Short-term memory and working memory in intellectual disability

Christopher Jarrold, University of Bristol

Jon Brock, University of Oxford

To appear in:

J. A. Burack, R. M. Hodapp, G. Iarocci, & E. Zigler (Eds.), Handbook of Intellectual Disability and Development, 2nd Edition. Oxford: Oxford University Press.

Introduction

Working memory refers to the active maintenance of information while the same or other information is simultaneously processed (e.g., Baddeley & Logie, 1999; Engle, Tuholski, Laughlin, & Conway, 1999; Just & Carpenter, 1992) and is an important aspect of cognitive development. This is demonstrated by the fact that performance on measures of working memory is an excellent predictor of educational attainment (Bayliss, Jarrold, Gunn, & Baddeley, 2003; Daneman & Merikle, 1996; Hitch, Towse & Hutton, 2001). Moreover, studies have consistently shown that working memory capacity is strongly related to intelligence – so-called psychometric g. Indeed, some researchers have argued that working memory is almost synonymous with g (Colom, Rebollo, Palacios, Juan-Espinosa, & Kyllonen, 2004; Kyllonen & Christal, 1990; see also Conway, Kane, & Engle, 2003; although see Ackerman, Beier, & Boyle, 2005 for a meta-analysis and critique of this field). For example, Süß, Oberauer, Wittman, Wilhelm, and Schulze (2002) have suggested that: “at present, working memory capacity is the best predictor for intelligence that has yet been derived from theories and research on human cognition” (p. 284). It is unsurprising, therefore, that researchers should focus on working memory as a possible underlying cause of many different forms of learning disability.

Much of the research into working memory deficits associated with intellectual disability has been guided by Baddeley’s (1986) model. According to Baddeley, working memory involves the combined functioning of a central control system, the central executive, and two peripheral short- term memory systems, the phonological loop and the visuo-spatial sketch pad, that are specialized for the maintenance of verbal and visuo-spatial information respectively. Researchers have typically been interested in whether these different components of the model can be impaired selectively or differentially in particular developmental disorders (see Alloway & Gathercole, 2006). However, our focus in this chapter is less on specific disorders (although examples from specific syndromes will be covered where relevant); rather, our aim is to provide an overview of the range of working memory impairments associated with learning disability, and the possible consequences of such deficits. In doing this we ask a number of questions, notably: are there aspects of short-term or working memory that are particularly vulnerable to intellectual disability; are there any syndrome- specific patterns of working memory impairments; and how might these relate to educational outcomes and other aspects of cognitive and linguistic development? In order to properly interpret findings from studies involving individuals with intellectual disability, we begin by raising a number of general methodological points about the assessment of working memory, and by emphasising the theoretical distinction between working memory and short-term memory.

Theoretical and methodological issues

Individuals with intellectual disability or learning difficulties are often unable to comprehend long sentences and follow complicated instructions and it may be necessary to 'break down' tasks into smaller more manageable chunks that can be processed step-by-step. In some cases, these difficulties can be attributed to basic memory problems. Thus, for example, by the end of a long sentence, the individual may have already forgotten the beginning. Often, however, difficulties in holding on to the information are exacerbated when the individual is required to engage in other activities, ignore extraneous information, or act upon the incoming information. For instance, in carrying out a set of instructions, the act of performing the initial operations may impede the ability to remember the remaining instructions (Gathercole & Alloway, 2006; Gathercole, Lamont, & Alloway, 2006). This distinction between basic memory processes and the ability to maintain information despite competing task requirements is fundamental to the distinction between short-term memory and working memory. These two terms are often used interchangeably; however, in this chapter, we will limit the use of the term working memory to situations in which individuals not only have to maintain information, but also have to actively transform that material or engage in some other distracting activity: we use the term short-term memory to refer to cases in which maintenance only is required.

In line with these definitions, short-term memory is typically assessed using so-called ‘simple span’ tasks in which participants recall, usually in correct serial order, the list of just-presented items. For example, visuo-spatial short-term memory is often assessed using the Corsi span task (cf. Milner, 1971), in which participants are required to recall series of spatial locations by recreating the just presented spatial sequence. Similarly, in digit and word span tasks participants are asked to repeat lists of varying lengths in order to determine the maximum number, or span, that they can accurately maintain.

Despite their structural similarity, many researchers would argue that digit and Corsi span tasks tap independent memory stores. This view follows directly from Baddeley’s (1986) model, which, as noted above, suggests that there are independent mechanisms for storing verbal and visuo-spatial information in the short-term. Indeed, there is considerable evidence that aspects of verbal and visuo-spatial short-term memory are dissociable, including data from the developmental literature. For example, Hale, Bronik, and Fry (1997) found that 8- and 10-year-old children’s digit and Corsi spans were subject to selective interference from verbal and visuo-spatial dual tasks respectively.

Similarly, factor analytic studies of children’s short-term memory have tended to produce separate verbal and visuo-spatial factors (e.g., Bayliss et al., 2003; Gathercole, Pickering, Ambridge, & Wearing, 2004). There are, nevertheless, apparent similarities between children’s performance on verbal and visuo-spatial short-term memory tasks, particularly in terms of the pattern of order errors observed (Pickering, Gathercole, & Peaker, 1998). Moreover, studies that have examined developmental changes in these measures have shown that they share substantial age-related variance (Bayliss, Jarrold, Baddeley, Gunn, & Leigh, 2005; Chuah & Maybery, 1999). One suggestion, therefore, is that the development of short-term memory rests on changes in the efficiency of a domain-general maintenance process (cf. Jones, Farrand, Stuart, & Morris, 1995) that operates on dissociable content domains (Jarrold & Bayliss, in press; Pickering et al., 1998).

In contrast to short-term memory, working memory is often measured using ‘complex span' tasks, in which participants are again required to recall a series of items, usually in correct serial order, but also have to complete a subsidiary task before the presentation of each item. In many instances, the completion of the interleaved subsidiary 'processing' tasks is what provides the participant with the to-be-remembered items. For example, in reading span tasks (e.g., Daneman & Carpenter, 1980), participants read a series of sentences, often judging them for veracity, and have to remember the final word of each sentence for subsequent recall. Other complex span measures have been developed which vary the modality of either the processing or storage component of the task (e.g., Case, Kurland, & Goldberg, 1982; Hitch & McAuley, 1991; Shah & Miyake, 1996) but all have in common the requirement to maintain target items in the face of the potentially distracting effects of concurrent processing operations.

Complex span tasks are not necessarily the only way of assessing working memory (see below) but, importantly, they have good construct validity insofar as they correlate well with higher-level abilities such as academic achievement and fluid intelligence (see Conway et al., 2005). Crucially, these correlations are typically stronger than those observed between higher-level abilities and simple span measures (Bayliss et al., 2003; Daneman & Merikle, 1986; Lépine, Barrouillet, & Camos, 2005; Oberauer, Schulze, Wilhelm, & Süß, 2005), indicating that working memory measures capture something more than short-term memory tasks. Although both simple and complex span tasks share a storage component, namely, the requirement to hold in mind information in correct serial order, complex span tasks differ from their simple span counterparts in two important respects: First, they involve an additional processing component, and consequently the efficiency with which one can complete this aspect of the task will affect overall performance. Second, the combination of processing and storage requirements in a complex span task introduces an additional element associated with the need to maintain storage items in the face of concurrent and potentially distracting processing. It is this element that is thought to correspond to the executive aspect of working memory (Engle et al., 1999; Engle 2002), or, more specifically, the central executive within Baddeley's (1986) model.

Bayliss et al. (2003) examined these two aspects of complex span performance by assessing the extent to which it was related to separate measures of individuals' ability to carry out the storage and processing aspects of the task. Performance on the separate processing task predicted complex span scores even when performance on the separate storage task was controlled for. In addition, the remaining ‘residual’ variance in complex span performance, over and beyond that attributable to the storage and processing components, was related to individuals’ academic attainment and intelligence (see also Bayliss, Jarrold, Baddeley, Gunn, & Leigh, 2005). This finding, the authors argued, is consistent with the view that complex span performance depends on the additional, executive ability of combining storage and processing operations.

In sum, complex span tasks share storage requirements with simple span tasks, but are additionally affected by individuals’ processing efficiency and their ability to combine processing and storage operations. Correspondingly, working memory can be viewed as an extension of short-term memory, insofar as both abilities involve short-term storage, but working memory has additional processing and executive control aspects. Having clarified this distinction, the remainder of the chapter considers the extent to which intellectual disability of various types is associated with (1) deficits in short-term storage of information and (2) the executive aspects of working memory.

