorder) in people exposed to trauma (Hoffman, Zhang, Erlich, & Boscarino, 2012). This finding presumably reflects associated neurocognitive differences in synaesthetes (in memory, mental imagery, etc.) rather than a direct causal influence of, say, experiencing the number 5 as yellow. In addition to observations of enhanced memory, synaesthetes self-report more vivid mental imagery across the range of senses (Spiller, Jonas, Simner, & Jansari, 2015). Autobiographical memories of synaesthetes are reported to have more vivid sensory details and show less diminution over time (i.e. childhood memories show less fading of sensory details) (Chin & Ward, 2018). Some synaesthetes can link their associations back to coloured childhood toys (Witthoft, Winawer, & Eagleman, 2015), which suggests that this kind of synaesthesia could be regarded as a memory association re-experienced in the perceptual present (rather like a flashback in PTSD). When retrieving and recognising visual memory associations (paired associations of images of fractals that do not induce synaesthesia), synaesthetes show differences, relative to neurotypicals, in activity over visual cortices even in the absence of a physical stimulus (Pfeifer, Ward, Chan, & Sigala, 2016).

Rothen et al. (2012) argued from findings such as these, that enhanced memory in grapheme-colour synaesthetes is attributable to 'enhanced perceptual functioning' such that synaesthetes rely more on perceptual representations for words, images, and so on for memory encoding and memory retrieval. They rely on them more because their perceptual processing is enhanced (both perception and mental imagery) and this extends beyond the synaesthesia itself. For instance, some studies show that grapheme-colour synaesthetes don't just have enhanced memory for words and digits (which elicit colour) but for images and abstract shapes (that do not) (Rothen & Meier, 2010). However, this theory is rather underspecified. For instance, it is unclear whether it affects all kinds of memory. Studies of working memory ability in synaesthesia, as opposed to long-term memory, have yielded particularly inconsistent results. Some find no effect (e.g. Rothen & Meier, 2010), whereas others find an effect but only for certain material or contexts (Teichmann, Nieuwenstein, & Rich, 2017; Terhune, Wudarczyk, Kochuparampil, & Kadosh, 2013). All contemporary models of memory postulate a distinction between working memory and long-term memory, but they do so in very different ways. In one class of model, working memory and long-term memory are separate stores with separate capacities and different neuroanatomical bases (e.g. Baddeley, 2012; Norris, 2017). Following from this, synaesthesia would be unlikely to affect both in the same way and to the same extent. In another class of model, working memory is regarded as the temporary activation of long-term memory (Cowan, 2001; D'Esposito, 2007). In this view, a single store of information is common to both types of memory; the capacity-limitation of working memory arises due to competition/interference between simultaneously activated information. Following from this, synaesthesia should affect both similarly (because it impacts a common store) although it may differ in magnitude (because the capacity-limitation reflects different processes responsible for long-term storage versus short-term activation). This meta-analysis will directly compare working memory and long-term memory in synaesthetes versus controls and, for each, will contrast it for verbal material (spoken or written words or digits) and visual images.

Within long-term memory one can also make a distinction between individual differences in the learning of material versus the retention of material. Thus, it might be the case that synaesthetes and controls learn material at the same rate but the synaesthetes retain it for longer (i.e. less forgetting) or it could be the case that synaesthetes learn more efficiently but forget at the same rate. And, of course, they could have both better learning and better retention. Studies that have looked for this effect (e.g. Rothen & Meier, 2010) have tended not to find a difference between immediate and delayed testing, but a meta-analysis holds the potential for greater statistical power collapsing across idiosyncratic differences across studies. As noted before, there is a suggestion of less forgetting with time in the case of autobiographical memories (Chin & Ward, 2018).

Theoretically, we are interested in trait-like individual differences in memory ability rather than 'in the moment' boosts of memory ability that may occur through, for instance, being highly motivated or use of effective mnemonic strategies. There is very little evidence that effort alone can boost someone's memory ability. One possible reason for this is that, in naturalistic settings, our memories are formed effortlessly as opposed to memory encoding being switched on or off at will (Ranganath, Flegal, & Kelly, 2011). For instance, Owen et al. (2010) reported that cognitive training in working memory and attention had no significant impact on episodic memory ability (but did enhance performance on measures similar to the ones trained) and this in spite of testing 11,430 participants who were, presumably, highly motivated (to complete multiple training sessions) and had expectations of improvement. Efficient encoding strategies, as opposed to effort per se, are well-known to boost memory performance. These include the use of 'deep' encoding strategies such as semantic processing or generating associations (as opposed to surface properties such as focussing on sounds or letters) (Craik, 2002) , or techniques for remembering sequences such as the method-of-loci (placing items in different locations along a familiar route) (Verhaeghen & Marcoen, 1996). A person who habitually applies efficient encoding strategies would <u>appear</u> to have better memory. However, this enhanced memory would be centered on the kinds of task/material where these techniques can be applied. Evidence suggests that people who are proficient in these mnemonic techniques have normal memory ability when given test material for which their pre-existing strategies are unhelpful (Maguire, Valentine, Wilding, & Kapur, 2003; Wilding & Valentine, 1994). To relate this back to synaesthesia, previous research has shown that people with synaesthesia have comparable levels of enhanced memory for words irrespective of whether efficient (deep encoding) or inefficient (shallow encoding) strategies were deployed (Radvansky, Gibson, & McNerney, 2011; Ward, Hovard, Jones, & Rothen, 2013), and synaesthetes have enhanced memory for stimuli not amenable to standard mnemonic strategies such as fractals and snowflakes (Mealor, Simner, & Ward, 2019; Ward et al., 2013). As such, this is suggestive of a genuine difference in memory ability rather than the employment of beneficial strategies. This is further explored in the meta-analysis to determine whether differences in memory are pervasive (suggestive of true ability) or related to specific contexts/material.

To summarise, this meta-analysis contrasts differences in memory ability between synaesthetes and controls. It compares working memory and long-term (episodic) memory and, within that, also contrasts verbal material and non-verbal visual material. Within working memory, we distinguish between passive and active processing of material and, within long-term memory, we distinguish between immediate versus delayed retention of material as well as recognition memory and recall testing formats.

**METHOD**

The overall approach of the meta-analysis was based on current recommended practice (Cooper, Maxwell, Stone, Sher, & Board, 2008; Field, 2013).

Inclusion and Exclusion Criteria

A basic overview of the search strategy and reasons for inclusion and exclusion is shown in Figure 1. The Supplementary Material describes the reasons for exclusion for each and every study considered in the initial search

INSERT FIGURE 1 ABOUT HERE

The main inclusion and exclusion criteria were that:

1) *The research was both quantitative and experimental in nature.* This excluded reviews and theoretical papers, but also interviews (not quantitative) and questionnaires (not experimental).
2) *The research was conducted on synaesthetes.* In the case of grapheme-colour synaesthesia there are consensually agreed procedures for determining who is likely to have it (Eagleman, Kagan, Nelson, Sagaram, & Sarma, 2007) and we ensured that researchers had employed this, or an equivalent procedure. We did not restrict the meta-analysis to grapheme-colour but

also considered (as a separately coded variable) other types of synaesthesia. In these cases, their status as synaesthetes were not always verified (e.g. due to lack of agreed procedures for doing so). Studies that tested 'synaesthetic tendencies' in the normal population (i.e. not treating synaesthesia as categorically distinct) were excluded, as were studies that experimentally trained participants to have synaesthesia-like experiences.

3) *The research involved direct measures of episodic memory or working memory.* A direct measure refers to the fact that participants were instructed to recall or recognise some previously presented material. Typical dependent measures would be percentage of items correctly recalled or recognised, span length in working memory (i.e. the number of items in a list that can be recalled accurately before performance deteriorates), and *d*-prime in recognition memory (normalised number of hits relative to false alarms). These measures contrast with indirect ones in which the primary behavioural outcome is not a measure of memory (e.g. response time to identify a word as quickly as possible), but may be influenced by memory (e.g. primed by a recent encounter). These indirect measures were excluded.
4) *The research was not based on single case studies.* This criterion was for statistical reasons: it is not possible to estimate the standard error of the effect size for $N = 1$.

It was our original intention to include both child and adult samples (and treat age as a moderator variable), but there were too few studies involving memory ability of child synaesthetes. These were excluded leaving only studies with adults.

