ELD revisited: A second look at a neuropsychological impairment of working memory affecting retention of visuo-spatial material

J. Richard Hanley (a)

&

Andrew W. Young (b)

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(a) Department of Psychology, University of Essex, Colchester CO4 9TN, UK

email = rhanley@essex.ac.uk

(b) Department of Psychology, University of York, York YO10 5DD, UK

email = andy.young@york.ac.uk

Corresponding author: J. Richard Hanley

Abstract

Neuropsychological case studies involving putative impairment of the visuo-spatial sketch-pad component of Baddeley’s (1986) working memory model have been uncommon, with our own investigation of case ELD still being one of the most comprehensive to date (Hanley, Pearson & Young, 1990; Hanley, Young & Pearson, 1991). A recent theoretical review by Morey (2018) has offered a critique of ELD's data that has sought to cast doubt on our claim that she showed a pattern that reflects a problem with a functional component equivalent to the visuo-spatial sketch-pad. The importance of neuropsychological evidence to understanding visuo-spatial short-term memory has prompted us to revisit this case study, correct errors and misunderstandings in Morey's (2018) description of it, and provide some additional statistical information. Whilst acknowledging that cognitive neuropsychological studies will often depend on more than a single patient to offer definitive resolution of such an important issue, we show that there are compelling reasons to reject many of the claims that Morey (2018) made about ELD.

Keywords: visuo-spatial sketch pad, working memory, anterograde memory, face recognition

Background

According to what remains the most widely used model of working memory (Baddeley, 1986), distinct modality-specific short-term buffers are responsible for the temporary storage of verbal (the phonological loop) and visuo-spatial information (the visuo-spatial sketch pad). This conception of working memory arose through adding a visuo-spatial sketch pad (VSSP) component to the original model suggested by Baddeley and Hitch (1974).

Neuropsychological data from patients with apparent lesions that compromise either one of these two buffer stores have offered a unique form of evidence in support of this functional architecture. There have been several reports of patients with very short verbal memory spans consistent with impairments to the phonological loop (e.g. Warrington & Shallice, 1969; Vallar & Baddeley, 1984). Reports of individuals with selective impairments to the visuo-spatial sketch-pad are less common. In the early 1990s, we published one of the most thorough investigations of a patient (ELD) whose performance was consistent with a working memory impairment that appeared to compromise the VSSP (Hanley, Pearson & Young, 1990; Hanley, Young & Pearson, 1991). ELD's ability to learn completely novel visual stimuli (such as faces and objects she had not previously encountered) was poor, yet she could remember new instances of pre-morbidly familiar visual forms (Hanley et al., 1990). Her verbal memory span was at least as good as that of controls, but she performed extremely poorly when attempting to reproduce sequences of material that seemed to require the temporary storage of visual and/or spatial information (Hanley et al., 1991). We argued that this particular combination of deficits provided strong support for the existence of a distinct visuo-spatial component of the working memory system.

It was already known at the time that a range of neuropsychological disorders could encompass aspects of visuo-spatial short-term memory and cognition (De Renzi and Nichelli, 1975; De Renzi, 1982). Nevertheless, it was relatively unusual to approach these deficits from the standpoint of the working memory model. Although theorising of this kind has since increased (e.g. Logie

1995; Logie & Della Sala, 2005; Bonni et al., 2014), other developments in the intervening years that offer alternative perspectives on visuo-spatial working memory have drawn mainly on new evidence from experimental psychology, functional brain imaging and primate neurophysiology rather than on evidence from neuropsychological case studies (e.g. Chun, 2011; Ma, Husain & Bays, 2014; Xu & Chun, 2006). The case of ELD, therefore, remains an important source of evidence in support of the existence of a visuo-spatial short-term store of the kind advocated by Baddeley (1986).

A recent theoretical review by Morey (2018) has offered a critique of the evidence that has been taken to support the existence of a specialised visuo-spatial short-term memory store. Morey's paper discussed a wide range of studies of normal participants (including both behavioural work and functional brain imaging) as well as studies of neuropsychological patients. Pulling no punches, she stated that her "examination of this evidence challenges multiple-component working memory theorists and those applying this working memory theory to practical problems to overcome the rut that assumptions about modularity has mired us in, and shift toward imagining alternative explanations" (Morey, 2018, p.856).