Short-term memory

As noted in the preceding section, short-term memory for verbal and visuo-spatial information is widely assumed to tap separable memory stores (Baddeley, 1986), although it is unclear to what extent common mechanisms support the retention of items in these systems. An important question, therefore, in the context of the study of learning disability and intellectual disability is whether short- term memory deficits dissociate along verbal and visuo-spatial lines and, if so, whether this reflects selective impairment to specific short-term memory systems, or more general problems in the verbal or visuo-spatial domains. In the immediately following subsections we examine these issues in relation to two developmental disorders, Down syndrome and Williams syndrome. Having addressed this question, we consider possible underlying causes of any such deficits in terms of potential problems in rehearsal, and in the representation of item and order information in short-term memory. We conclude this section by looking at potential consequences of impaired short-term memory.

Domain-specific short-term memory impairments in Down syndrome and Williams syndrome

Down and Williams syndrome are genetic disorders associated with intellectual disability, although this is often more marked in those with Down syndrome (e.g., Klein & Mervis, 1999). Cognitive profiles in both disorders are somewhat uneven; individuals with Down syndrome tend to have poorer verbal than nonverbal abilities (e.g., Chapman, 1997; Laws & Bishop, 2004), whereas Williams syndrome is associated with specific deficits in visuo-spatial cognition (e.g., Farran & Jarrold, 2003; Mervis, Morris, Robinson, & Bertrand, 1999). This dissociation between verbal and visuospatial capabilities has been mirrored in studies comparing short-term memory in the two disorders, In the first such study, Wang and Bellugi (1994) found that individuals with Down syndrome performed less well than individuals with Williams syndrome on a digit span task, while the opposite pattern was observed on the Corsi span task. Subsequent studies have largely replicated this pattern of findings (Klein & Mervis, 1999; Vicari et al., 2004). In particular, Jarrold , Baddeley, and Hewes (1999) reported that, relative to individuals with intellectual disability of unspecified etiology, individuals with Down syndrome were selectively impaired on the digit span task, whereas individuals with Williams syndrome were selectively impaired on the Corsi span task. It is important to note, however, that neither verbal short-term memory in Williams syndrome nor visuo-spatial short-term memory in Down syndrome can be considered to be intact; in both disorders, short-term memory is impaired relative to chronological age expectations. As such, the contrast between short-term memory capabilities in Williams and Down syndrome should not be portrayed as a ‘pure’ double dissociation.

An important consideration here is whether apparently selective deficits in short-term memory may in fact be caused by more general representational deficits; as noted above, poor short-term memory performance can be characterised in terms of an impairment to a specific subsytem with Baddeley’s (1986) working memory model, but it may reflect more general difficulties in dealing with verbal or visuo-spatial information. This issue is particularly relevant in this instance because Williams syndrome is associated with severe deficits in visuo-spatial cognition. Indeed, Jarrold et al. (1999) found that the performance of individuals with Williams syndrome on the Corsi span task was no worse than that of individuals with undifferentiated intellectual disability when visuo-spatial skills were controlled for. Thus, although visuo-spatial short-term memory in Williams syndrome may well be poorer than one would expect given individuals' overall level of ability, we cannot yet be certain that it is any poorer than expected given the general visuo-spatial difficulties associated with the condition.

A similar argument could also be applied to verbal short-term memory deficits in Down syndrome. As noted above, Down syndrome is associated with severe language deficits and there is considerable evidence to suggest that individuals' knowledge of the lexical, and perhaps also sublexical, properties of their language can support their performance on tests of verbal short-term memory (see Brener, 1940; Majerus & Van der Linden, 2003; Thorn & Frankish, 2005). As Hulme and Roodenrys (1995) have pointed out, individuals with relatively impoverished language knowledge would be expected to perform less well on tests of verbal short-term memory than comparison groups with a richer language knowledge. In addition, many individuals with Down syndrome have severe speech production difficulties that would be predicted to impact more on verbal tasks than on non-verbal tasks and may therefore contribute to poor verbal short-term memory performance (cf. Cairns & Jarrold, 2005).

Our recent research in Down syndrome has explored the extent to which verbal short-term memory deficits can be 'explained away' in terms of more general speech and language difficulties. Our approach has been to use verbal short-term memory measures that avoid the need to give a spoken response and then look at the impact of linguistic knowledge on performance. In our first study (Brock & Jarrold, 2004), we presented participants with an item recognition task, asking them to listen to two lists and then determine whether the items were the same or different. Unsurprisingly, performance was superior when the items were real words as opposed to made-up nonwords. Importantly, however, this 'lexicality effect' was larger among individuals with Down syndrome than among control children, suggesting that, if anything, the Down syndrome group were more reliant on linguistic knowledge to support task performance. This was despite the fact that their overall performance was poorer. Participants were also given an order recognition task, in which the two lists always contained the same items, but with a change to the order of presentation of items in the second list on 50% of trials. Consistent with previous findings (Gathercole, Pickering, Hall, & Peaker, 2001; Thorn, Gathercole, & Frankish, 2002), the lexicality effect was minimized, indicating that word knowledge did not substantially affect performance. Nevertheless, individuals with Down syndrome still performed poorly on this task (see also Jarrold, Baddeley, & Phillips, 2002). In a second study (Brock & Jarrold, 2005) we showed that individuals with Down syndrome were significantly impaired on a digit reconstruction task in which they were required to point to numbers on a touchscreen in response to a spoken list of digits. This was true, even when controlling for performance on a closely matched Corsi span task and the speed with which individuals could identify and search for spoken digits on the screen. Together, these findings suggest that the deficit seen among individuals with Down syndrome on traditional verbal short-term memory tasks such as digit span is not caused by domain-general problems, but rather by specific difficulties in representing verbal information in short-term memory.

Mechanisms of verbal short-term memory impairments

The above review of short-term memory deficits associated with intellectual disability shows that although generalised visuo-spatial or linguistic difficulties can certainly account for poor short-term memory performance in some cases, and may well play a part in accounting for deficits in others, there are developmental conditions that appear to be associated with more fundamental impairments in the way information is represented in short-term memory. This evidence is strongest in the case of verbal short-term memory, and the following subsections consider the specific mechanisms that might underpin such deficits.

Rehearsal

Many studies investigating verbal short-term memory deficits in intellectual disability have been motivated by Baddeley's (1986) model of the phonological loop. This involves two components – a limited capacity phonological store and rehearsal mechanism that is used for refreshing decayed phonological traces. According to the phonological loop model, the efficiency of rehearsal depends on the speed with which items can be rehearsed. This can explain why participants are better at recalling lists of short words than they are at recalling lists of long words, and why individuals with rapid speech rates (and presumably, therefore, faster rehearsal) perform better on serial recall tasks than those with slower speech rates (Baddeley, Thomson, & Buchanan, 1975). The presence of word- length effects has therefore been taken as an index of whether or not a certain group are engaging in rehearsal, and overt speech rate has been used to assess the speed or efficiency of that rehearsal.

Hulme and Mackenzie (1992) argued that verbal short-term memory deficits may arise in various forms of intellectual disability as a consequence of inefficient or even absent subvocal rehearsal processes. Indeed, studies have shown that a relative reduction in overt speech rate can account for observed verbal short-term memory deficits in individuals with reading disability (Avons & Hanna, 1995; Swanson & Ashbaker, 2000), speech production difficulties (Raine, Hulme, Chadderton, & Bailey, 1991; White, Craft, Hale, & Park, 1994), and Williams syndrome (Jarrold, Cowan, Hewes, & Riby, 2004). In a similar vein, a number of authors have argued that individuals with Down syndrome might show particularly poor verbal short-term memory performance because of a failure to engage in articulatory rehearsal (Broadley & MacDonald, 1993; Comblain, 1994). Consistent with this view, Hulme and McKenzie (1992) found that individuals with Down syndrome did not demonstrate a reliable word-length effect (although see Jarrold, Baddeley, & Hewes, 2000) or a reliable relationship between overt speech rate and short-term memory performance (see also Jarrold, Cowan, et al., 2004). However, it appears unlikely that a failure to rehearse can entirely account for poor verbal short-term memory performance in Down syndrome. Evidence suggests that typically developing children do not develop specific verbal rehearsal strategies until around the age of 7 years (Flavell, Beach, & Chinsky, 1966; Gathercole, Adams, & Hitch, 1994). Studies of Down syndrome usually involve typically developing children who are somewhat younger than this and are, therefore, unlikely to be rehearsing either. If this is the case and yet these children still outperform individuals with Down syndrome, then this implies that the absence of rehearsal cannot account for verbal short- term memory deficits in Down syndrome. Furthermore, verbal short-term memory deficits have been observed among individuals with Down syndrome relative to comparison groups who have comparable speech rates, and who would therefore presumably have comparable rates of rehearsal were rehearsal taking place (Jarrold et al., 2000; Kanno & Ikeda, 2002).