Search Strategies

The primary search terms were "memory" and "synaesthesia" or "synesthesia" (UK and US spellings respectively). Two academic databases were searched in June 2017: web-of-knowledge and PubMed. To identify unpublished material we performed a general web search (via Google), emailed all corresponding authors of published studies identified in our initial search to ask about unpublished data, and posted a request on a synaesthesia forum used by researchers (the Synaesthesia List; http://www.daysyn.com/Synesthesia-List.html). This strategy aimed to reduce the file-drawer problem and minimise publication bias (Rosenthal, 1979). Three of the unpublished studies, not presently 'in press', are described in brief in the supplementary material. In addition, authors from five published studies were emailed to provide missing data (e.g. if means and SDs were presented only in graphical form), and three did so, with the remaining two studies being excluded.

After removing duplicates generated by multiple searches, the search yielded 148 candidate articles (see Figure 1). After applying the four main inclusion and exclusion criteria noted above 35 articles were retained. There were a further exclusions due to missing and unobtainable data ($k$ = 2), child synaesthetes ($k$ = 1), the same data had been reported both in conference and paper form ($k$ = 1), and due to the dependent measure not being readily comparable to others in the literature ($k$ = 1). Specifically, Teichmann et al. (2017) varied presentation time of stimuli in a staircase procedure to equate memory performance across groups.

## Coding Procedures

Each study was assigned a numerical study id, so that multiple tasks and measures within a study could be grouped. Each measure within a study was classified according to the criteria listed below, which were generated a priori based on the previous literature, and standard distinctions within the memory literature. Our classifications closely followed the initial categorisation of the study by the original authors. The actual codes used and the statistical data are available in Supplementary Material.

1) *Working memory v. long-term (episodic) memory*. The key features of working memory are limited capacity (i.e. the ability to retain a relatively small amount of information accurately) and ongoing rehearsal (or 'holding in mind') between encoding and retrieval. Long-term episodic memory, by contrast, either has a delay between encoding and retrieval (with

minimal rehearsal during the delay) and/or has more material to be encoded than can be retained by working memory (e.g. free recall of a list of 20 words).

2) *The type of synaesthesia being tested*. These were classed as grapheme-colour synaesthesia, sequence-space synaesthesia, and lexical-gustatory synaesthesia.

3) *The nature of the material being encoded*. The primary distinction was between verbal material (words, digits, letters, sentences) and non-verbal material (e.g. shapes, colours, images of scenes). For people with grapheme-colour synaesthesia, verbal material acts as an inducer of synaesthesia but non-verbal material (typically) does not. Within the non-verbal domain, a secondary division was introduced as to whether colour was the memoranda. This is based on previous claims that memory for colour may be particularly enhanced (at least in grapheme-colour synaesthesia; Yaro & Ward, 2007).

4) *Recall v. recognition*. Recall refers to testing procedures in which participants have to self-generate remembered items based on either partial information (cued recall) or no information (free recall), whereas in recognition procedures participants simply have to confirm whether an item was part of the remembered set (old) or not (new).

5) *Immediate v. delayed*. Within long-term memory, all measures were coded according to whether recall was immediate (i.e. following presentation of the material) or delayed (i.e. during which some intervening task was performed or following a non-trivial lapse of time beyond a few minutes).

6) *Active v. passive*. Within working memory, a distinction was made according to whether the to-be-remembered material was actively or passively processed - essentially a distinction between working memory proper and short-term memory (Aben, Stapert, & Blokland, 2012). Active processing includes reordering of items in working memory (e.g. backwards digit span), or making some other decision about the material being presented (e.g. grammaticality judgments) in addition to holding it in mind. Passive processing, by contrast, requires no

additional cognitive processes beyond holding the material in mind (e.g. forwards digit span, or tests based on Corsi blocks).

Statistical Methods

Cohen's *d* was used as the effect size of interest. Where this statistic was stated in the original paper, this value was used in the meta-analysis. Where means and SDs were available, Cohen's *d* was calculated as the numerical difference in means divided by the pooled standard deviation ($S_p$). The pooled SD of two samples, SD1 and SD2, was calculated as a weighted average of the variances that corrects d for small sample bias and is given by:

$$s_p = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}}$$

where n1 and n2 are the sample sizes of the two groups. The standard error (SE) of the effect size for Cohen's *d* is given by the formula:

$$SE_d = \sqrt{\left(\frac{n_1 + n_2}{n_1 n_2} + \frac{d^2}{2(n_1 + n_2 - 2)}\right)\left(\frac{n_1 + n_2}{n_1 + n_2 - 2}\right)}$$

In general, the approach was to calculate effect sizes for each measure of interest highlighted in the original research rather than to aggregate measures. However, where the exact same test was repeated on the same participants without variation (e.g. a set of items was learned over 3 blocks) our approach was to extract a single measure for that test (Cohen's *d* based on the group means and *SD*s averaged across blocks). From the 30 studies included, we extracted 155 effect sizes. In addition, there were 4 measures which were considered to be too close to ceiling (in at least one of the groups) to be a fair measure of between group differences. One effect size was also considered to be related more to memory recall strategy (degree of orderedness in recall; Gibson, Radvansky, Johnson, & McNerney, 2012) rather than memory ability. These were excluded, leaving 150 effect sizes, and the exclusions are highlighted in the Supplementary Material. These final effect sizes are based on a cumulative *N* = 2604 synaesthetes and *N* = 6521 non-synaesthetes (noting that individuals can contribute to multiple measures within a study).

The meta-analysis was conducted using the metafor package (Viechtbauer, 2010) for R 3.6.0 (R Core Team, 2019). The fact that some studies reported multiple effect sizes, and others reported a single effect size will potentially distort the overall effect size (in favour of the former). Moreover, multiple effect sizes from the same study violate the assumption of independence of effect sizes (Field, 2015). To ensure that dependency between effect sizes from the same study was modelled we performed a multi-level meta-analysis in which effect sizes (level 1) are nested within studies (level 2) (see, for example, Goldstein, Yang, Omar, Turner, & Thompson, 2000; Turner, Omar, Yang, Goldstein, & Thompson, 2000). This model was fit using the *rma.mv()* function with restricted maximum-likelihood estimation. Effect sizes were allowed to vary across studies (random effects) and moderators were entered as fixed effects. We estimated robust confidence intervals for model parameters using the *robust()* function in metafor which adjusts for heteroscedasticity using a cluster robust estimator (Hedges, Tipton, & Johnson, 2010).

Two statistical approaches were adopted to consider possible effects of publication bias. To detect possible publication bias we tested for asymmetry in the funnel plot using the regression method of Peters, Sutton, Jones, Abrams, and Rushton (2006). No publication bias is indicated by a linear fit when contrasting effect sizes against standard errors. This procedure necessitated aggregating effect sizes within studies so that effect sizes from different studies were independent. The *regtest()* function was then applied to these aggregated effect sizes. Secondly, Vevea and Woods (2005) proposed a method for modelling the potential impact of publication bias by recalculating effect sizes after adding a proportion of hypothetical null results. We modelled severe publication bias by assuming that null results in the $0.05 < p < 0.50$ were half as likely to be published as significant results and null results in the $0.50 < p < 1.00$ range were a fifth as likely. In such a scenario there would be far more null results in the ‘file drawer’ than significant results in the public domain. We also modelled moderate publication bias by assuming that null results in the $0.05 < p < 0.50$ were 0.8 as likely to be published as significant results and null results in the $0.50 < p < 1.00$ range were 0.6 as likely. This was implemented using the *weightfunct()* function in the weightr package (Coburn & Vevea, 2019).

**RESULTS**

The results are presented in increasing levels of granularity: starting with the overall picture, followed by a division into episodic and working memory, and finally looking at distinctions within each of these domains.

Working Memory versus Episodic Memory

There were 99 and 51 effect sizes relating to episodic memory and working memory respectively. These were first analysed by performing a meta-analysis on the combined $k = 150$ sample with episodic v. working memory as a moderator and study number as a random effect. The effect of the moderator was significant ($z = 6.722$, $p < .001$) with significant residual heterogeneity between studies ($Q(148) = 293.893$, $p < .001$). As such, the effects of the moderation analysis show that the synaesthetic memory advantage is greater for episodic memory than for working memory.

Separate meta-analyses for working memory and episodic memory with robust 95% confidence intervals revealed that the effect size for working memory was $\hat{d} = 0.356$ [0.103, 0.608], $z = 3.049$, $p < .001$], and for episodic memory was 0.606 [0.395, 0.817], $z = 5.937$, $p < .001$. Thus, relative to controls, both episodic memory and working memory are enhanced. To put this another way, the average synaesthete is at the 73$^{rd}$ percentile of neurotypical episodic memory ability and 64$^{th}$ percentile for working memory.