Clearly much is at stake here, but a response to the claims that Morey made concerning the data from neurologically normal participants is beyond the scope of what we seek to do in this commentary. Rather, we focus on Morey's discussion of the case of ELD in which she claimed that aspects of ELD's performance were inconsistent with a VSSP impairment, and that there were additional methodological limitations that made interpretation of the case equivocal. Morey accepted that neuropsychological evidence in general, and the case of ELD in particular, had played a significant role in bolstering support for the existence of a separate visuo-spatial short-term memory store. Morey's attempt to weaken the claim that ELD showed a pattern that reflects a problem with the visuo-spatial sketch-pad therefore represented an important element of her overall argument against the existence of modality specific short-term memory buffers.

We fully accept the role of re-evaluating findings in facilitating scientific progress and hope that we are still receptive to new ideas. Nevertheless, we believe that Morey's account of the performance of ELD contains some errors and misinterpretations and that she has misjudged the theoretical implications of ELD's case as a consequence. Below, therefore, we re-visit our account of ELD after more than 25 years and consider whether her case continues to provide support for the existence of the VSSP. We also include the results of some additional statistical analyses that we have performed on ELD's data. These techniques were developed by Crawford and his colleagues specifically for use in single-case studies (e.g. Crawford & Howell, 1998; Crawford & Garthwaite, 2005) in the years following the publication of our findings with ELD and could not therefore be used at the time we carried out our studies.

Impaired memory for new visual forms (Hanley et al., 1990)

ELD first came to our attention because she reported problems in learning new faces and new routes following treatment of a haematoma caused by a right middle cerebral artery aneurysm some three years previously. Initially, we focussed on the problem in learning new faces, which was reminiscent of a small number of patients previously described in the neurological literature as suffering from what Ross (1980, 1982) called 'isolated loss of visual recent memory' as a consequence of right hemisphere brain injury. We therefore undertook a detailed investigation of ELD's anterograde memory deficit (Hanley et al., 1990).

We did not find any problems with visual perception that could account for ELD's problems with learning new faces. Although her contrast sensitivity function was slightly impaired above 3 cycles per degree, people with impaired contrast sensitivity do not invariably have problems with recent visual memory. Likewise whilst her colour vision was not normal (total error score of 274 on the Farnsworth-Munsell 100 hue test), ELD was always tested for face learning and recognition with greyscale stimuli. Moreover, all our tests suggested that ELD showed normal perceptual processing of faces, scoring 44/54 on the Benton Facial Recognition Test (normal range 40-54), 40/40 correct on classifying the sex of an unfamiliar face, 40/40 on classifying a face as young or old, and successfully matching facial expressions as same or different across 30/32 pairs of different unfamiliar faces (control mean = 29.79).

It was also immediately apparent that this anterograde memory impairment did not compromise recognition memory for words; on the Warrington (1984) Recognition Memory Test (RMT) ELD scored 43/50 for words, a score that was within the normal range (chance level would be 25/50 correct). However, she scored 34/50 for faces, a score that was over 2.5 standard deviations below the mean for her age group. Only 5% of Warrington's controls had a difference as large as this between their words and faces score. We noted too that when retested at a later time, ELD showed an even larger discrepancy, scoring 49/50 on words and 29/50 on faces (Hanley et al., 1990). Moreover, an independent recognition memory task (Hanley et al., 1990, Experiment 1) confirmed a substantial impairment of recognition memory for faces.

The stimuli used in the RMT for faces and the additional recognition memory test for faces alluded to above were all photographs of unfamiliar individuals. Consistent with this recognition memory problem for unfamiliar faces we found that, in line with her subjective reports, ELD was very poor at identifying the faces of people who had become famous since the time of her illness (Hanley et al., 1990, Experiment 2). In contrast, her identification of pre-morbidly familiar faces was unimpaired (Hanley et al., 1990, Experiments 2, 3). This pattern of preserved recognition of pre-morbidly familiar faces held even when we made the task particularly difficult by using only low familiarity items (Hanley et al., 1990, Experiment 3). In effect, ELD had severe problems with learning the faces of newly encountered individuals. In contrast, there were no corresponding difficulties with the identification of the names of the people who had become famous since her illness (Hanley et al., 1990, Experiment 2), again demonstrating relatively preserved learning of new verbal material.

To look at ELD's problem in learning unfamiliar faces in more detail, we devised new tasks involving variants of the RMT procedure of studying a list of items (in this case, photographs of faces) and then testing recognition memory immediately through two-alternative forced choice. On these tests of episodic memory for faces, ELD could recognize which faces she had seen a few minutes earlier if the faces were already familiar to her (Hanley et al., 1990, Experiments 4, 5) but not if they were unfamiliar (Hanley et al., 1990, Experiment 5).