In sum, although there is evidence consistent with the view that failure to rehearse or a reduced efficiency of rehearsal can account for the difficulties that some individuals with intellectual disability have on digit- or word-span tasks, this is not conclusive and certainly does not provide a complete explanation of all observed verbal short-term memory deficits. From the point of view of the phonological loop model, one must conclude by default that Down syndrome is associated with an impaired phonological store (Jarrold, Purser, & Brock, 2006) – a deficit that may well also be present in other developmental disorders.

Item and order memory

The phonological loop model does not itself specify the mechanisms by which information is maintained in the phonological store. More recent models have, however, attempted to address this issue. Although they differ in the precise mechanisms involved, a common feature of these models is that they incorporate independent mechanisms for maintaining information about the items in a list and for encoding their serial order (see e.g., Brown, Preece, & Hulme, 2000; Burgess & Hitch, 1999; Page & Norris, 1998; see Burgess & Hitch, 2005 for a review). Such models raise the question of whether poor verbal short-term memory in intellectual disability is a reflection of impaired item memory or a deficit in serial order memory. In general, the available evidence suggests that order memory mechanisms are more vulnerable in intellectual disability (or at least that order memory deficits contribute most to group differences in verbal short-term memory performance). For example, Brock, McCormack, and Boucher (2005) reported that children with Williams syndrome or with intellectual disability of unknown aetiology showed a selective deficit in order as opposed to item memory. Participants completed a probed serial recall task, in which they were presented with a list of words or nonwords and were then required to recall the single item that had occurred at a specified position in the list. The performance of these two groups of children was significantly poorer than that of a typically developing comparison group matched on receptive vocabulary knowledge. Importantly, however, error analyses revealed that group differences were driven almost exclusively by order errors (recalling an item that had occurred at a different position in the list), with no significant differences in item errors (recalling an item from outside the list or giving no response). A similar pattern of findings was observed in a recent study of Velo-cardio-facial syndrome (VCFS) by Majerus, Van der Linden, Bressand, and Eliez (2006). Individuals with VCFS demonstrated significant impairments relative to controls on two serial order tasks – a test of order reconstruction and an order recognition task. However, there were no significant group differences on an item recognition task, in which participants were required to determine whether or not a single item was included in a just-presented list.

A slightly different pattern of results was found in our study of item and order memory in Down syndrome reviewed above (Brock & Jarrold, 2004). Although individuals with Down syndrome performed poorly on an order recognition task, they performed even less well on an item recognition task, in which they were required to decide whether a repeated list contained a single-phoneme change in one of the items. However, individuals with Down syndrome also showed a trend towards poorer performance on a simple phonological discrimination task that had minimal memory demands. This finding suggests that basic memory deficits may have been exacerbated by phonological discrimination difficulties that are perhaps related to hearing problems common in Down syndrome (e.g., Marcell & Cohen, 1992). As such, this study should not really be taken as conclusive evidence that individuals with Down syndrome have selectively impaired item memory.

A number of studies have investigated short-term memory for item information among individuals with developmental delay by assessing their ability to 'scan' for targets within to-be-remembered lists (c.f., Sternberg, 1966). More specifically, participants are given a list of target items to remember, followed by a series of individual probe items, and have to judge whether each probe item is a member of the target list. The typical finding from this task is that individuals' response times depend on the number of items in the target set, suggesting that a search of the target set occurs in response to each probe (Sternberg, 1966). Consequently, the slope of the search function with increasing target set size is thought to provide an index of efficiency of memory search (Hulme, Newton, Cowan, Stuart, & Brown, 1999; but see Monsell, 1978). Studies of individuals with intellectual disability have provided evidence for increases in the intercept of the slope function but somewhat weaker evidence for increases in search slopes (Mosley, 1985; Phillips & Nettlebeck, 1984; Todman & Gibb, 1985). It is, therefore, possible that reductions in speed of processing that one would expect to be associated with intellectual disability lead to a fixed, general slowing in reaction times rather than a slower rate of search. However, the inconsistency observed across these studies may well be a reflection of heterogeneity in the samples employed, as this work has tended to focus on populations with relatively general learning difficulties rather than specific disorders. Consequently, there is a limit to what one can infer from these findings (cf.

Burack, Iarocci, Flanagan, & Bowler, 2004).

In sum, there is more evidence of difficulties in the maintenance of serial order information among individuals with intellectual disability than there is of difficulties in the representation of item information, although the latter may clearly be compromised by encoding difficulties associated with any particular condition. This suggests that serial order memory deficits in intellectual disability may often reflect a reduction in the fidelity of a temporal ordering mechanism or a difficulty in making associations between items and their serial position (cf. Brown et al., 2000). What is less clear is whether such a deficit is specific to problems of serial ordering of verbal information, or rather reflects domain-general ordering difficulties. As noted above, there is evidence from typical development to suggest that a common mechanism is involved in the maintenance of order information in both verbal and visuo-spatial short-term memory tasks (Bayliss, Jarrold, Baddeley, Gunn, & Leigh, 2005; Chuah & Maybery, 1999; Pickering et al., 1998). However, Brock and Jarrold (2005) found specific deficits in the reconstruction of verbal serial order rather than visuo-spatial serial order in Down syndrome, raising the possibility that order information in these two domains may be supported by separable systems, which happen to develop in parallel in the typical case.

The consequences of short-term memory impairments

It has long been argued that short-term memory plays an important role in aspects of long-term learning (Atkinson & Shiffrin, 1968). Baddeley (2000) has recently speculated that visuo-spatial short-term memory may be involved in the learning of ‘spatial semantics’ such as route finding; and there is some evidence from the adult neuropsychological literature to suggest that visuo-spatial short-term memory deficits might cause problems of spatial learning (Hanley, Young, & Pearson, 1991). Farran, Blades, Tranter, and Boucher (2006) recently reported that individuals with Williams syndrome had relative difficulties in retracing an unfamiliar route and also performed poorly on a small-scale maze task. While it may be tempting to hypothesize that these difficulties are a result of visuo-spatial short-term memory impairments, as noted above, it is impossible to be sure at present whether short-term memory difficulties in Williams syndrome are a cause or consequence of visuo- spatial impairments.

Researchers have paid considerably more attention to the possible causal relationship between short- term memory and long-term learning in the verbal domain. Baddeley, Gathercole, and Papagno, (1998) have proposed that short-term memory capacity places an important constraint on language development and, more specifically, is critically involved in vocabulary acquisition, because the accuracy with which one maintains a representation of the phonological form of new items determines the ease of novel word learning. Consistent with this view, there is evidence from studies of typically developing children that early verbal short-term memory skills predict later vocabulary development (Gathercole, Willis, Emslie, & Baddeley, 1992) as well as performance on word- learning tasks (Gathercole, Hitch, Service, & Martin, 1997). Somewhat less clear cut results were reported in a recent study looking at the language capabilities of 8-year-old children who, three years previously, had been identified as having specific verbal short-term memory deficits (Gathercole, Tiffany, Briscoe, Thorn, & The ALSPAC team, 2005). Vocabulary knowledge was unimpaired amongst a subgroup of children with persisting verbal short-term memory problems but was impaired among a separate subgroup whose verbal short-term memory problems had resolved over time.

Baddeley et al.'s (1998) account implies that short-term memory impairments may contribute to deficits or delays in language development. However, proving causation is extremely difficult, as illustrated by research on specific language impairment (SLI). It has been widely argued that children with SLI have extremely poor verbal short-term memory and that this may be an underlying cause of their language difficulties (see e.g., Gathercole & Baddeley, 1990; Kirchner & Klatzky, 1985). In fact, most of the evidence here comes from studies using tests of nonword repetition, in which participants are required to repeat exactly a series of nonsense words such as 'perplisteronk' (e.g., Archibald & Gathercole, 2006; Dollaghan & Campbell 1998; Gathercole & Baddeley, 1990). While such tasks clearly involve the recall of verbal material (e.g., Gathercole, Willis, Emslie, & Baddeley, 1994), the poor performance of individuals with SLI could equally be a reflection of difficulties in identifying phonemes or poor knowledge of the 'phonotactic' constraints in their native language (e.g., Snowling, Chiat, & Hulme, 1991; van der Lely & Howard, 1993). Surprisingly few studies have directly measured performance on digit- or word-span tasks and, while these studies have shown that performance on such tasks is below age-expectations (Briscoe, Bishop, & Norbury, 2001), the levels observed tend not to be significantly worse than those seen in language-matched comparison groups (Gathercole & Baddeley, 1990; van der Lely & Howard, 1993). It is, therefore, difficult to rule out the alternative hypothesis that language impairments lead to poor performance on verbal short-term memory (cf. Hulme & Roodenrys, 1995).