Figure 2 shows a forest plot for episodic memory ordered by study number. It is noteworthy that the four lowest effect sizes (in which synaesthetes have a memory disadvantage) come from studies in which their synaesthetic associations may have hindered new learning. For instance, Brang et al. (2013) trained grapheme-colour synaesthetes to associate colours to Japanese kana and concluded that synaesthetes may have implicit colour associations to those characters which prevented learning.

INSERT FIGURE 2 ABOUT HERE

Figure 3 shows a forest plot for working memory ordered by study number. In contrast to the medium effect sizes ($\hat{d}$ > 0.5) for episodic memory, the effect sizes for conventional STM tests such as forwards Corsi blocks and forwards digit span were never found to exceed small effects, even though digits are a common synaesthetic inducer. It suggests that cognitive advantage is more strongly linked to the type of memory process than the type of stimulus (as shown further below).

INSERT FIGURE 3 ABOUT HERE

In summary, although synaesthetes show significantly enhanced memory (relative to controls) this is significantly more pronounced for episodic memory. This failure to adequately distinguish between different kinds of memory, together with variability in effect sizes due to small samples, explains many of the previous inconsistencies in the literature.

Differences within Episodic Memory

The effects of moderators relating to episodic memory were considered, again entering study number as a random effect. These are summarised in Table 1.

Effect sizes ($k$ = 99) were divided into those that require immediate retrieval of information after presentation ($k$ = 81) versus retrieval after performing either some intervening activity or after a period of elapsed time ($k$ = 17). This moderator had no significant effect on the group difference (z = 0.366, $p$ = .714). The distinction between recognition ($k$ = 50) and recall ($k$ = 49; either cued or free recall) was not a significant moderator ($z$ = 0.284, $p$ = .777; with one exclusion as it was a composite of an immediate and delayed measure). Similarly, the distinction between verbal ($k$ = 51) and visual (*k* = 46) memoranda was not a significant moderator (*z* = 1.704, *p* = .088; two effect sizes relating to music were excluded).

Previous research has argued that memory for colour may be particularly enhanced in grapheme-colour synaesthetes (Yaro & Ward, 2007). Entering colour as a memoranda (*k* = 15) versus all other stimuli (*k* = 84) was indeed shown to be a significant moderator (*z* = 3.998, *p* < .001) with memory for colour being relatively better, although memory for all kinds of material remained enhanced in synaesthetes with respect to controls (i.e. effect sizes for both kinds of memoranda had confidence intervals not touching zero). There were three studies that directly contrasted LTM for verbal material presented in synaesthetically incongruent colours versus congruent/neutral colours but congruency was not a moderator of memory performance, *z* = .699, *p* = .484.

<u>Differences within Working Memory</u>

The effects of moderators relating to working memory were considered, again entering study number as a random effect. These are shown in Table 2. Effect sizes were divided into those requiring passive retention of information (*k* = 34; e.g. traditional STM measures such as digit span) versus retention with some other ongoing manipulation or active updating (*k* = 16; e.g. measures such as N-back, or sentence verification together with retention) with one unclassified (the composite working memory score of Chun and Hupe, 2016). The passive-active distinction was not a significant moderator of the group difference (*z* = 0.981, *p* = .326). Similarly, the distinction between verbal memoranda (*k* = 19; e.g. digits, words both spoken and written) and visual memoranda (*k* = 31; e.g. colours, spatial locations) was not a significant moderator (*z* = .609, p = .542). Entering colour as a memoranda (*k* = 20) versus all other stimuli (*k* = 31) suggested that this did not moderate memory ability (*z* = 0.415, *p* = .678). There were three studies that directly contrasted LTM for verbal material presented in synaesthetically incongruent colours versus congruent/neutral colours but congruency was not a moderator of memory performance (*z* = 0.265, *p* = .791).

Differences between Synaesthetes

The vast majority of findings come from grapheme-colour synaesthetes (*k* = 91 and 45 for LTM and WM respectively), although it is to be noted that many of these synaesthetes are likely to have multiple other kinds of synaesthesia too. A number of studies have explored memory in sequence-space synaesthesia (*k* = 4 and *k* = 6 for LTM and WM respectively) and there is one episodic memory study with lexical-gustatory synaesthesia (*k* = 4 reflecting different memoranda). Given the scarcity, they were collapsed into a non-GCS synaesthete category. Within LTM, the type of synaesthesia experienced was not a significant moderator ($z$ = 1.278, $p$ = .201) and nor was it for working memory ($z$ = -0.913, $p$ = .361). Further research is clearly needed on other types of synaesthesia.

Publication Bias and Stability of the Results

Figure 4 shows a funnel plot of effect sizes. A funnel plot displays the effect sizes on the x-axis and the standard error (SE) on the y-axis. Studies with low SE (high on the y-axis) typically involve larger sample sizes and, hence, should be less variable in their estimates of effect size, whereas studies with high SE (low on the y-axis) have less power and should be more variable in their estimates of effect size. This gives rise to the resulting triangular 'funnel' shape. Importantly, the distribution should be approximately left-right symmetrical. An absence of underpowered studies with low effect sizes (the bottom left of the triangle) is potentially indicative of publication bias. By contrast, high-powered studies (top of the triangle) and under-powered studies with larger than average effect sizes (bottom right of the triangle) are more likely to enter the literature. In this case, the distribution was approximately symmetrical (74 left and 76 right of centre), suggesting minimal publication bias.

INSERT FIGURE 4 ABOUT HERE

The funnel plot also enables identification of outliers: i.e. effect sizes that are unusually small (left of the triangle) or unusually large (right of the triangle) based on the overall distribution of effect sizes, the limits of which (i.e. edges of the triangle) reflect 95% confidence intervals. In the aggregated sample, there were twenty two outliers. These outliers could reflect heterogeneity in the memory processes under consideration, or incidental differences across studies (e.g. recruitment of unusually good/bad synaesthetes).

With regards to possible publication bias, Peters et al. (2006) regression test of funnel plot asymmetry was not significant for either episodic memory ($z$ = -.508, $p$ = .612) or working memory ($z$ = -1.432, $p$ = .152) indicating non-significant publication bias. Even if one were to assume that there was publication bias, then the results are relatively robust against these effects, at least for episodic memory. Using the Vevea and Woods (2005) method, moderate and severe publication biases would reduce the effect size for episodic memory down to $\hat{d}$ = 0.547 and 0.363 respectively. For working memory, moderate and severe publication biases would reduce the effect size to more trivial levels of $\hat{d}$ = 0.246 and 0.124 respectively.

Finally, we explored the stability of these findings to identify other possible sources of bias. Firstly, we recalculated the effect sizes including only published studies. The estimates for episodic memory were virtually unchanged at $\hat{d}$ = 0.563 [0.316, 0.811] and for working memory were $\hat{d}$ = 0.283 [0.118, 0.449]. Furthermore, we were aware of the possibility that the same participants could have contributed to multiple publications within the same research group over time and these participants may have developed some expertise in these kinds of tests. As such, we also recalculated the population effect size estimates including only the first known study on memory and synaesthesia from each research group (Asgeirsson, Nordfang, & Sorensen, 2015; Bankieris & Aslin, 2016; Brang, Teuscher, Ramachandran, & Coulson, 2010; Chun & Hupe, 2016; Gross, Neargarder, Caldwell-Harris, & Cronin-Golomb, 2011; Radvansky et al., 2011; Rothen & Meier, 2009; Simner, Mayo, & Spiller, 2009; Teichmann, Nieuwenstein, & Rich, 2015; Terhune et al., 2013; Watson, Blair, Kozik, Akins, & Enns, 2012; Yaro & Ward, 2007). This analysis also ensures that data coming from one particular lab group cannot exert an undue bias on the overall results. The estimates for episodic memory were similar or, if anything, larger at $\hat{d}$ = 0.669 [CI 0.179, 1.159] and for working memory were $\hat{d}$ = 0.226 [CI 0.138, 0.315].