A particularly striking additional finding from these newly devised recognition memory tasks was that ELD could remember which view of a face or an object she had seen a few minutes earlier if the face or object was familiar, but not if it was an unfamiliar face or a novel object (Hanley et al., 1990, Experiment 5). In these cases, the recognition memory test involved two slightly different views of one of the studied faces or objects and ELD's forced-choice recognition task was to choose the exact photograph she had seen from the closely similar distractor view of the same item. ELD's pattern of performance showed that she could remember new *visual* material (i.e., a new photograph) as long as it pertained to a pre-morbidly familiar visual form (a known face or a known object) but not when it involved an unfamiliar face or an unknown object. The breakdown of picture memory was therefore directly related to the pre-morbid familiarity of the items used.

Hanley et al. (1990) maintained that ELD's case had important implications for understanding visual memory and its impairments. It demonstrated that what Ross (1980) called visual recent memory loss need not involve impairment of all recent visual memories. Instead, ELD 's visual recent memory was normal for pre-morbidly familiar items, placing clear constraints on any satisfactory account of the creation of visual memories. In line with the standard interpretation of recognition memory performance, Hanley et al. (1990) assumed that even though the retention interval is short, tests such as the Warrington RMT are tests of long-term retention and that ELD's poor recognition of visual information reflected a problem in retaining new information in a visual long-term memory store.

At the time, however, Hanley et al. (1990) did not raise the question of whether there was any impairment to ELD's VSSP. None of their experiments seemed to address directly this issue because they involved the use of supra-span lists. In fact, we did not yet see the importance of the idea that the ability to learn certain types of new material might involve working memory. As we explain in more detail below, our subsequent understanding of this point led us to examine whether

ELD's problems in learning new visual forms (such as new faces or new objects) reflected an impairment of the VSSP (Hanley et al., 1991).

Nevertheless, Morey (2018) did not accept this interpretation. Instead, she claimed the finding that ELD was able to recognize some faces in tests of episodic memory was inconsistent with a VSSP impairment. Morey (2018) maintained that "when E.L.D. performed a task that required her to indicate which of two faces or objects she had seen recently, she performed nearly as well as controls" (Morey, 2018, p.858), that "E.L.D. demonstrated recognition memory for visual materials comparable to controls when the test decisions were limited to a two-choice scenario" (Morey, 2018, p.858), and that "she had little difficulty recognizing which of two unfamiliar faces she had encountered in a recent experimental session" (Morey, 2018, p.858).

Unfortunately, these statements are all misleading or incorrect. As described above, Hanley et al. (1990) tested ELD's ability to remember unfamiliar faces and unfamiliar objects on various occasions and in various ways, yet ELD was *never* able to recognize unfamiliar faces or unfamiliar objects at the same level as controls. This held even when the test decisions were "limited to a two-choice scenario", as in the Warrington RMT or in Hanley et al.'s (1990) Experiment 5.

Perhaps Morey meant to say that ELD's ability to recognize *familiar* faces in tests of episodic memory was preserved. This was indeed what we found. Even if so, however, preserved recognition memory for photographs of familiar faces (such as in Hanley et al., 1990, Experiments 4 and 5) does not establish whether or not ELD had a VSSP deficit. The materials that ELD was asked to remember in the two experiments in which she showed good recognition memory for familiar faces would have far exceeded the capacity of a short-term memory buffer. In Experiment 4, the list length was 50 faces; in Experiment 5, there were 40 items per list. Consequently, recognition performance in these experiments cannot simply be considered to reflect the contents of a visual STM buffer; as already noted they are tests of long-term memory, albeit tested across a short retention interval. Instead, ELD's good recognition memory for familiar faces appears to be analogous to findings of preserved learning of familiar verbal material in cases involving putative impairments of the phonological loop (e.g. Warrington & Shallice, 1969; Shallice & Warrington, 1970). Yet Morey (2018) thought that this was one of the most important pieces of evidence against a VSSP impairment (our italics): "…her entire portfolio of cognitive deficits includes many examples of problems that are inconsistent with the idea that she suffers from an impaired visual-spatial short-term memory buffer, *most especially her intact ability to detect which of two faces were shown on a recent trial*" (Morey, 2018, p.858). This opinion reflects a misinterpretation of ELD's data (because she was only able to achieve good performance with premorbidly familiar faces) and of the literature on deficits of working memory more generally (because ELD's intact ability to remember familiar faces is nonetheless consistent with impairment of the VSSP; the inference of a VSSP impairment is linked to her difficulty in learning new faces).