Clearly, such arguments also have important implications for theories of language development in individuals with intellectual disability. Jarrold, Baddeley, Hewes, Leeke, and Phillips (2004, study 2) attempted to tease apart the alternative causal hypotheses by testing a large sample of children with intellectual disability of unknown aetiology, dividing them into two groups that were matched on receptive vocabulary knowledge at around the 5-year equivalent level, but were mismatched on age and therefore also on rate of vocabulary acquisition. If verbal short-term memory deficits are simply a reflection of poor verbal abilities, then one would predict that the two groups, matched on verbal ability, would perform similarly on short-term memory tasks. In fact, the younger group, who had acquired the same vocabulary knowledge at a much faster rate, outperformed the older group on a range of measures of verbal short-term memory. This is consistent with the view that verbal short- term memory skills determine the rate of vocabulary acquisition among such individuals. Once again, this study is open to the criticism that the sample was heterogeneous, and that different individuals may have had different underlying causes of their intellectual disability. However, there is no reason to suspect that the two subsamples created from the larger group differed from one another in terms of their heterogeneity. It is also worth pointing out that similar patterns of performance have been observed in studies, reviewed above, showing that individuals with Down syndrome have poorer verbal short-term memories than younger, typically developing children or children with other developmental disorders, even when vocabulary knowledge is controlled for. As noted previously, such findings are inconsistent with the view that poor vocabulary knowledge leads to poor short-term memory performance, but are compatible with claims that impaired verbal short-term memory leads to a slower rate of language acquisition (cf. Chapman, 1995; Jarrold, Baddeley, & Phillips, 1999; Laws, 1998).

In sum, the evidence to support the causal hypothesis that short-term memory deficits lead to impaired language acquisition remains indirect. Given that Baddeley et al.'s (1998) account predicts that vocabulary learning in particular should be adversely affected by such a deficit; there is a surprising lack of studies investigating new word learning in individuals with language delay (Gathercole & Alloway, 2006). The one study that has looked explicitly at new word learning in Down syndrome using experimental measures found that individuals were unimpaired at producing the phonological label that they had been told applied to a novel item (Chapman, Kay-Raining Bird, & Schwartz, 1990), a finding at odds with the predictions of a verbal short-term memory deficit account. However, in this study participants were only required to learn one name of one object, and rather lenient scoring criteria for the accuracy of the production of this name were employed. Consequently this test may have lacked the power to observe group differences. It is also important to note that receptive vocabulary is a relative strength among the various language functions in Down syndrome (Chapman, 1997; Vicari, Caselli, Gagliardi, Tonucci, & Volterra, 2002), which again calls into question the extent to which verbal short-term memory deficits lead to problems of vocabulary acquisition in the condition. One possibility is that individuals with Down syndrome, and perhaps also SLI, acquire vocabulary in an atypical way and compensate for problems in verbal short-term memory by relying more on lexical and semantic associations between novel words and existing lexical entries (cf. Baddeley, 1993). However, at present this suggestion is only speculative, and remains to be verified empirically.

Working Memory

As noted above, working memory capacity – as opposed to short-term memory – is strongly associated with intelligence and educational outcomes. It is perhaps unsurprising, therefore, that individuals with learning difficulties often show severe deficits on working memory tasks. For example, Henry (2001) compared simple and complex span performance in individuals who were matched for age but who varied in degree of severity of their learning disability, and found that the various different 'IQ groups' differed more in complex span than in simple span performance. Similarly, Gathercole and Pickering (2001) found that children in mainstream educational settings who had been identified as having 'special educational needs' differed more from their peers on complex span tasks than on measures of short-term memory. It is, however, worth noting that the task that most clearly distinguished the groups was backwards digit recall. This task is assumed to tap working memory because it involves the manipulation of to-be-remembered information; in this case to allow recall of the presented items in reverse order. Although this measure differs in form from complex span tasks, evidence suggests that it taps the same underlying construct (Conway et al., 2005). Having said this, the analysis of complex span performance presented at the start of this chapter showed that individuals can perform poorly on working memory tasks for a number of reasons. Indeed, in a study in which individuals with generalised learning difficulties were given complex span tasks as well as separate measures of storage ability and processing efficiency, Bayliss, Jarrold, Baddeley, and Leigh (2005) found that levels of complex span performance were unimpaired in this group. However, the individuals with learning difficulties performed less well than typically developing comparison individuals on simple span storage measures, while showing generally faster speed of processing. Although one must, again, be cautious in placing too much weight on data from a potentially heterogenous sample, these results do show that comparable levels of complex span performance can be reached in different ways; in this case, reflecting a different balance of strengths and weaknesses in the storage and processing aspects of the task.

More generally, when evaluating overall performance on complex span tasks, or indeed, many other working memory measures, one needs to ensure that poor performance is not simply a consequence of individuals having difficulty on the short-term memory components that are necessarily embedded in these tasks. For example, it would not be at all surprising to find that individuals with Down syndrome performed poorly on a reading span task, given that one would expect them to find the verbal recall component of this task difficult (though see Pennington, Moon, Edgin, Stedron, & Nadel, 2003). Similarly, one would expect individuals to struggle on complex span tasks if they have particular difficulties in completing the processing components of such tasks (cf. Daneman & Tardif, 1987). For example, Siegel and Ryan (1989) found that individuals with mathematical learning difficulties performed poorly on a counting span working memory task in which they had to count the number of dots shown on a series of cards and remember these totals for subsequent recall (cf. Case et al. 1982). This finding was subsequently replicated by Hitch and McAuley (1991) who went on to show that, in their sample at least, this deficit in working memory performance was matched by a deficit in the time taken to carry out the processing component of the complex span task; that is, in counting the dots to generate the to-be-remembered totals. In other words, these findings indicate that individuals with learning difficulties might show poor working memory 'performance' simply because they have difficulty in completing the component processing operations of the task. Crucially, one would not want to argue that this reflects an impairment to any executive aspect of working memory, because carrying out processing operations such as counting dots on cards is not necessarily executive in nature (Jarrold & Bayliss, in press). Rather, to be certain that individuals are experiencing executively-mediated deficits in combining the storage and processing operations of any working memory task, one needs to examine whether individuals have more difficulties on complex span tasks than one would expect given their general storage capacity and processing efficiency (Bayliss et al., 2003; Engle et al., 1999; Kyllonen & Cristal. 1990). In other words, the stringent test of an executive account of working memory difficulties involves showing a reliably greater impairment in working memory performance than in short-term memory or general speed of processing considered in isolation.

Executive control and working memory

Few studies of working memory among individuals with intellectual disability have properly applied such a stringent test and examined whether any deficits in performance exist over and beyond those attributable to deficits in short-term memory capacity or processing efficiency. However, there are studies of developmental disorders that are not consistently associated with intellectual disability, which nevertheless show how such an approach might be informative, and which indicate that the executive aspect of working memory might well be closely related to IQ differences among such individuals.

Attention deficit / hyperactivity disorder

Attention deficit / hyperactivity disorder (ADHD) is associated with problems of executive control, although, perhaps unsurprisingly, deficits in inhibitory control appear to be the most marked feature of the executive impairments associated with the condition (Barkley, 1997; Pennington & Ozonoff, 1996). Although ADHD is not clearly associated with intellectual disability, studies of working memory in the condition (reviewed comprehensively in Roodenrys et al., 2006). suggest that the extent of any deficit observed may depend on whether or not comparison groups are equated for IQ.

For example, two studies have shown evidence of deficits in working memory in ADHD that appear not to be attributable to problems in short-term memory or processing efficiency, but which were observed relative to comparison groups who were of higher IQ. Karatekin (2004) examined both short-term and working memory among individuals with ADHD. Short-term memory was assessed using verbal and visuo-spatial versions of the 'scanning' tasks described above, in which participants were presented with a memory set of a number of letters that were presented in different spatial locations on the screen. Following a variable delay, a probe letter was presented in a position on the screen, and participants were either asked to judge whether that letter (verbal condition) or that location (visuo-spatial condition) had been presented in the initial memory set. Individuals with ADHD were unimpaired, relative to an age-matched comparison group in terms of accuracy on this task. However, these individuals were impaired on a separate, working memory dual task in which they were required to make speeded responses following the onset of a visual target, and, in one condition, simultaneously hold in mind a list of digits. Individuals with ADHD showed a reliably greater slowing of reaction times than the comparison individuals when simultaneously required to maintain a digit load, suggesting they suffered particularly from the combination of a memory load and a processing task.

Similar results were reported by Cornoldi et al. (2001, Study 1), who compared the performance of individuals with ADHD and an age-matched comparison group on a complex span task that required the inhibition of potentially distracting processing information, as well as on a control 'dual' task in which processing material did not need to be inhibited. In the complex span task, participants were presented with a series of sub-lists of nouns. They had to tap the table whenever an animal name was heard, and remember the last noun presented within each sub-list. In the control task, participants still had to tap whenever an animal was presented, but had to remember all the items presented (fewer items in total were presented in this task). This control task therefore involved both processing and storage but, crucially, did not require individuals to resist interference from animal names they had responded to with a tap. There was a trend for individuals with ADHD to be impaired on the latter task, but the groups clearly differed on the complex span task. Moreover, when individuals with ADHD made errors they were much more likely to respond with an animal name that they should have inhibited (a similar finding was reported in a second study which employed a visuo-spatial complex span task, but no control dual task).