**Discussion**

This study performed a meta-analysis of memory ability in people with synaesthesia (primarily grapheme-colour synaesthesia) relative to controls. Consistent with much previous research it was found that synaesthesia is linked to enhanced memory. For episodic (long-term) memory, the effect sizes were around half a standard deviation ($\hat{d}$ = 0.61). It is highly likely that these lab-based memory benefits extend into real world advantages: an average synaesthete lies at the 73rd percentile of episodic memory ability. A novel finding is that working (or short-term) memory is enhanced significantly less in synaesthetes ($\hat{d}$ = 0.36), but nonetheless exceeds that of neurotypical controls. Beyond this difference between episodic and working memory, the effects of synaesthesia were pervasive. That is, moderation analyses showed that memory enhancements extended equally to all kinds of stimuli (albeit with an even greater enhancement for episodic memory for colour), all kinds of test format (recall v. recognition, passive v. active maintenance, immediate v. delayed testing), and all kinds of synaesthete (insofar as this has been tested). This statement requires some qualification because it is tantamount to endorsement of null hypotheses. On the one hand, this meta-analysis is the most statistically high-powered study to date to explore this. On the other hand, meta-analysis can be a blunt tool because it aggregates together other potentially important differences across studies. These limitations are discussed further below and the data and code used for the analysis is available to other researchers to use. The remainder of the discussion considers separately the implications for synaesthesia, and the implications for memory.

Implications for synaesthesia

Much of the initial interest in memory and synaesthesia was motivated by fascinating case studies of exceptional memory (Luria, 1968; Tammet, 2006). Through more systematic investigations of synaesthetes this view has largely been over-turned by the more realistic scenario that, whilst synaesthetes do outperform controls on memory tasks, their advantage is rarely exceptional. However, a shift in the mean of the normal distribution by +0.6 (illustrated in Figure 5) has interesting implications at the upper tail due to its non-linearity, namely that the relative proportion of synaesthetes increases sharply the further along the distribution one goes (e.g. an 11:1 ratio at $z > 4$). Thus, synaesthetes are likely to be over-represented in people with exceptional memory even if the average synaesthete does not have exceptional memory. Of course, some of these people such as Shereshevskii and Tammet have also developed effective mnemonic strategies that undoubtedly play a role too. It is also worth emphasising that 'enhanced' memory is not the same as 'above average' memory. If all synaesthetes had, for whatever reason, a memory boost of +0.6 (as depicted in Figure 5) then some people will shift from good memory (e.g. $z = +1.5$) to exceptional memory ($z = +2.1$) whereas others will shift from poor memory ($z = -1.5$) to below-average memory ($z = -0.9$) but, nevertheless – by definition – everyone's memory will be enhanced. Whether this theoretical argument holds true empirically is something that future research can assess by considering a wider variety of types of synaesthesia and modelling the distribution of scores more formally to consider the shape (e.g. squatness, or bulging at the tail) as well as central tendency (Ward, in press).

INSERT FIGURE 5 ABOUT HERE

Intuitively, one might expect that synaesthetes such as those who experience colours for letters and numbers might have particularly good memory for those stimuli because synaesthetes can treat them as colourful visual images as well as meaningful words. That is, they have been endowed with a unique dual-coding strategy that is not readily available to non-synaesthetes (for similar ideas see Paivio, 1995). Whilst some synaesthetes may well employ this strategy (e.g. Tammet, 2006, describes using it for recalling the sequence of pi), there is little evidence to support the hypothesis that this accounts for the overall pattern of memory ability in synaesthetes. For instance, this technique should work just as well for digit span as for long-term memory of word lists (perhaps more so) and this hypotheses predicts that memory should be better overall for verbal stimuli (for both working memory and long-term memory). Instead, synaesthesia is not strongly linked to the visual-verbal distinction (but is linked to different memory processes). Wilding and Valentine (1997) discuss the different potential cognitive characteristics of superior memory and conclude that pervasiveness across stimuli types (including stimuli not amenable to typical mnemonic strategies) is a key element. This appears to be the case for synaesthesia. They also make a distinction between people with enhanced learning who forget normally and people with normal learning rates who forget less. The meta-analysis suggests that synaesthetes more closely fit the first profile in that they appear to have a larger capacity for learning new information (e.g. recalling or recognising more items from a list) but no difference between immediate and delayed recall (obviously they do remember more than controls after a delay but this reflects their higher starting point). However, further research is warranted: there was a numerical trend for delayed memory retrieval to be better. Moreover, it is important to make a distinction between different forgetting mechanisms such as temporal decay (assessed by most delayed recall methods) versus interference from competing associations. Some evidence suggests that synaesthetes might have particular problems in 'unlearning' old information in the light of new, competing information (Bankieris, Qian, & Aslin, in press; Bankieris & Aslin, 2016) and, in these situations, show a reversal of the normal memory enhancement (i.e. making new learning comparatively worse).

If synaesthetic experiences do not directly give rise to enhanced memory, then the alternative suggestion is that enhanced memory is part of a neurocognitive disposition for the emergence of synaesthesia (Rothen et al., 2012; Ward, in press). That is, synaesthetic experiences serve as a kind of phenotypic 'marker' for underlying differences in brain structure and brain function that involve memory and other aspects of cognition (perception, imagery). For example, Shriki, Sadeh, and Ward (2016) developed a neural network module of synaesthesia containing two inter-connected pools of neurons receiving different inputs (e.g. colour v. sound) in which the learning regime was to maximise the overall sensory sensitivity of the model. Under most scenarios synaesthesia did not emerge (zero-weighted connections develop between the modules) but under other scenarios, including increased plasticity of the learning algorithm, it did start to emerge. In this simple example, synaesthesia was an emergent property linked to individual differences in learning/memory and sensory sensitivity. This stands in contrast to the alternative account that synaesthesia itself (e.g. having colours for numbers) acts as a causal influence on memory ability. These ideas are returned to in the next section.

## Implications for memory

Surprisingly little is known about why some people have better episodic memory than others. We are doubtful that enhanced episodic memory in synaesthetes can be easily reduced to the concept of intelligence, although further research is needed on this area. Evidence from individual differences research suggests that measures of memory and intelligence are best accounted for by multi-factor models rather than a single general ability (Holdnack, Zhou, Larrabee, Millis, & Salthouse, 2011), and evidence from neuropsychology typically links fluid intelligence (and working memory) with fronto-parietal circuits (Jung & Haier, 2007) and episodic memory with the medial temporal lobes (Squire, Stark, & Clark, 2004). If intelligence were the source of the enhanced memory of synaesthetes then we would expect to see it manifest primarily on active (or complex) working memory tasks (Engle, Tuholski, Laughlin, & Conway, 1999).

In general, research has tended to focus on reasons for having poorer long-term memory and its implications for cognitive ageing. Most common neurodevelopmental conditions, such as high-functioning autism, schizophrenia or ADHD are not linked with improvements in long-term memory that are observed in synaesthesia: if anything, they have worse memory (Aleman, Hijman, de Haan, & Kahn, 1999; Hervey, Epstein, & Curry, 2004; Velikonja, Fett, & Velthorst, 2019). Being ‘special’ or having unusual experiences is, in itself, no guarantee of better memory. For instance, reports of enhanced memory in autism tend to be limited to their specialist area of interest/expertise rather than extending to standard lab-based measures of memory (Pring, 2008). As such, synaesthesia occupies a (possibly) unique position of being the only known neurodevelopmental condition linked to a pervasive enhancement of long-term memory (although it is by no means the only known positive influence on memory). Other research that focuses on having unusually good memory, such as research on 'super-agers' (Harrison, Weintraub, Mesulam, & Rogalski, 2012) should take into account whether these participants have synaesthesia. If young synaesthetes start life with enhanced memory then they may decline to a neurotypically youthful level of memory in old age, and there is evidence for this (Mealor et al., 2019). However, having enhanced memory may not always be a good thing, as it is sometimes adaptive to not remember (e.g. in the case of trauma).

The present research suggests that episodic memory can be relatively selectively enhanced without comparable enhancements in working memory. However, the fact that working memory is nevertheless enhanced (albeit less than episodic) is worthy for discussion as it points to the existence of some shared mechanism between the two. One possibility is that the tasks themselves are not process-pure. Notably, some tasks commonly classed as working memory place demands on long-term memory (Shipstead, Lindsey, Marshall, & Engle, 2014). For example, complex span tasks involve performing a judgment on a sentence and then committing the final word of the sentence into working memory, alongside other previous words. The to-be-remembered items are drawn from an open set (i.e. all words in the lexicon) rather than a smaller closed set (e.g. the set of 10 digits that participate in digit span). It is noteworthy that the study of working memory with the largest synaesthetic advantage had these open set and complex span characteristics (Radvansky, Gibson, & McNerney, 2014). Thus, one possibility is that enhanced memory in synaesthetes is only found for long-term memory, with these benefits carrying over (to a lesser extent) in certain tasks of working memory because these tasks are not pure.