Morey (2018) also argued that, in one experiment, ELD's impaired performance might have come about because: "E.L.D. performed this task at a delay of one month, a substantially longer delay than the control sample experienced....This difference in measurement alone is sufficient to explain any difference in performance between E.L.D. and the healthy control sample" (Morey, 2018, p.858). This claim is incorrect because ELD and control participants received identical retention intervals in all of our experiments. The error appears to have arisen as a result of a misunderstanding of our statement that "E.L.D. received the which-view (objects) test a month later" (Hanley et al., 1990, p.1140). All this sentence was intended to do was simply to note that ELD happened to have performed this task (which involved both a study presentation phase and a recognition test phase) a month after administration of the three previous tests in this series. We had already stated that the task was designed using this "study presentation phase followed immediately by recognition test phase" procedure because it was modelled directly on the procedure used in the RMT (Warrington, 1984), with the intention of arriving at a better understanding of ELD's poor performance with the 'faces' part of that test. The delay in administering test items was never more than a matter of minutes.

Impairment of the visuo-spatial sketch pad (Hanley et al., 1991)

As described above, our first approach to understanding ELD's problems (Hanley et al., 1990) was to consider them as a form of anterograde memory impairment in many respects comparable to cases described at the time as 'visual recent memory loss' (Ross, 1980) or 'anterograde prosopagnosia' (Tranel, Damasio & Damasio, 1988), and later termed 'prosopamnesia' by Tippett, Miller & Farah (2000). In so doing, though, we were conscious of neglecting ELD's subjective problems in finding her way around. She had moved to a different part of her city and described her topographical problems as resulting from an inability to form a mental picture of the new routes on which she had recently travelled. She said that she relied on recognising familiar visual landmarks and that following her move she found it difficult to alight at the appropriate bus stop following a trip to the city centre. She also said that she sometimes woke up in the middle of the night unable to remember the layout of her new bedroom in the darkness.

Although Hanley et al. (1990) noted that such problems might well be consistent with a loss of recent visual memory, they did not follow them up. There was of course also an obvious parallel with the co-occurrence of problems in recognising faces and finding one's way around reported in several cases of prosopagnosia (Meadows, 1974) and one possible interpretation was that ELD might have problems in learning new visual landmarks as well as new faces. However, other problems can also lead to topographical disorientation, including more fundamentally 'spatial' deficits that would impair the learning of the layouts of new routes (Aguirre & D'Esposito, 1999; Wilson et al., 2005). Any of these causes would be consistent with impairment of the VSSP. Alternatively, though, ELD’s co-occurring problems in learning new faces and finding her way about might have been coincidental and largely unrelated.

Our investigation of a possible VSSP impairment commenced several months later as a result of a conversation between one of us (AWY) and Alan Baddeley in which he suggested that ELD's inability to learn and recognize new faces was consistent with a deficit of this kind. The basis for his prediction was that the phonological STM patient PV found it difficult to learn new phonological information such as foreign vocabulary or paired associates that involved pseudowords (Baddeley, Papagno & Vallar, 1988). Conversely, it has long been known that the learning of paired-associates comprising familiar verbal items and the free recall of familiar word lists is preserved in phonological STM patients (e.g. Warrington & Shallice, 1969). Consequently, Baddeley and his colleagues have argued that maintenance of items within the phonological loop is crucial for the consolidation of new phonological information in long-term memory, but is not required for storing new information that is associated with familiar words or concepts. This account therefore raised the possibility that ELD's combination of preserved learning of pre-morbidly familiar visual material with problems in acquiring new visual information such as novel faces and objects might be caused by an equivalent difficulty in maintaining information in the VSSP.

Morey (2018) did not acknowledge the force of this analogy. On the contrary, she argued that because ELD had difficulties in learning new visual memories, her pattern of deficits: "is certainly not the reverse of the pattern shown by so-called auditory short-term memory patients, who could learn aurally-presented verbal information with long delays (Basso, et al., 1982; Warrington & Shallice, 1969)" (Morey, 2018, p.859). Again, Morey's claim is misleading. Whilst it is true that patients with phonological loop deficits can learn auditorily presented verbal information such as lists of already known words (e.g. Warrington & Shallice, 1969), it was precisely because the auditory short-term memory patient PV *did* find it difficult to learn *new* verbal information such as foreign vocabulary items that we thought it worthwhile to investigate a possible VSSP deficit in the case of ELD.