These results are clearly consistent with the view that individuals with ADHD have difficulties in resisting interference in working memory due to their inhibitory difficulties. However, other studies that have examined complex span performance in the condition have found no evidence of deficits relative to comparison individuals matched for IQ (Siegal & Ryan 1989; Willcutt et al., 2001; see also Kunsti, Oosterlaan & Stevenson, 2001). In fact this may not be so surprising given the evidence that variation in working memory capacity is closely related to variation in intelligence in the general population. In other words, if working memory capacity plays a role in determining IQ differences, and if, by extension, working memory deficits cause delayed IQ among individuals with intellectual disability, then one will struggle to observe such deficits in studies in which comparison groups are IQ matched.

Autism

These points on IQ matching are also relevant to the question of whether autism is associated with working memory deficits, because although autism is not necessarily associated with intellectual disability, many individuals with autism do have IQs outside the normal range (Bailey, Phillips, & Rutter, 1996). In addition, autism is a condition that is also associated with impaired executive functions (Hill, 2004), although Pennington and Ozonoff (1996) have suggested that there is less evidence of inhibitory difficulties in autism than there is in ADHD, and correspondingly more evidence of problems in 'cognitive flexibility'. Individuals with autism also perform poorly on planning tasks (e.g., Hughes, Russell, & Robbins, 1994), a deficit that might reflect problems in holding goal states in working memory (Ozonoff, Pennington, & Rogers, 1991; cf. Kimberg & Farah 1992). One might, therefore, expect that individuals with autism would have specific difficulties in working memory tasks, particularly given the need to switch flexibly between processing and memory requirements in such tasks. Importantly, there is reasonable evidence to indicate that individuals with autism have no particular problems on either verbal or visuo-spatial short-term memory measures (Bennetto, Pennington, & Rogers, 1996; Joseph, Steele, Meyer, & Tager-Flusberg, 2005; Russell, Jarrold, & Henry, 1996; Williams, Goldstein, & Minshew, 2006; though see Whitehouse, Maybery, & Durkin, 2006), and consequently if working memory deficits are observed then they are unlikely to be explainable in terms of storage problems alone.

Most studies of working memory in autism have, in fact, reported little evidence of specific impairments. Indeed, some authors have explicitly argued that working memory is 'intact' in autism (Ozonoff & Strayer, 2001). However, such claims may be premature as many of the tasks used in studies of autism have questionable status as working memory measures. For example, Lopez, Lincoln, Ozonoff, and Lai (2005) reported unimpaired working memory among individuals with autism using a working memory index derived from performance on three subcomponents of the Wechsler Adult Intelligence Scale. One of these subtests was Arithmetic, which is at best partially determined by working memory ability, while another was the Digit Span subtest which is itself a combination of forward and backwards recall.

Ozonoff and Strayer (2001) similarly reported unimpaired performance in autism on three 'working memory' tasks. The first of these was an n-back task in which participants have to judge whether a presented item matches one presented n-back in a sequence (see also Williams et al., 2006). Although such tasks are often used as tests of working memory, particularly in neuroimaging studies, it is not clear that they necessarily involve the kind of manipulation of information that characterizes working memory (Conway et al., 2005; Jarrold & Towse, 2006; Ruiz, Elousúa, & Lechuga, 2005). Moreover, the maximum value of n in this study was 2, and some have suggested that n-back tasks place minimal working memory demands on participants when n is less than 3 (Hockey & Geffen, 2004; see Jarrold & Towse, 2006);. The second task was a spatial memory task in which participants were simultaneously shown a set of different shapes in fixed spatial locations for a limited period, followed by a central probe that matched one of the previously presented shapes. The participants' task was to select the spatial position in which that item had appeared. Once again there is no clear sense in which this task, which is essentially a delayed recognition test, requires anything other than holding information in mind, although it may well require individuals to 'bind' item and location information at encoding (Chalfonte & Johnson, 1996).

In the third task employed by Ozonoff and Strayer (2001), participants were presented with a computer screen displaying a series of coloured boxes, some of which contained reward items. At the start of any trial the participant was ignorant of which locations contained rewards, and had to search each potential box in turn. After each search, the position of the boxes changed, and the participant therefore needed to keep track of the colour of the boxes they had already visited. Individuals with autism did not differ from controls in the number of times they revisited previously searched boxes. Although this task does capture something of the ‘storage plus concurrent processing’ aspect of accepted working memory measures, it is worth noting that a more recent study by Goldberg et al. (2005) found that a similar task was the only one of a number of potentially executive measures that clearly showed impaired performance among individuals with autism relative to typical controls (see also Joseph et al., 2005).

To date only two studies have examined complex span performance in autism. Bennetto et al. (1996) found that their sample of high functioning individuals with autism were impaired relative to controls on both reading and counting versions of complex span tasks. Crucially, the impairment in working memory remained even when potential differences in short-term memory (digit span) were accounted for. The authors suggested that autism may be characterized by a general working memory deficit that prevents individuals from solving context-specific problems that require integration of multiple pieces of information over space and time. However, Bennetto et al. did not control for possible differences in reading and counting efficiency that might also account for the group difference in complex span performance. This concern was addressed by Russell et al. (1996), who gave individuals with autism, and comparison groups of equivalent verbal mental age, three complex span tasks: a counting span task; an operation span task, in which individuals complete a series of sums while remembering the successive totals; and an odd-man-out task in which participants had to locate successive targets that differed in form from their neighbours while remembering the positions of these targets (cf. Hitch & McAuley, 1991). Individuals with autism were found to be unimpaired on the latter two tasks but did show impaired counting span in one of two versions of the counting span task. However, this deficit could be directly attributed to the greater time taken by individuals with autism to count the dots within the processing episodes of this task (cf. Jarrold & Russell, 1997).

Taken together, the evidence for working memory deficits in autism appears rather weak. Having said this, there are relatively few studies in the autism literature that employ incontrovertible working memory measures and which control for individuals’ ability to complete the storage and processing components of such measures, in order to examine the executive requirements associated with combining them. Certainly there is room for more work aimed at examining whether executive deficits in autism, and also in ADHD, lead to working memory impairments.

Summary

One of the points that comes out most clearly from the above review is that researchers differ in how they conceptualise working memory, with consequent inconsistencies in the tasks used to tap working memory function. Although the use of multiple measures to tap an underlying construct is, in theory, an informative research approach, this only holds if these measures have construct validity (cf. Conway et al., 2005). The ability of some of the measures reviewed above to tap working memory is questionable, and this alone could account for some of the inconsistency in findings highlighted in certain sections above. Baddeley's working memory model (Baddeley 1986, 2000) provides one but by no means the only (see Miyake & Shah, 1999) theoretical framework in which to interpret working memory deficits among individuals with intellectual disability. This model has a number of strengths in this regard. In particular, the above review shows that individuals with different forms of intellectual disability can differ in either their verbal or visuo-spatial short-term memory performance, while other individuals show more deficits on working memory than on short- term memory measures. This pattern of strengths and weaknesses supports the view that the verbal and visuo-spatial aspects short-term memory should be dissociated, and that working memory needs to be conceptually distinguished from short-term memory.

At the same time, the above review indicates that poor short-term memory or working memory performance can arise for a number of reasons, and that simply observing a deficit on either simple or complex tasks in a particular group is not in itself evidence of a fundamental short-term or working memory impairment. Individuals will perform poorly on these tasks if they struggle to encode or reproduce to-be-remembered items, or if they find it difficult to carry out any processing embedded in such tasks. Arguably, impaired performance that results from these effects does not reflect a fundamental memory deficit, and in the context of the study of intellectual disability, poor memory performance may therefore be secondary to the more general learning difficulties that are associated with any given condition.

Having said this, it remains possible that fundamental short-term and working memory deficits themselves lie at the heart of some of the learning difficulties experienced by such individuals. As the above review has highlighted, short-term memory deficits do appear to occur, and would be expected to lead on to problems in long-term learning; in particular the verbal short-term memory deficits associated with conditions such as Down syndrome have been linked to problems in language acquisition. Similarly, given the close association between working memory performance and general intelligence seen in the general population, one might expect working memory deficits to play a causal role in constraining intellectual development among individuals with intellectual disability. One clearly needs to be cautious in hypothesising a single cause for all forms of intellectual disability, and in making the associated assumption that intellectual disability is in itself a single, homogeneous entity (Burack, 1990). Nevertheless, the fact that working memory has been shown to be closely related to intelligence and reasoning (Kyllonen & Christal, 1990; Oberauer et al., 2005) means that working memory deficits are certainly a potential cause of intellectual disability. Consequently, the extent of such deficits in these populations does deserve investigation, although this chapter has clearly shown the need for further work in this area.