For models in which working memory is the temporary activation of long-term memory (e.g. D'Esposito, 2007), then having more robust or precise representations in LTM would be expected to impact both types of memory (and, in this framework, it makes no sense to talk about 'pure' tasks as there will always be an overlap). However, it will not necessarily be case that the memory benefit will be quantitatively the same because each type of task has its own source of capacity limitation: degree of interference between active representations in working memory, versus mechanisms of plasticity and stimulus encoding in LTM.

The Representational-Hierarchical model goes one step further by arguing that the same representations that support memory (both long-term and working) also support perception (Kent, Hvoslef-Eide, Saksida, & Bussey, 2016; Murray, Bussey, & Saksida, 2007). In this view, there is no sharp division between perception and memory but, instead, there is a hierarchical division between the type of information is processed (simple features, feature conjunctions, objects, object conjunctions) and this information supports both memory and perception. So a region such as the hippocampus is specialised by virtue of the kinds of information it processes (e.g. certain kinds of spatial associations) rather than acting as a memory system per se. Some research has argued that this may offer be a way of explaining the memory advantages in synaesthetes because they also show certain behavioural advantages in perception as well as memory (Banissy, Kadosh, Maus, Walsh, & Ward, 2009; J. Ward, Rothen, Chang, & Kanai, 2017) and also show differences (relative to controls) in visual cortex activity, in fMRI, during memory retrieval and recognition (Pfeifer et al., 2016). For instance, both colour perception (Banissy et al., 2009; Ward et al., 2017) and colour memory (Pritchard, Rothen, Coolbear, & Ward, 2013; Yaro & Ward, 2007) have been reported to be enhanced in synaesthesia. The latter was also found in this meta-analysis, at least for episodic memory in which colour was the memoranda. Kent et al. (2016) argue that one generic mechanism that could support both perception and memory (across many brain systems) is pattern separation, defined as "a process of reducing overlap between similar input patterns to minimize interference amongst stored representations" (p. 99). In effect, more efficient pattern separation would lead to different stimuli having more different (less correlated) neural representations rendering them more distinct perceptually and mnestically. It is not clear what, neurobiologically, would give rise to individual differences in this process, although the computational model of synaesthesia by Shriki et al. (2016) was effectively set to maximise pattern separation of sensory stimuli under different plasticity regimes.

Conclusion

This meta-analysis definitively establishes that synaesthesia is linked to significantly better long-term episodic memory. This is pervasive insofar as it is found across many kinds of stimuli and different kinds of test (recognition and recall with immediate and delayed testing). Although we did not find moderating effects (i.e. relative differences in the level of enhancement), further evidence is still warranted. These results have important implications for understanding individual differences in memory (which typically do not consider synaesthesia), including those that are clinically relevant.

*Table 1: Effects of moderators on synaesthetic episodic memory advantage showing the estimated Cohen's d and confidence intervals. K refers to the number of effect sizes.*

| Moderator | k | Estimate ($\widehat{d}$) | Robust 95% CIs | Significance |
|---|---|---|---|---|
| <u>Stimulus properties</u> | | | | |
| Verbal | 51 | 0.599 | [0.347, 0.852] | p = .088 |
| Visual | 46 | 0.621 | [0.370, 0.872] | |
| | | | | |
| Colour | 15 | 0.852 | [0.156, 1.548] | p < .001 |
| All non-colour | 84 | 0.586 | [0.420, 0.753] | |
| | | | | |
| Congruent | 3 | 0.733 | [-1.785, 3.251] | p = .484 |
| Incongruent | 3 | 0.531 | [-1.252, 2.313] | |
| | | | | |
| <u>Test properties</u> | | | | |
| Recall | 49 | 0.731 | [0.341, 1.120] | p = .777 |
| Recognition | 50 | 0.521 | [0.327, 0.715] | |
| | | | | |
| Immediate | 81 | 0.577 | [0.371, 0.783] | p = .714 |
| Delayed | 17 | 1.097 | [-0.007, 2.199] | |
| | | | | |
| <u>Participant properties</u> | | | | |
| Grapheme-colour | 91 | 0.602 | [0.383, 0.822] | p = .201 |
| Other syns | 8 | 0.486 | [0.071, 0.901] | |

*Table 2: Effects of moderators on synaesthetic working memory advantage showing the estimated Cohen's d and confidence intervals.*

| **Moderator** | ***k*** | **Estimate ($\hat{d}$)** | **Robust 95% CI** | **Significance** |
|---|---|---|---|---|
| <u>Stimulus properties</u> | | | | |
| Verbal | 19 | 0.398 | [-0.032, 0.828] | p = .542 |
| Visual | 31 | 0.252 | [0.142, 0.361] | |
| | | | | |
| Colour | 20 | 0.305 | [-0.204, 0.814] | p = .678 |
| All non-colour | 31 | 0.337 | [0.066, 0.609] | |
| | | | | |
| Congruent | 3 | 0.543 | [0.020, 1.066] | p = .791 |
| Incongruent | 3 | 0.448 | [0.301, 0.596] | |
| | | | | |
| <u>Test properties</u> | | | | |
| Passive (/simple) | 34 | 0.276 | [0.005, 0.546] | p = .326 |
| Active (/complex) | 16 | 0.372 | [-0.122, 0.866] | |
| | | | | |
| <u>Participant properties</u> | | | | |
| Grapheme-colour | 45 | 0.333 | [0.076, 0.589] | p = .361 |
| Other syns | 6 | 0.529 | [-1.491, 2.550] | |