As well as allowing us to investigate the possibility of a direct analogy between the overall patterns of deficits affecting the phonological loop or VSSP components of the working memory model, we were impressed that Baddeley's suggestion entailed a number of falsifiable predictions that did not follow from any other extant theory. In particular, from findings of previous behavioural studies, we could predict that a neuropsychological impairment of working memory that compromised the VSSP would lead to reduced spans in spatial tasks such as Corsi blocks and a reduced benefit of invoking visual imagery in (for example) the Brooks (1967) matrix task.

We therefore investigated the possible existence of a VSSP impairment by administering a series of tests that examined ELD's ability to retain short sequences of visual and/or spatial information. The tasks included the Corsi blocks, in which the experimenter taps a series of arbitrarily positioned wooden blocks one at a time and the participant must reproduce the sequence as soon as presentation is complete (Hanley et al., 1991, Experiment 2). This test of short-term spatial memory had previously been performed normally by patient PV who had a verbal short-term memory impairment (Basso, et al., 1982). ELD started to make errors on this task as soon as the sequence length exceeded three items. Crawford and Howell's (1998) modified t-test shows that ELD's scores were significantly impaired relative to controls on sequences comprising 4 ($t = 2.89$, $p = .017$) and 5 items ($t = 3.81$, $p < .01$).

Another test (Hanley et al., 1991, Experiment 1) investigated performance by ELD on the Brooks (1967) matrix, a task that, according to Baddeley and Lieberman (1980), involves the use of the VSSP when performed by normal participants. In the Brooks task, participants are asked to recall sequences of sentences in their order of presentation. In a spatial imagery condition, each sentence describes the location of a number in a 4x4 matrix and participants are told to imagine the location of the number on a mental image of the grid. At recall, the location of these numbers in the grid can be used to reconstruct the order of the sentences. For neurologically normal participants, recall of sentences in this spatial imagery condition leads to better performance than for sentences in a 'nonsense' condition for which the matrix numbers are replaced by irrelevant words and the sentences must be stored through verbal rather than spatial coding. One of the attractive features of this test is that the response demands in the imagery and nonsense conditions are identical. When we tested ELD with a version of the Brooks task based on eight sentences, however, her performance was much better in the nonsense condition, with 4 times as many errors in the spatial imagery condition (Hanley et al., 1991, p.105). To follow up this observation we looked at the effect of sequence length (from 3 to 8 sentences) in the spatial imagery condition of the Brooks paradigm (Hanley et al., 1991, Experiment 1). As with the Corsi blocks task, ELD was again able to cope with shorter sequences and started to make errors as the sequence length increased. Performance was significantly worse than controls when the sequence length was six items ($t = 3.68$, $p = .011$) and eight items ($t = 4.15$, $p < .01$).

When discussing ELD's performance, Morey (2018) emphasised the finding that she performed well on both of these two tasks with short sequences and only performed badly as list length increased: "Her spatial sequence memory was poorer than controls but perfect for short lists, presumably of the length that would be maintained in a visual-spatial short-term memory buffer. Her performance of a verbal memory task with a spatial imagery component was likewise perfect for short lists, but deficient compared to controls' performance as sequence length increased" (Morey, 2018, p.858).

We accept that ELD's relative success with short sequences suggests that her VSSP may not have been completely abolished. We would point out, however, that the first sentence in the Brooks matrix is always the same: "In the starting square put a 1", so ELD's ability to recall a five item sequence requires retention of only four new list items. Likewise, at least four of the locations in the Corsi blocks task are easily amenable to verbal coding (e.g. "upper leftmost", "upper rightmost", "lower leftmost", and "lower rightmost"). Furthermore, it is simply speculative to imply that successful recall of short sequences means that capacity is somehow adequate. It is actually quite common in studies of individuals with a neuropsychological deficit for impairments to reveal themselves only as the level of difficulty increases. This phenomenon is often called graceful degradation. Graceful degradation can also be observed in the performance of the STM patient PV on the serial recall of verbal material in both the auditory and visual modalities (Vallar & Baddeley, 1984).