However, one issue that needs to be borne in mind in carrying out such work is the extent to which matching groups, in order to determine whether deficits are specific or general, may risk 'matching away' the deficit of interest. In particular, if one hypothesises that working memory impairments cause intellectual deficits and reduced IQ, then one will struggle to show working memory deficits among groups that are matched for IQ. Indeed, the above review of working memory skills in ADHD and autism suggests that any evidence of working memory problems in these populations tends to be seen when groups are not equated for IQ, and tends to disappear when IQ is controlled for. While it is clearly important to question whether any observed working memory deficit is specific to a disorder, or rather is associated with general intellectual disability that might also be associated with that condition, there is a very real sense in which one might never expect to see working memory deficits among groups matched for IQ. If so, then the most fruitful approach to future work in this area might involve assessing working memory skills within a group of individuals with a given developmental disorder who themselves vary in IQ in order to determine whether this variation in intellectual ability is closely related to variance in working memory capacity.

References

Ackerman, P. L., Beier, M. E., & Boyle, M. O. (2005). Working memory and intelligence: The same or different constructs? Psychological Bulletin, 131, 30-60.

Alloway, T. P., & Gathercole, S. E. (2006). Working memory in neurodevelopmental conditions. Hove, UK: Psychology Press.

Archibald, L. M. D., & Gathercole, S. E. (2006). Short-term memory and working memory in specific language impairment. In T, P. Alloway & S. E. Gathercole (Eds.), Working memory in neurodevelopmental conditions (pp. 139-160). Hove UK: Psychology Press.

Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes. In K. W. Spence & J. T. Spence (Eds.), The psychology of learning and motivation, vol. 2 (pp. 89-105). New York: Academic Press.

Avons, S. E., & Hanna, C. (1995). The memory-span deficit in children with specific reading disability: Is speech rate responsible? British Journal of Developmental Psychology, 13, 303-311.

Baddeley, A. (1993). Short-term phonological memory and long-term learning: A single-case study. European Journal of Cognitive Psychology, 5, 129-148.

Baddeley, A. D. (1986). Working memory. Oxford: Oxford University Press. Baddeley, A. (2000). The episodic buffer: A new component of working memory? Trends in

Cognitive Sciences, 4, 417-423. Baddeley, A., Gathercole, S., & Papagno, C. (1998). The phonological loop as a language learning device. Psychological Review, 105, 158-173.

Baddeley, A. D., & Logie, R. H. (1999). Working memory: The multiple-component model. In A. Miyake & P. Shah (Eds.), Models of working memory: Mechanisms of active maintenance and executive control (pp. 28-61). Cambridge: Cambridge University Press.

Baddeley, A. D., Thomson, N., & Buchanan, M. (1975). Word length and the structure of short-term memory. Journal of Verbal Learning and Verbal Behavior, 14, 575-589.

Bailey, A., Phillips, W., & Rutter, M. (1996). Autism: Towards an integration of clinical, genetic, neuropsychological, and neurobiological perspectives. Journal of Child Psychology and Psychiatry, 37, 89-126.

Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. Psychological Bulletin, 121, 65-94.

Bayliss, D. M., Jarrold, C., Baddeley, A. D., Gunn, D. M., & Leigh, E. (2005). Mapping the developmental constraints on working memory span performance. Developmental Psychology, 41, 579-597.

Bayliss, D. M., Jarrold, C., Baddeley, A. D., & Leigh, E. (2005). Differential constraints on the working memory and reading abilities of individuals with learning difficulties and typically developing children. Journal of Experimental Child Psychology, 92, 76-99.

Bayliss, D. M., Jarrold, C., Gunn, D. M., & Baddeley, A. D. (2003). The complexities of complex span: Explaining individual differences in working memory in children and adults. Journal of Experimental Psychology: General, 132, 71-92.

Bennetto, L., Pennington, B. F., & Rogers, S. J. (1996). Intact and impaired memory functions in autism. Child Development, 67, 1816-1835.

Bishop, D. V. M., North, T., & Donlan, C. (1995). Genetic basis of specific language impairment: Evidence from a twin study. Developmental Medicine and Child Neurology, 37, 56-71.

Brener, R. (1940). An experimental investigation of memory span. Journal of Experimental Psychology, 26, 467-482.

Briscoe, J., Bishop, D. V. M., & Norbury, C. F. (2001). Phonological processing, language, and literacy: a comparison of children with mild-to-moderate sensorineural hearing loss and those with specific language impairment. Journal of Child Psychology and Psychiatry, 42, 329-340.

Broadley, I., & MacDonald, J. (1993). Teaching short term memory skills to children with Down's syndrome. Down's Syndrome: Research and Practice, 1, 56-62.

Brock, J., & Jarrold, C. (2004). Language influences on verbal short-term memory performance in Down syndrome: Item and order recognition. Journal of Speech, Language, and Hearing Research, 47, 1334-1346.

Brock, J., & Jarrold, C. (2005). Serial order reconstruction in Down syndrome: Evidence for a selective deficit in verbal short-term memory. Journal of Child Psychology and Psychiatry, 46, 304- 316.

Brock, J., McCormack, T., & Boucher, J. (2005). Probed serial recall in Williams syndrome: Lexical influences on phonological short-term memory. Journal of Speech, Language, and Hearing Research, 48, 360-371.

Brown, G. D. A., Preece, T., & Hulme, C. (2000). Oscillator-based memory for serial order. Psychological Review, 107, 127-181.

Burack, J. A. (1990). Differentiating mental retardation: The two-group approach and beyond. In R. M. Hodapp. J. A. Burack, & E. Zigler (Ed.s), Issues in the developmental approach to mental retardation (pp. 27-48). Cambridge: Cambridge University Press.

Burack, J., Iarocci, G., Flanagan, T., & Bowler, D. (2004). On mosaics and melting pots: Conceptual considerations of comparison and matching strategies. Journal of Autism and Developmental Disorders, 34, 65-73.

Burgess, N., & Hitch, G. J. (1999). Memory for serial order: A network model of the phonological loop and its timing. Psychological Review, 106, 551-581.

Burgess, N., & Hitch, G. (2005). Computational models of working memory: putting long-term memory into context. Trends in Cognitive Sciences, 9, 535-541.

Cairns, P., & Jarrold, C. (2005). Exploring the correlates of impaired nonword repetition in Down syndrome. British Journal of Developmental Psychology, 23, 401-416.

Case, R., Kurland, D. M., & Goldberg, J. (1982). Operational efficiency and the growth of short-term memory span. Journal of Experimental Child Psychology, 33, 386-404.

Chalfonte, B. L., & Johnson, M. K. (1996). Feature memory and binding in young and older adults. Memory and Cognition, 24, 403-416.

Chapman, R.S. (1995). Language development in children and adolescents with Down syndrome. In P. Fletcher & B. MacWhinney (Eds.), Handbook of child language (pp. 641–663). Oxford: Blackwell.

Chapman, R. S. (1997). Language development in children and adolescents with Down syndrome. Mental Retardation and Developmental Disabilities Research Reviews, 3, 307-312.

Chapman, R. S., Kay-Raining Bird, E., & Schwartz, S. E. (1990). Fast mapping of words in event contexts by children with Down syndrome. Journal of Speech and Hearing

Disorders, 55, 761-770.

Chuah, Y. M. L., & Maybery, M. T. (1999). Verbal and spatial short-term memory: Common sources of developmental change? Journal of Experimental Child Psychology, 73, 7-44.

Colom, R., Rebollo, I., Palacios, A., Juan-Espinosa, M., & Kyllonen, P. C. (2004). Working memory is (almost) perfectly predicted by g. Intelligence, 32, 277-296.

Comblain, A. (1994). Working memory in Down's syndrome: Training the rehearsal strategy. Down's Syndrome: Research and Practice, 2, 123-126.

Conway, A. R. A., Kane, M. J., Bunting, M. F., Hambrick, D. Z., Wilhelm, O., & Engle, R. W. (2005). Working memory span tasks: A methodological review and user's guide. Psychonomic Bulletin and Review, 12, 769-786.

Conway, A. R. A., Kane, M. J., & Engle, R. W. (2003). Working memory capacity and its relation to general intelligence. Trends in Cognitive Sciences, 7, 547-552.

Cornoldi, C., Marzocchi, G. M., Belotti, M., Caroli, M. G., De Meo, T., & Braga, C. (2001). Working memory interference control deficit in children referred by teachers for ADHD symptoms. Child Neuropsychology, 7, 230-240.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. Journal of Verbal Learning and Verbal Behavior, 19, 450-466.

Daneman, M., & Merikle, P. M. (1996). Working memory and language comprehension: A meta- analysis. Psychonomic Bulletin and Review, 3, 422-433.