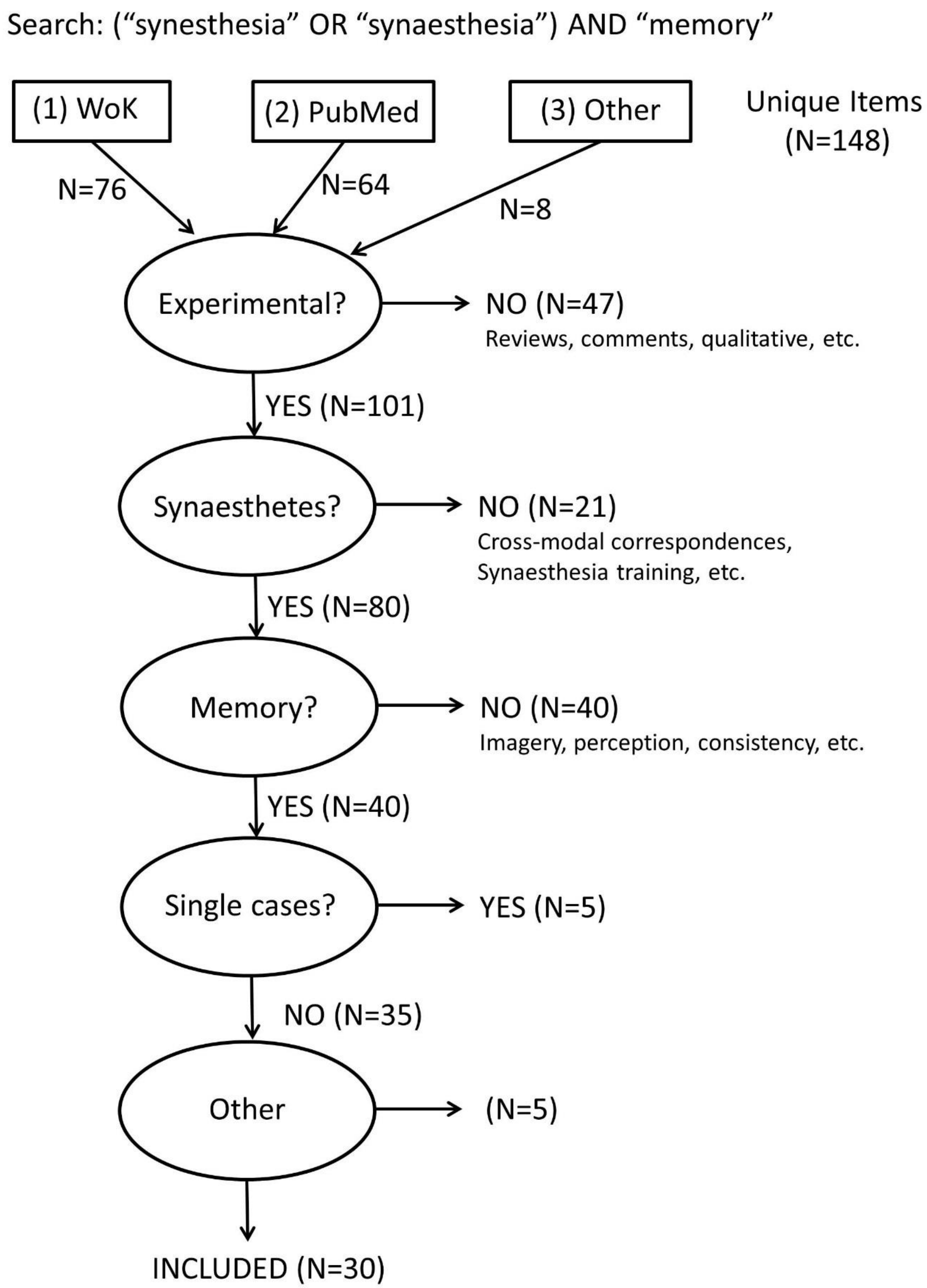
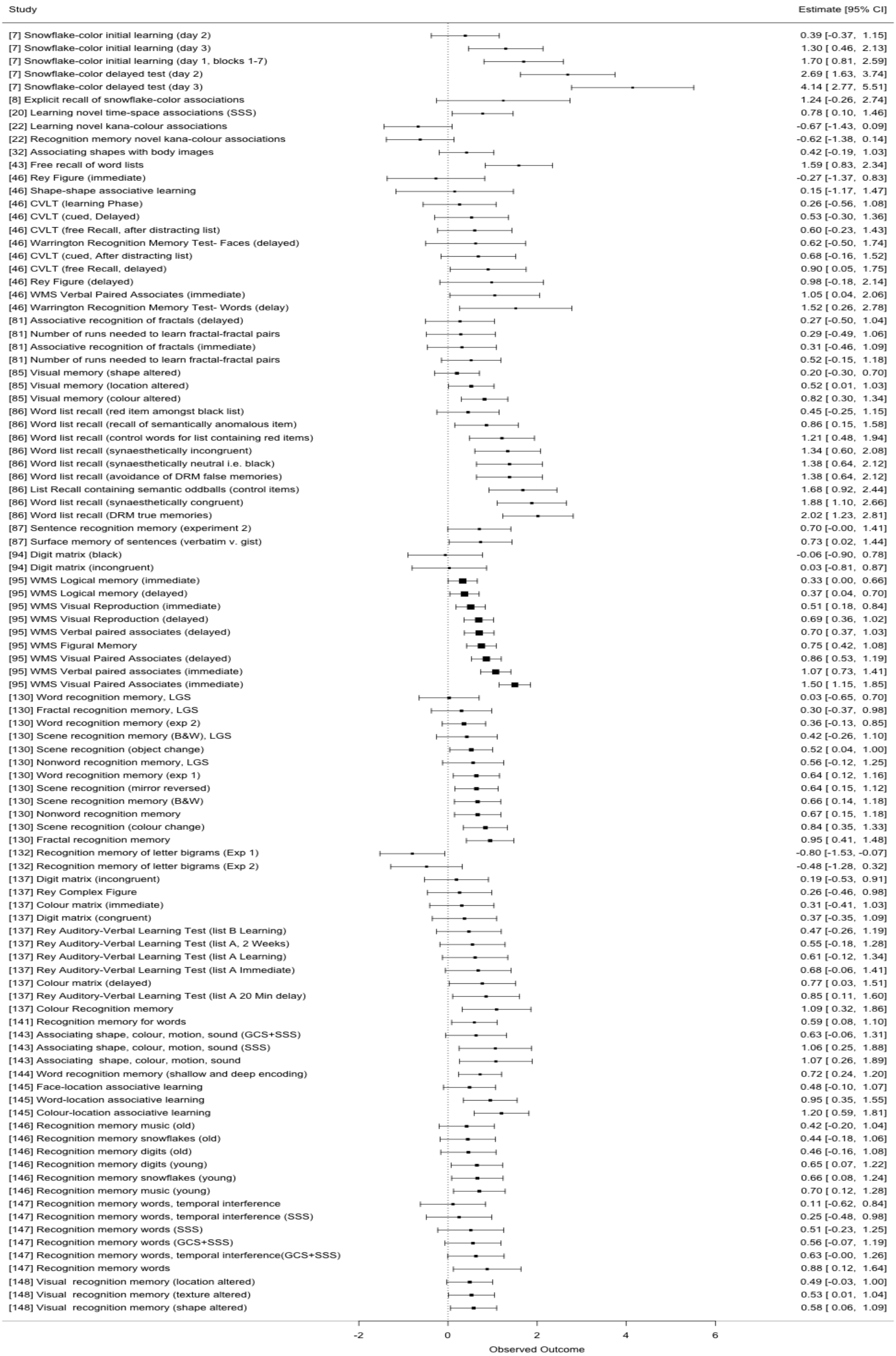
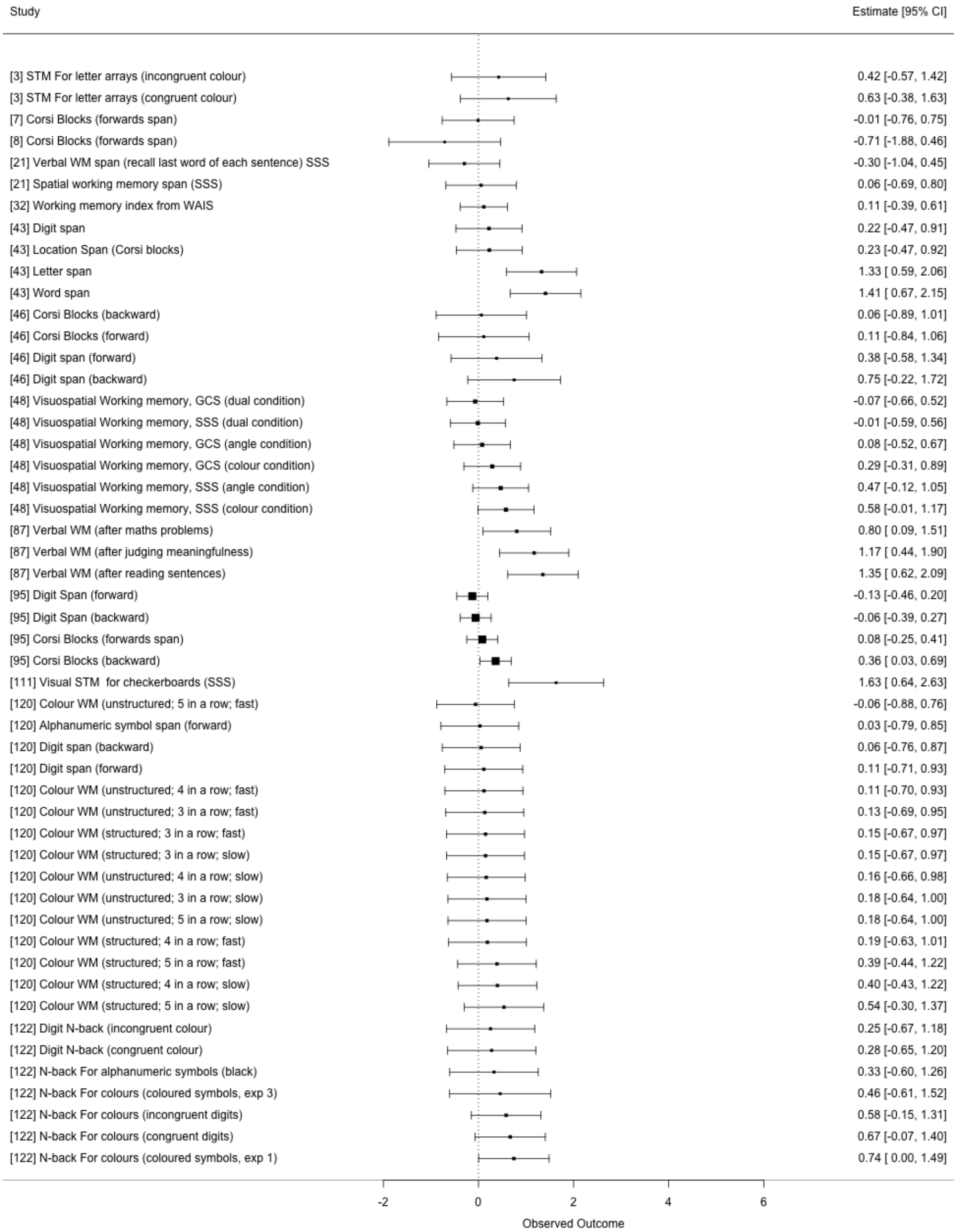



Figure 1: A summary of the search process and application of the inclusion and exclusion criteria.