Another task examined short-term memory for sequences of four unfamiliar faces (Hanley et al., 1991, Experiment 3). Immediately following presentation of each sequence, the participant was presented with all four faces simultaneously and was asked to point to them in their order of presentation. We note that whether all of the items in a sequence of four faces can be maintained in a short-term memory buffer is by no means certain. Xu and Chun (2006) have argued that visual STM capacity is no greater than two items when the stimuli are complex, and Warrington and Taylor (1973) claimed that only the most recently presented face in a sequence can be retained in a visual STM. Consistent with this perspective, it was striking that our control participants showed a marked single-item recency effect for the final face whereas ELD showed no improvement on the final list item. We recently applied Crawford and Garthwaite's (2005) revised standardized difference (RSD) to these data. This analysis compares the difference between an individual's scores on two measures with the corresponding difference shown by controls. The RSD revealed that the difference between the scores of ELD and the controls was significantly larger on the final item (ELD = 9.0; control mean = 15.0, sd = 0.93) than on the mean for the three earlier items (ELD = 10.7; control mean = 13.8, sd = 2.5), $t = 5.97$, $p < .01$. This test estimates that less than 0.5% of the population would show such an extreme pattern of performance as this. ELD's failure to show a recency effect in a visual STM task is analogous to PV's failure to show a recency effect for auditorily presented material (Vallar & Papagno, 1986). These results are also consistent with the view (Warrington & Taylor, 1973; Xu and Chun, 2006) that the capacity of visual STM is relatively limited for complex materials such as faces.

ELD's immediate serial recall of verbal material was investigated in Experiment 4 (Hanley et al., 1991). In contrast to her impaired performance on visuo-spatial serial recall tests, ELD performed consistently well with both auditory and visual presentation of verbal material. Performance was good even when articulation was supressed. There was therefore no evidence that ELD had a phonological loop impairment despite her VSSP impairment. This represents a double dissociation with the case of PV (Basso et al., 1982; Vallar & Baddeley, 1984) consistent with the claim that immediate recall of visuo-spatial material requires a separate buffer system from immediate recall of verbal information.

When discussing this issue, Morey made the following claim: "... because healthy participants are expected to perform more poorly on visual than verbal STM tasks, we cannot rely on similar reversals when comparing patients with visual deficits with controls. Instead, one must show that difference between verbal and visual STM is larger in patients than would be expected in controls, a subtler distinction that would require greater sensitivity to detect" (Morey, 2018, pp.862-863). This caveat cannot be applied to ELD's performance on visuo-spatial and verbal STM tasks. ELD actually performed descriptively better than controls on verbal STM tasks despite performing significantly worse than controls on visuo-spatial STM tasks. That is, ELD recalled fewer sequences correctly than any of the controls on the Brooks matrix task, the Corsi blocks task and the STM for faces task (Hanley et al., 1991). On the verbal STM tasks (pp 110-112), however, she generally recalled slightly more sequences correctly than the average number recalled by the controls. It is therefore clear that ELD shows a much greater difference between her verbal and visuo-spatial STM performance than controls.

Another claim made by Morey (2018, p.862) was that while cases such as ELD: "..may be consistent with the idea of a specialized visual short-term memory system, they are just as consistent with propositions that maintaining memories in visual-spatial code is more dependent on general cognitive resources than maintaining verbal memoranda is". Our rejoinder is that it seems doubtful whether the face sequences test, the Brooks matrix or the Corsi blocks require more support from general cognitive resources than does the immediate serial recall of verbal material under articulatory suppression (Hanley et al., 1991, Experiment 4). But without a comprehensive model of each task, this kind of argument is purely intuitive. In the absence of any independent theory or even an index of the amount of cognitive resources that particular tasks require, *ad hoc* criticisms such as this can be all too easily applied to any experimental findings that happen to be inconsistent with the theoretical stance that a critic chooses to adopt.

Unresolved questions

Whilst we have argued that the papers published by Hanley et al. (1990, 1991) continue to provide convincing evidence consistent with a working memory deficit involving visuo-spatial material, we acknowledge that our work with ELD contained some loose ends. A concern expressed by Morey (2018) involves the extent to which apparent double dissociations such as that between cases PV and ELD may reflect different combinations of sources of influence, including differences in the ways in which memories are typically measured; for example, testing recall of phonological material compared to testing recognition memory or reconstructing the order of presentation with visuo-spatial items. We recognise that such issues can only be resolved by further case studies.