Daneman, M., & Tardif, T. (1987). Working memory and reading re-examined. In M. Coltheart (Ed.), Attention and performance XII (pp. 491-508). Hillsdale, NJ: Erlbaum.

Dollaghan, C. A., & Campbell, T. F. (1998). Nonword repetition and child language impairment. Journal of Speech, Language, and Hearing Research, 41, 1136-1146.

Engle, R. W. (2002). Working memory capacity as executive attention. Current Directions in Psychological Science, 11, 19-23.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, R. A. (1999). Working memory, short- term memory, and general fluid intelligence: A latent-variable approach. Journal of Experimental Psychology: General, 128, 309-311.

Farran, E. K., & Jarrold, C. (2003). Visuospatial cognition in Williams syndrome: Reviewing and accounting for strengths and weaknesses. Developmental Neuropsychology, 23, 173-200.

Farran, E.K., Blades, M., Tranter, L., & Boucher, J. (2006). How do individuals with Williams syndrome learn a route? Paper presented at the British Psychological Society: Developmental Section Annual Conference, September. London, U.K.

Flavell, J. H., Beach, D. R., & Chinsky, J. M. (1966). Spontaneous verbal rehearsal in a memory task as a function of age. Child Development, 37, 283-299.

Gathercole, S. E., Adams, A. M., & Hitch, G. J. (1994). Do young children rehearse? An individual differences analysis. Memory and Cognition, 22, 201-207.

Gathercole, S. E., & Alloway, T. P. (2006). Practitioner review: Short-term and working memory impairments in neurodevelopmental disorders: Diagnosis and remedial support. Journal of Child Psychology and Psychiatry, 47, 4-15.

Gathercole, S. E., & Baddeley, A. D. (1990). Phonological memory deficits in language disordered children: Is there a causal connection? Journal of Memory and Language, 29, 336-360.

Gathercole, S. E., Hitch, G. J., Service, E., & Martin, A. J. (1997). Phonological short-term memory and new word learning in children. Developmental Psychology, 6, 966-979.

Gathercole, S. E., Lamont, E., & Alloway, T. P. (2006). Working memory in the classroom. In S. Pickering (Ed.), Working memory and education. Elsevier Press.

Gathercole, S., & Pickering, S. (2001). Working memory deficits in children with special educational needs. British Journal of Special Education, 28, 89-97.

Gathercole, S. E., Pickering, S. J., Ambridge, B., & Wearing, H. (2004). The structure of working memory from 4 to 15 years of age. Developmental Psychology, 40, 177-190.

Gathercole, S. E., Pickering, S. J., Hall, M., & Peaker, S. M. (2001). Dissociable lexical and phonological influences on serial recognition and serial recall. Quarterly Journal of Experimental Psychology, 54A, 1-30.

Gathercole, S. E., Tiffany, C., Briscoe, J., Thorn, A., & The ALSPAC team (2005). Developmental consequences of poor phonological short-term memory function in childhood: A longitudinal study. Journal of Child Psychology and Psychiatry, 46, 598-611.

Gathercole, S. E., Willis, C. S., Emslie, H., & Baddeley, A. D. (1992). Phonological memory and vocabulary development during the early school years: A longitudinal study. Developmental Psychology, 5, 887-898.

Gathercole, S.E., Willis, C., Emslie, H., & Baddeley, A.D. (1994). The Children's Test of Nonword Repetition: A test of phonological working memory. Memory, 2, 103-127.

Goldberg, M. C., Mostofsky, S. H., Cutting, L. E., Mahone, E. M., Astor, B. C., Denckla, M. B., et al. (2005). Subtle executive impairment in children with autism and children with ADHD. Journal of Autism and Developmental Disorders, 35, 279-293.

Hale, S., Bronik, M. D., & Fry, A. F. (1997). Verbal and spatial working memory in school-aged children: Developmental differences in susceptibility to interference. Developmental Psychology, 33, 364-371.

Hanley, J. R., Young, A. W., & Pearson, N. A. (1991). Impairment of the visuo-spatial sketch pad. The Quarterly Journal of Experimental Psychology, 43A, 101-125.

Henry, L. A. (2001). How does the severity of a learning disability affect working memory performance? Memory, 9, 233-247.

Hill, E. L. (2004). Executive dysfunction in autism. Trends in Cognitive Sciences, 8, 26-32. Hitch, G. J., & McAuley, E. (1991). Working memory in children with specific arithmetical learning difficulties. British Journal of Psychology, 82, 375-386.

Hitch, G. J., Towse, J. N., & Hutton, U. (2001). What limits children's working memory span? Theoretical accounts and applications for scholastic development. Journal of Experimental Psychology: General, 130, 184-198.

Hockey, A., & Geffen, G. (2004). The concurrent validity and test-retest reliability of a visuospatial working memory test. Intelligence, 32, 591-605.

Hughes, C., Russell, J., & Robbins, T. R. (1994). Evidence for executive dysfunction in autism. Neuropsychologia, 32, 477-492.

Hulme, C., & Mackenzie, S. (1992). Working memory and severe learning difficulties. Hove: Lawrence Erlbaum Associates.

Hulme, C., Newton, P., Cowan, N., Stuart, G., & Brown, G. (1999). Think before you speak: Pauses, memory search, and trace redintegration processes in verbal memory span. Journal of Experimental Psychology: Learning, Memory, and Cognition, 25, 447-463.

Hulme, C., & Roodenrys, S. (1995). Practitioner review: Verbal working memory development and its disorders. Journal of Child Psychology and Psychiatry, 36, 373-398.

Jarrold, C., Baddeley, A. D., & Hewes, A. K. (1999). Genetically dissociated components of working memory: Evidence from Down's and Williams syndrome. Neuropsychologia, 37, 637-651.

Jarrold, C., Baddeley, A. D., & Hewes, A. K. (2000). Verbal short-term memory deficits in Down syndrome: A consequence of problems in rehearsal? Journal of Child Psychology and Psychiatry, 41, 233-244.

Jarrold, C., Baddeley, A. D., Hewes, A. K., Leeke, T., & Phillips, C. (2004). What links verbal short- term memory performance and vocabulary level? Evidence of changing relationships among individuals with learning disability. Journal of Memory and Language, 50, 134-148.

Jarrold, C., Baddeley, A.D., & Phillips, C. (1999). Down syndrome and the phonological loop: The evidence for, and importance of, a specific verbal short-term memory deficit. Down Syndrome Research and Practice, 6, 61–75.

Jarrold, C., Baddeley, A. D., & Phillips, C. E. (2002). Verbal short-term memory in Down syndrome: A problem of memory, audition, or speech? Journal of Speech, Language, and Hearing Research, 45, 531-544.

Jarrold, C. & Bayliss, D. M. (in press). Variation in working memory due to typical and atypical development. In A. R. A. Conway, C. Jarrold, M. J. Kane, A. Miyake, & J. N. Towse (Eds.), Variation in working memory. Oxford: Oxford University Press.

Jarrold, C., Cowan, N., Hewes, A. K., & Riby, D. M. (2004). Speech timing and verbal short-term memory: Evidence for contrasting deficits in Down syndrome and Williams syndrome. Journal of Memory and Language, 51, 365-380.

Jarrold, C., Purser, H. R. M., & Brock, J. (2006). Short-term memory in Down syndrome. In T. P. Alloway & S. E. Gathercole (Eds.), Working memory and neurodevelopmental conditions (pp. 239- 266). Hove, UK: Psychology Press.

Jarrold, C., & Russell, J. (1997). Counting abilities in autism: Possible implications for central coherence theory. Journal of Autism and Developmental Disorders, 27, 25-37.

Jarrold, C., & Towse, J. T. N. (2006). Individual differences in working memory. Neuroscience, 139, 39-50.

Jones, D., Farrand, P., Stuart, G., & Morris, N. (1995). Functional equivalence of verbal and spatial information in serial short-term memory. Journal of Experimental Psychology: Learning, Memory, and Cognition, 21, 1008-1018.

Joseph, R. M., Steele, S. D., Meyer, E., & Tager-Flusberg, H. (2005). Self-ordered pointing in children with autism: Failure to use verbal mediation in the service of working memory? Neuropsychologia, 43, 1400-1411.

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. Psychological Review, 99, 122-129.

Kanno, K., & Ikeda, Y. (2002). Word-length effect in verbal short-term memory in individuals with Down's syndrome. Journal of Intellectual Disability Research, 46, 613-618.

Karatekin, C. (2004). A test of the integrity of the components of Baddeley's model of working memory in attention-deficit/hyperactivity disorder (ADHD). Journal of Child Psychology and Psychiatry, 45, 912-926.

Kimberg, D. Y., & Farah, M. J. (1992). A unified account of cognitive impairments following frontal lobe damage: The role of working memory in complex, organized behavior. Journal of Experimental Psychology: General, 122, 411-428.