Study
Estimate [95% CI]
[7] Snowflake-color initial learning (day 2) 0.39 [-0.37, 1.15]
[7] Snowflake-color initial learning (day 3) 1.30 [ 0.46, 2.13]
[7] Snowflake-color initial learning (day 1, blocks 1-7) 1.70 [ 0.81, 2.59]
[7] Snowflake-color delayed test (day 2) 2.69 [ 1.63, 3.74]
[7] Snowflake-color delayed test (day 3) 4.14 [ 2.77, 5.51]
[8] Explicit recall of snowflake-color associations 1.24 [-0.26, 2.74]
[20] Learning novel time-space associations (SSS) 0.78 [ 0.10, 1.46]
[22] Learning novel kana-colour associations -0.67 [-1.43, 0.09]
[22] Recognition memory novel kana-colour associations -0.62 [-1.38, 0.14]
[32] Associating shapes with body images 0.42 [-0.19, 1.03]
[43] Free recall of word lists 1.59 [ 0.83, 2.34]
[46] Rey Figure (immediate) -0.27 [-1.37, 0.83]
[46] Shape-shape associative learning 0.15 [-1.17, 1.47]
[46] CVLT (learning Phase) 0.26 [-0.56, 1.08]
[46] CVLT (cued, Delayed) 0.53 [-0.30, 1.36]
[46] CVLT (free Recall, after distracting list) 0.60 [-0.23, 1.43]
[46] Warrington Recognition Memory Test- Faces (delayed) 0.62 [-0.50, 1.74]
[46] CVLT (cued, After distracting list) 0.68 [-0.16, 1.52]
[46] CVLT (free Recall, delayed) 0.90 [ 0.05, 1.75]
[46] Rey Figure (delayed) 0.98 [-0.18, 2.14]
[46] WMS Verbal Paired Associates (immediate) 1.05 [ 0.04, 2.06]
[46] Warrington Recognition Memory Test- Words (delay) 1.52 [ 0.26, 2.78]
[81] Associative recognition of fractals (delayed) 0.27 [-0.50, 1.04]
[81] Number of runs needed to learn fractal-fractal pairs 0.29 [-0.49, 1.06]
[81] Associative recognition of fractals (immediate) 0.31 [-0.46, 1.09]
[81] Number of runs needed to learn fractal-fractal pairs 0.52 [-0.15, 1.18]
[85] Visual memory (shape altered) 0.20 [-0.30, 0.70]
[85] Visual memory (location altered) 0.52 [ 0.01, 1.03]
[85] Visual memory (colour altered) 0.82 [ 0.30, 1.34]
[86] Word list recall (red item amongst black list) 0.45 [-0.25, 1.15]
[86] Word list recall (recall of semantically anomalous item) 0.86 [ 0.15, 1.58]
[86] Word list recall (control words for list containing red items) 1.21 [ 0.48, 1.94]
[86] Word list recall (synaesthetically incongruent) 1.34 [ 0.60, 2.08]
[86] Word list recall (synaesthetically neutral i.e. black) 1.38 [ 0.64, 2.12]
[86] Word list recall (avoidance of DRM false memories) 1.38 [ 0.64, 2.12]
[86] List Recall containing semantic oddballs (control items) 1.68 [ 0.92, 2.44]
[86] Word list recall (synaesthetically congruent) 1.88 [ 1.10, 2.66]
[86] Word list recall (DRM true memories) 2.02 [ 1.23, 2.81]
[87] Sentence recognition memory (experiment 2) 0.70 [-0.00, 1.41]
[87] Surface memory of sentences (verbatim v. gist) 0.73 [ 0.02, 1.44]
[94] Digit matrix (black) -0.06 [-0.90, 0.78]
[94] Digit matrix (incongruent) 0.03 [-0.81, 0.87]
[95] WMS Logical memory (immediate) 0.33 [ 0.00, 0.66]
[95] WMS Logical memory (delayed) 0.37 [ 0.04, 0.70]
[95] WMS Visual Reproduction (immediate) 0.51 [ 0.18, 0.84]
[95] WMS Visual Reproduction (delayed) 0.69 [ 0.36, 1.02]
[95] WMS Verbal paired associates (delayed) 0.70 [ 0.37, 1.03]
[95] WMS Figural Memory 0.75 [ 0.42, 1.08]
[95] WMS Visual Paired Associates (delayed) 0.86 [ 0.53, 1.19]
[95] WMS Verbal paired associates (immediate) 1.07 [ 0.73, 1.41]
[95] WMS Visual Paired Associates (immediate) 1.50 [ 1.15, 1.85]
[130] Word recognition memory, LGS 0.03 [-0.65, 0.70]
[130] Fractal recognition memory, LGS 0.30 [-0.37, 0.98]
[130] Word recognition memory (exp 2) 0.36 [-0.13, 0.85]
[130] Scene recognition memory (B&W), LGS 0.42 [-0.26, 1.10]
[130] Scene recognition (object change) 0.52 [ 0.04, 1.00]
[130] Nonword recognition memory, LGS 0.56 [-0.12, 1.25]
[130] Word recognition memory (exp 1) 0.64 [ 0.12, 1.16]
[130] Scene recognition (mirror reversed) 0.64 [ 0.15, 1.12]
[130] Scene recognition memory (B&W) 0.66 [ 0.14, 1.18]
[130] Nonword recognition memory 0.67 [ 0.15, 1.18]
[130] Scene recognition (colour change) 0.84 [ 0.35, 1.33]
[130] Fractal recognition memory 0.95 [ 0.41, 1.48]
[132] Recognition memory of letter bigrams (Exp 1) -0.80 [-1.53, -0.07]
[132] Recognition memory of letter bigrams (Exp 2) -0.48 [-1.28, 0.32]
[137] Digit matrix (incongruent) 0.19 [-0.53, 0.91]
[137] Rey Complex Figure 0.26 [-0.46, 0.98]
[137] Colour matrix (immediate) 0.31 [-0.41, 1.03]
[137] Digit matrix (congruent) 0.37 [-0.35, 1.09]
[137] Rey Auditory-Verbal Learning Test (list B Learning) 0.47 [-0.26, 1.19]
[137] Rey Auditory-Verbal Learning Test (list A, 2 Weeks) 0.55 [-0.18, 1.28]
[137] Rey Auditory-Verbal Learning Test (list A Learning) 0.61 [-0.12, 1.34]
[137] Rey Auditory-Verbal Learning Test (list A Immediate) 0.68 [-0.06, 1.41]
[137] Colour matrix (delayed) 0.77 [ 0.03, 1.51]
[137] Rey Auditory-Verbal Learning Test (list A 20 Min delay) 0.85 [ 0.11, 1.60]
[137] Colour Recognition memory 1.09 [ 0.32, 1.86]
[141] Recognition memory for words 0.59 [ 0.08, 1.10]
[143] Associating shape, colour, motion, sound (GCS+SSS) 0.63 [-0.06, 1.31]
[143] Associating shape, colour, motion, sound (SSS) 1.06 [ 0.25, 1.88]
[143] Associating shape, colour, motion, sound 1.07 [ 0.26, 1.89]
[144] Word recognition memory (shallow and deep encoding) 0.72 [ 0.24, 1.20]
[145] Face-location associative learning 0.48 [-0.10, 1.07]
[145] Word-location associative learning 0.95 [ 0.35, 1.55]
[145] Colour-location associative learning 1.20 [ 0.59, 1.81]
[146] Recognition memory music (old) 0.42 [-0.20, 1.04]
[146] Recognition memory snowflakes (old) 0.44 [-0.18, 1.06]
[146] Recognition memory digits (old) 0.46 [-0.16, 1.08]
[146] Recognition memory digits (young) 0.65 [ 0.07, 1.22]
[146] Recognition memory snowflakes (young) 0.66 [ 0.08, 1.24]
[146] Recognition memory music (young) 0.70 [ 0.12, 1.28]
[147] Recognition memory words, temporal interference 0.11 [-0.62, 0.84]
[147] Recognition memory words, temporal interference (SSS) 0.25 [-0.48, 0.98]
[147] Recognition memory words (SSS) 0.51 [-0.23, 1.25]
[147] Recognition memory words (GCS+SSS) 0.56 [-0.07, 1.19]
[147] Recognition memory words, temporal interference(GCS+SSS) 0.63 [-0.00, 1.26]
[147] Recognition memory words 0.88 [ 0.12, 1.64]
[148] Visual recognition memory (location altered) 0.49 [-0.03, 1.00]
[148] Visual recognition memory (texture altered) 0.53 [ 0.01, 1.04]
[148] Visual recognition memory (shape altered) 0.58 [ 0.06, 1.09]
-2
0
2
4
6
Observed Outcome