Other unresolved questions from ELD's case involved deficits that were not immediately explicable in terms of the VSSP component of the working memory model as defined at the time (Baddeley, 1986). We note too that although the working memory model has been updated since (Baddeley, 2017) and there have been developments in the area of visual working memory more generally (Chun, 2011; Logie, 1995; Logie & Della Sala, 2005; Ma et al., 2014; Xu & Chun, 2006), they would not predict the two deficits we now discuss.

First, ELD's Memory Quotient of 100 on the Wechsler Memory Scale was lower than her Verbal IQ of 119. Of course, the lowered MQ would in part have reflected the problems that Hanley et al. (1990, 1991) investigated, but there was also some evidence that ELD's performance was relatively low on subtests involving episodic recall (e.g., Memory Passages and Paired-Associate Learning). She also performed poorly when recalling paired associates comprising familiar words in an experiment reported by Hanley et al. (1991). Nevertheless, an MQ of 100 by definition represents an averagely good memory and Hanley et al. (1990) noted that ELD's scores on these specific subtests were within 1 SD of normal performance, making it clear (as did the other tests reported by Hanley et al. 1990, 1991) that she did not suffer from a general memory impairment.

Second, and we think more interestingly, ELD showed problems in recognition memory for unfamiliar voices (Hanley et al., 1990, Experiment 8). As auditory stimuli, voices cannot fall within the domain of the VSSP. Again, studies of other patients are needed to identify whether an inability to recognise new faces and new voices form inevitably associated deficits or were simply a coincidence of two co-occurring but fundamentally different problems in ELD's case. An advantage of cognitive neuropsychology is that it can proceed iteratively, by using a theory to account for a patient's deficits and then using additional case studies to further test and if necessary modify or even falsify the theory itself (Coltheart, 2008; Ellis & Young, 1988; Shallice, 1988). If the concept of the VSSP is accurate then other patients with an impaired VSSP may not have the associated impairment that made it hard for ELD to learn new voices. If on the other hand problems in learning new faces and voices always co-occur then it might be more useful to think in terms of a rehearsal buffer that can deal with *nonverbal* material rather than visuo-spatial stimuli *per se*.

We think, though, that in part Morey's (2018) critique of ELD was based on a fundamentally different conception of what cognitive neuropsychology entails. Morey (2018) emphasised that the additional problems we noted above suggest that ELD's "impairments extended beyond visual memory specifically" (Morey, 2018, p.858) and that "sufficient evidence of deficits in tasks that could not be dependent on visual or spatial STM make clear that she is not an example of someone with a selectively impaired visual STM system" (Morey, 2018, p.859). These comments seem to us to involve an expectation that neuropsychology should deliver uncomplicated cases of completely selective cognitive impairments. That is seldom the case, as Morey conceded when she wrote that, "Given the strong likelihood of comorbidity of neuropsychological deficits, one may argue that this standard was impossible to observe" (Morey, 2018, p.862). We agree. Instead, as we have pointed out here, the enterprise relies on carefully investigating neuropsychological cases to see how well they fit or contradict different theoretical positions. In this way, strong inferences can be made despite the presence of comorbid associated deficits. For example, Warrington and Shallice (1969) and Shallice and Warrington (1970) showed that patient KF was able to commit some types of verbal material to long-term memory despite his severe problems with verbal repetition. This immediately called into question all theories that supposed that material can only enter long-term memory via short-term storage. The relation between long-term and short-term memory was further clarified by later work by Baddeley et al. (1988) showing that such patients do find it difficult to learn new phonological information, demonstrating a more circumscribed but nonetheless important role for the putative phonological loop component of working memory in creating entirely new items in verbal memory.

Our work with ELD showed a closely comparable pattern of poor short-term memory for visuo-spatial material together with poor learning of new visuo-spatial items (new faces or new objects) despite preserved long-term memory for pre-morbidly familiar material (faces or objects she knew before her haemorrhage). As already noted, this pattern is, at a minimum, consistent with an impairment of working memory involving what Baddeley (1986) called the VSSP. This conclusion is not substantively altered by the possibility that there might be other impairments.

Indeed, Morey (2018, p.859) did acknowledge that ELD's impairments "appear to leave verbal serial STM unaffected, justifying the conclusion that verbal serial short-term memory relies on processes beyond those needed for visual or spatial cognition". One could add that ELD's pattern of impairment equally justifies the conclusion that visuo-spatial STM relies on processes beyond those involved in verbal memory. So, it cannot reasonably be claimed that ELD's visuo-spatial STM problems are caused by a single general memory deficit or that her problems in remembering unfamiliar voices seriously undermine the claim that she has a VSSP impairment.