Kirchner, D.M., & Klatzky, R.L. (1985). Verbal rehearsal and memory in language-disordered children. Journal of Speech and Hearing Research, 28, 556-565.

Klein, B. P., & Mervis, C. B. (1999). Cognitive strengths and weaknesses of 9- and 10-year-olds with Williams syndrome or Down syndrome. Developmental Neuropsychology, 16, 177-196.

Kuntsi, J., Oosterlaan, J., & Stevenson, J. (2001). Psychological mechanisms in hyperactivity: I response inhibition deficit, working memory impairment, delay aversion, or something else? Journal of Child Psychology and Psychiatry, 42, 199-210.

Kyllonen, P. C., & Christal, R. E. (1990). Reasoning ability is (little more than) working memory capacity?! Intelligence, 14, 389-433.

Laws, G., & Bishop, D. V. M. (2004). Verbal deficits in Down syndrome and specific language impairment: A comparison. International Journal of Language and Communication Disorders, 39, 423-451.

Lépine, R., Barrouillet, P., & Camos, V. (2005). What makes working memory spans so predictive of high level cognition? Psychonomic Bulletin and Review, 12, 165-170.

Lopez, B. R., Lincoln, A. J., Ozonoff, S., & Lai, Z. (2005). Examining the relationship between executive functions and restricted, repetitive symptoms of autistic disorder. Journal of Autism and Developmental Disorders, 35, 445-460.

Majerus, S., & Van der Linden, M. (2003). Long-term memory effects on verbal short-term memory: a replication study. British Journal of Developmental Psychology, 21, 303-310.

Majerus, S., Van der Linden, M., Bressand, V., Eliez, S. (2006). Verbal short-term memory in children and adults with a chromosome 22q11.2 deletion. A specific deficit in serial order retention capacities? Manuscript submitted for publication.

Marcell, M. M., & Cohen, S. (1992). Hearing abilities of Down syndrome and other mentally handicapped adolescents. Research in Developmental Disabilities, 15, 533-551.

Mervis, C., Morris, C. A., Bertrand, J., & Robinson, B. F. (1999). Williams syndrome: Findings from an integrated program of research. In H. Tager-Flusberg (Ed.), Neurodevelopmental disorders: Contribution to a new framework from the cognitive neurosciences (pp. 65-110). Cambridge, MA: MIT Press.

Milner, B. (1971). Interhemispheric differences in the localisation of psychological processes in man. British Medical Bulletin, 27, 272-277.

Miyake, A., & Shah, P. (1999). Models of working memory: Mechanisms of active maintenance and executive control. Cambridge: Cambridge University Press.

Monsell, S. (1978). Recency, immediate recognition memory, and reaction time. Cognitive Psychology, 10, 465-501.

Mosley, J. L. (1985). High-speed memory-scanning task performance of mildly mentally retarded and nonretarded individuals. American Journal of Mental Deficiency, 90, 81-89.

Oberauer, K., Schulze, R., Wilhelm, O., & Süß, H.-M. (2005). Working memory and intelligence – their correlation and their relation: Comment on Ackerman, Beier, and Boyle (2005). Psychological Bulletin, 131, 61-65.

Ozonoff, S., Pennington, B. F., & Rogers, S. J. (1991). Executive function deficits in high-functioning autistic individuals: Relationship to theory of mind. Journal of Child Psychology and Psychiatry, 32, 1081-1105.

Ozonoff, S., & Strayer, D. L. (2001). Further evidence of intact working memory in autism. Journal of Autism and Developmental Disorders, 31, 257-263.

Page, M. P. A., & Norris, D. (1998). The primacy model: A new model of immediate serial recall. Psychological Review, 105, 761-781.

Pennington, B. F., Moon, J., Edgin, J., Stedron, J., & Nadel, L. (2003). The neuropsychology of Down syndrome: Evidence for hippocampul dysfunction. Child Development, 74, 75-93.

Pennington, B. F., & Ozonoff, S. (1996). Executive functions and developmental psychopathology. Journal of Child Psychology and Psychiatry, 37, 51-87.

Phillips, C. J., & Nettlebeck, T. (1984). Effects of procedure on memory scanning of mild mentally retarded adults. American Journal of Mental Deficiency, 88, 668-677.

Pickering, S. J., Gathercole, S. E., & Peaker, S. M. (1998). Verbal and visuo-spatial short-term memory in children: Evidence for common and distinct mechanisms. Memory and Cognition, 26, 1117-1130.

Raine, A., Hulme, C., Chadderton, H., & Bailey, P. (1991). Verbal short-term memory span in speech-disordered children: Implications for articulatory coding in short-term memory. Child Development, 62, 415-423.

Roodenrys, S. (2006). Working memory function in attention deficit hyperactivity disorder. In T, P. Alloway & S. E. Gathercole (Eds.), Working memory in neurodevelopmental conditions (pp. 187- 211). Hove, UK: Psychology Press.

Ruiz, M., Elousúa, M. R., & Lechuga, M. T. (2005). Old-fashioned responses in an updating memory task. The Quarterly Journal of Experimental Psychology, 58A, 887-908.

Russell, J., Jarrold, C., & Henry, L. (1996). Working memory in children with autism and with moderate learning difficulties. Journal of Child Psychology and Psychiatry, 37, 673-686.

Shah, P., & Miyake, A. (1996). The separability of working memory resources for spatial thinking and language processing: An individual differences approach. Journal of Experimental Psychology: General, 125, 4-27.

Siegel, L. S., & Ryan, E. B. (1989). The development of working memory in normally achieving and subtypes of learning disabled children. Child Development, 60, 973-980.

Snowling, M., Chiat, S., & Hulme, C. (1991). Words, nonwords, and phonological processes: Some comments on Gathercole, Willis, Emslie, and Baddeley. Applied Psycholinguistics, 12, 369-373.

Sternberg, S. (1966). High-speed scanning in human memory. Science, 153, 652-654.

Süß, H.-M., Oberauer, K., Wittmann, W. W., Wilhelm, O., & Schulze, R. (2002). Working-memory capacity explains reasoning ability – and a little bit more. Intelligence, 30, 261-288.

Swanson, H. L., & Ashbaker, M. H. (2000). Working memory, short-term memory, speech rate, word recognition and reading comprehension in learning disabled readers: Does the executive system have a role? Intelligence, 28, 1-30.

Thorn, A. S. C., & Frankish, C. R. (2005). Long-term knowledge effects on serial recall of nonwords are not exclusively lexical. Journal of Experimental Psychology: Learning, Memory, and Cognition, 31, 729-735.

Thorn, A. S. C., Gathercole, S. E., & Frankish, C. R. (2002). Language familiarity effects in short- term memory: The role of output delay and long-term knowledge. The Quarterly Journal of Experimental Psychology, 55A, 1363-1383.

Todman, J., & Gibb, C. M. (1985). High speed memory scanning in retarded and non-retarded adolescents. British Journal of Psychology, 76, 49-57.

van der Lely, H. K. J., & Howard, D. (1993). Children with specific language impairment: Linguistic impairment or short-term memory deficit? Journal of Speech and Hearing Research, 36, 1193-1207.

Vicari, S., Bates, E., Caselli, M. C., Pasqualetti, P., Gagliardi, C., Tonucci, F., & Volterra,

V. (2004). Neuropsychological profile of Italians with Williams syndrome: an example of a dissociation between language and cognition? Journal of the International Neuropsychological Society, 10, 862- 876.

Vicari, S., Caselli, M. C., Gagliardi, C., Tonucci, F., & Volterra, V. (2002). Language acquisition in special populations: A comparison between Down and Williams syndromes. Neuropsychologia, 40, 2461-2470.

Wang, P. P., & Bellugi, U. (1994). Evidence from two genetic syndromes for a dissociation between verbal and visual-spatial short-term memory. Journal of Clinical and Experimental Neuropsychology, 16, 317-322.

White, D. A., Craft, S., Hale, S., & Park, T. S. (1994). Working memory and articulation rate in children with spastic cerebral palsy. Neuropsychology, 8, 180-186.

Whitehouse, A. J. O., Maybery, M. T., & Durkin, K. (2006). Inner speech impairments in autism. Journal of Child Psychology and Psychiatry, 47, 857-865.

Willcutt, E. G., Pennington, B. F., Boada, R., Ogline, J. S., Tunick, R. A., Chhabildas, N. A., et al. (2001). A comparison of the cognitive deficits in reading disability and attention-deficit/hyperactivity disorder. Journal of Abnormal Psychology, 110, 157-172.

Williams, D. L., Goldstein, G., & Minshew, N. J. (2006). The profile of memory function in children with autism. Neuropsychology, 20, 21-29.

Author Note

Correspondence concerning this article should be addressed to: Chris Jarrold, Department of Experimental Psychology, University of Bristol, 8 Woodland Road, Bristol BS8 1TN, UK. Electronic mail: C.Jarrold@bristol.ac.uk