*<u>Figure 2</u>: Forest plot showing individual effect sizes for episodic memory. Data is from grapheme-colour synaesthesia (GCS) unless otherwise indicated (LGS: lexical-gustatory synaesthesia; SSS: sequence-space synaesthesia). Numbers in square brackets refer to study identifiers [7] Bankieris & Aslin (2016); [8] Bankieris & Aslin (2017); [20] Brang et al. (2010); [22] Brang et al. (2013b); [32] Chun & Hupe (2016); [43] Gibson et al. (2012); [46] Gross et al. (2011); [81] Pfeifer et al. (2014 [85] Pritchard et al. (2013); [86] Radvansky et al. (2011); [87] Radvansky et al. (2013); [94] Rothen & Meier (2009); [95] Rothen & Meier (2010); [130] Ward et al. (2013); [132] Watson et al. (2012); [137] Yaro & Ward (2007); [141] Rothen et al. (under review); [143] Mealor & Ward (unpublished); [144] Ward et al. (unpublished); [145] Woodley & Ward(unpublished); [146] Mealor, et al. (2019); [147] Ward et al. (unpublished); [148] Mealor & Ward (unpublished).*




*<u>Figure 3</u>: Forest plot showing individual effect sizes for working memory. Data is from grapheme-colour synaesthesia (GCS) unless otherwise indicated (LGS: lexical-gustatory synaesthesia; SSS: sequence-space synaesthesia). Numbers in square brackets refer to study identifiers. [3] Asgeirsson et al. (2015); [7] Bankieris & Aslin (2016); [8] Bankieris & Aslin (2017); [21] Brang et al. (2013a); [32] Chun & Hupe (2016); [43] Gibson et al. (2012); [46] Gross et al. (2011); [48] Hale et al. (2014); [87]*

*Radvansky et al. (2013); [95] Rothen & Meier (2010); [111] Simner et al. (2009); [120] Teichmann et al. (2015); [122] Terhune et al. (2013).*

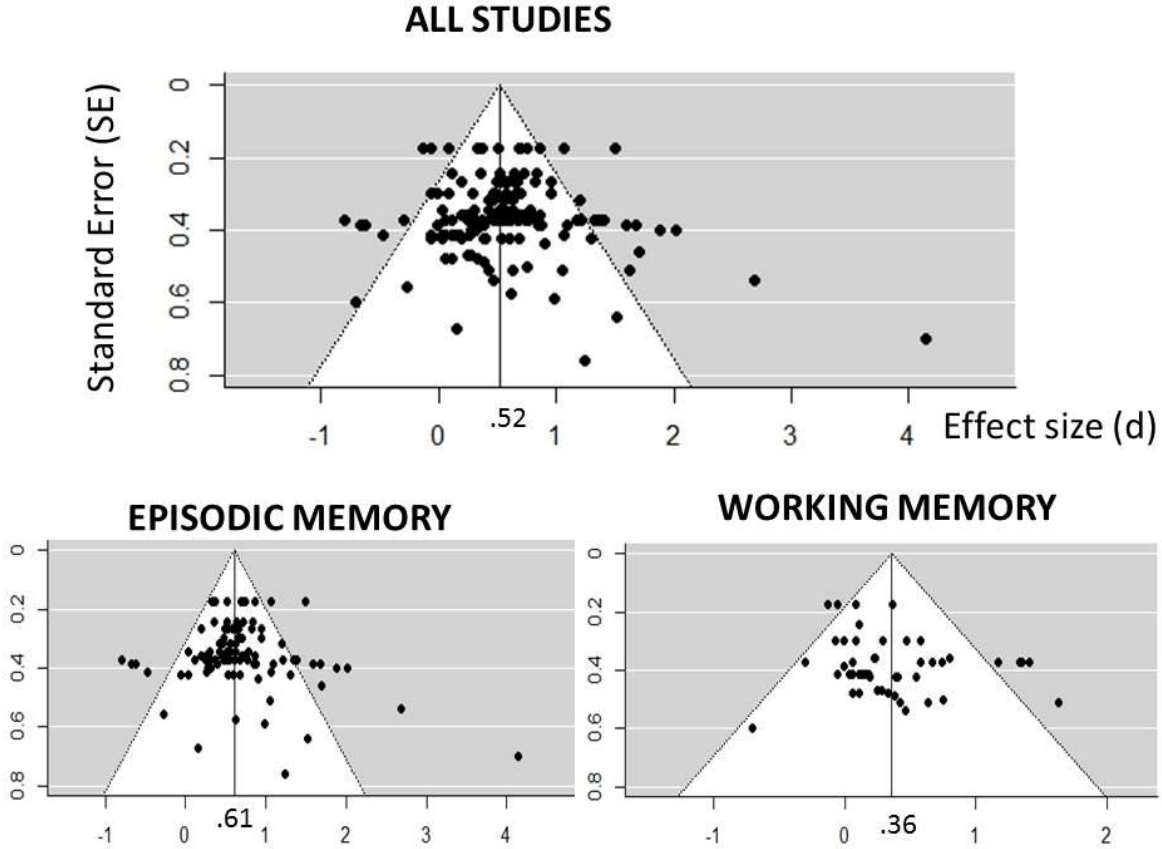
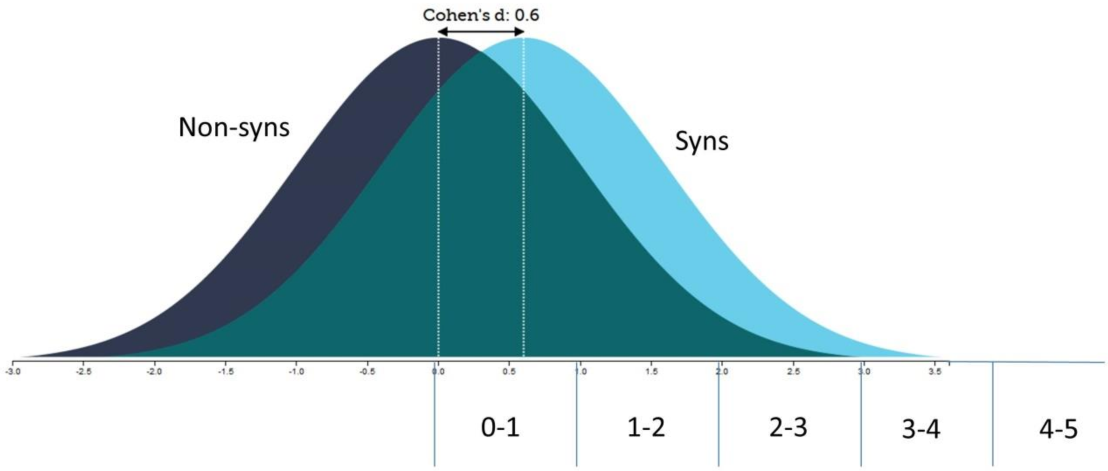



Figure 4: Funnel plots for all studies (top) and broken down into episodic memory and working memory (bottom). Each data point depicts a separate effect size within the multi-level model. The edges of the funnel plot represent 95% confidence limits.




| | 0-1 | 1-2 | 2-3 | 3-4 | 4-5 |
|---|---|---|---|---|---|
| % Syns | 38.0 | 26.8 | 7.51 | 0.83 | 0.04 |
| % Non-syns | 34.1 | 13.6 | 2.14 | 0.13 | 0.003 |
| Ratio | **1.1** | **2.0** | **3.5** | **6.3** | **11.4** |

*Figure 5: An idealised distribution of memory abilities for synaesthetes and non-synaesthetes (controls) based on a Cohen's d of 0.6. Note how the whole distribution is shifted (i.e. every synaesthete is enhanced) and that the relative ratio of synaesthetes to non-synaesthetes increases dramatically in the exceptional zone of ability (z>2).*

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