It is surprising, then, that Morey (2018, p.856) should see work in this area as being in a "rut that assumptions about modularity has mired us in". For the neuropsychological evidence, at least, we think that far from being in a rut, progress has instead been hampered by a dearth of really detailed case studies. In our opinion, some of the most important questions concern whether there might be further fractionation of the VSSP in cases investigated in the future, as might for example be expected from other theoretical conceptions of working memory (Logie & Della Sala, 2005; Xu & Chun, 2006). However, we acknowledge the danger of unthinkingly reifying the constructs used in functional models. Because they are intended as high-level descriptions of how processes involved in a domain of cognition relate to each other, it is an empirical question how far concepts such as the VSSP can be directly mapped onto distinct neurological components. Coltheart

(2006, 2008) characterises this as the difference between theories couched at a psychological level of description (as is the working memory model, or the broader concept of STM buffer stores) and work in cognitive neuroscience (which is more directly concerned with questions of neural organisation); a relation between these levels of explanation must undoubtedly exist, but its specification remains a matter under discussion.

Conclusions

From our work with ELD (Hanley et al., 1990, 1991) we concluded that she showed a combination of impaired immediate memory for sequences of visual or spatial material together with relatively preserved long-term memory for pre-morbidly familiar items that extended even to remembering the precise photographs she had been shown. Yet at the same time ELD was severely impaired at creating entries corresponding to new visual (faces or object encountered after her brain injury) and new spatial material (new routes and the layout of rooms in her new flat, though these problems were noted anecdotally rather than from formal testing). In multiple respects this pattern was noted to be consistent with an impairment of the VSSP component of Baddeley's (1986) working memory model.

In contrast, there appear to be compelling reasons to reject many of the claims that Morey (2018) made about ELD:

1. Contrary to Morey's (2018) description of our data, ELD had a consistent problem in remembering which unfamiliar faces she saw recently on tests of both short and long-term memory. In all of these demonstrations, the retention interval was the same for ELD as for controls.

2. The performance of ELD does in key respects represent a double dissociation with cases of impairment involving the phonological loop component of Baddeley's (1986) working memory model, such as PV (e.g. Vallar et al., 1984). Most importantly, PV performs well on the Corsi blocks but badly on immediate verbal serial recall. Conversely, ELD performs badly on Corsi blocks but well on immediate verbal serial recall. Yet both PV and ELD found it difficult to learn new information

in their impaired modality, underlining the importance of these short-term buffer systems to the creation of certain types of long-term memory.

3. ELD's poor visuo-spatial STM performance is not easily explicable as the consequence of a difficulty in marshalling general resources or as the consequence of a more general memory deficit.

As things stand, then, it appears reasonable to reject Morey's (2018, p.858) claims that ELD's "portfolio of cognitive deficits includes many examples of problems that are inconsistent with the idea that she suffers from an impaired visual-spatial STM buffer". On the contrary, the claim that ELD suffered an impairment to the VSSP but not to the phonological loop can explain her STM performance in both modalities and her inability to learn new visual material. This pattern fits Baddeley's (1986) working memory model which, impressively, was also able to predict otherwise untested and unexpected impairments in tasks such as Corsi blocks and the Brooks matrix. In the absence of an equally parsimonious and well-developed alternative account of ELD's modality-specific memory impairments, there appears to be no reason to abandon the theoretical position that we employed to explain ELD in our original publications.

Ultimately, though, data must be the arbiter between different theoretical claims. In this respect we reiterate that impairment of the VSSP does not explain *everything* we noted from our work with ELD. In particular, she also had problems in learning new voices and patchy evidence of milder difficulties with recall from long-term verbal episodic memory. Whilst cognitive neuropsychological studies can offer powerful insights, the interpretation of associated deficits is always a problem (Coltheart, 2008; Ellis & Young, 1988; Shallice, 1988). At the moment, based on a suitably detailed study of only one individual we cannot evaluate whether these unexpected problems experienced by ELD were simply coincidental deficits reflecting anatomical proximity of potentially dissociable neural structures or whether our theoretical understanding of working memory must be revised to give them a more central role. We hope that by revisiting ELD's case we will encourage the additional detailed case studies of further patients that can move things forward.

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