Number and arithmetic skills in children with Down syndrome

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It is clear that arithmetic and number skills are areas of particular difficulty for individuals with Down syndrome. Studies of arithmetic development in typically developing children suggest that a pre-verbal "number sense" system and counting skills provide two critical foundations for the development of arithmetic. Studies of children with Down syndrome suggest that the development of both these foundational skills present difficulties for them, though these conclusions are based on relatively small samples of children. It would seem that further studies of arithmetic and number skills in children with Down syndrome, involving larger samples of children and broader ranges of measures, are badly needed.

Basic number skills, such as knowing how to count and solve simple arithmetic problems, are essential for everyday independent living. It is clear that arithmetic and number skills are areas of particular difficulty for individuals with Down syndrome. So far, we have quite limited understanding of the cognitive bases of the problems with number skills seen in children with Down syndrome. However, major advances have been made in research on the development of number skills in typically developing children and it appears that these advances offer the prospect of better understanding the problems seen in children with Down syndrome.

Levels of attainment in arithmetic in children with Down syndrome

Studies of arithmetic attainment in individuals with Down syndrome consistently report very low levels of attainment. Carr reported that more than half of her sample of 41 individuals aged 21 years, could only recognise numbers and count on the Vernon's arithmetic-mathematics test[1]. Buckley and Sacks surveyed the number skills of 90 individuals with Down syndrome aged between 11 and 17 years and found that only 18% of the sample could count beyond 20 and only around half of the sample could solve simple addition problems[2]. This pattern contrasts with the increasingly positive achievement levels in reading skills that children with Down syndrome are attaining (e.g. REF 3). Indeed the most consistent finding in the literature is that reading accuracy is significantly higher than arithmetic attainment[1-6]. Age equivalents on standardised number tests are typically reported to lag age equivalent reading scores by around two years in children with Down syndrome (e.g. REF 1). Brigstocke et al. report measures of arithmetic ability from a group of 49 children with Down syndrome[7]. The sample ranged in age from 5:06 to 16:02, and had an average BPVS standard score of 60 (range 39-91). Of this sample 45 children had measurable single word reading skills on the BAS reading test (average standard score 67, range 55-115). However, only 27 of the sample could score on the BAS basic number skills test, and for these children their scores were very low (average standard score 62; range 55-111). It is clear therefore that in this sample, like others studied, number skills are much weaker than reading skills.

In typically developing children education and age are strong predictors of arithmetic performance[8]. Language skills are generally predictive of variations in arithmetic ability, and in line with this, children with specific language impairment typically have low arithmetic achievement despite average IQ[9]. Nonverbal ability is also associated with arithmetic achievement in typical and atypical development (e.g. REF 10). Working memory and knowledge of number facts are also important predictors of arithmetic performance[11,12]. Number facts are learned from associations between the problem and the retrieved answer, which is a function of experience, and working memory capacity. These findings are particularly relevant given the cognitive profile typically noted in Down syndrome in which language skills[13,14] and verbal short-term memory[15,16] are weak relative to nonverbal abilities.

In common with typical development, number skills in children with Down syndrome appear to improve with age [17,18,19] but this is not always the case and wide individual differences are noted in all studies. The relationship between achievement levels and mental age in Down syndrome is not clear so far. Findings are inconsistent (e.g. REFS 17,20,21) but this may reflect the variety and generality of the measures used to assess number skills. Floor effects on standardised IQ tests can also be a problem (e.g. REF 22). Moreover, general ability is a wide measure and the mechanisms that govern the relationship between IQ and mathematical achievement are not clear even in typical development, which makes interpretation difficult. Language skills are related to achievement in number skills in children with Down syndrome (e.g. REFS 5,23,24). For example in recently collected data there is a strong correlation between verbal ability measured by the BPVS and both single word reading standard scores (r = .69) and BAS arithmetic standard scores (r = .63)[7].

Education clearly has a positive influence on achievement levels in arithmetic. This is indicated by the success of small intervention studies (e.g. REFS 19,25,26). Children with Down syndrome in mainstream schools have better attainments in arithmetic than those in special schools; but this is likely to be confounded with selection biases[1,17,27,28]. Nye et al. note that individual differences in response to an intervention using Numicon were related to the quality and quantity of teaching[26].

The Numicon approach to teaching numbers skills and arithmetic[29,30] is based on a system of structured visual representation first developed by Catherine Stern which makes clear the stable order of the number system, and how different numbers are related[31]. One of the key features of the scheme is it provides children with representations of whole numbers which are used to develop mental imagery of numbers, and makes an explicit connection between the preverbal number system, counting and arithmetical operations. Therefore, the scheme uses the perception of whole numbers to support mental arithmetic, rather than using counting as the basis for arithmetic, as is often the case in UK numeracy teaching. Whilst the scheme has been developed for all children to use it was thought to be particularly appropriate for trialling with children with Down syndrome as it complements their particular cognitive profile (e.g. having strengths in visual processing), and targets many of the areas of numeracy that they have difficulty with.

The recent Portsmouth project followed the development of number skills in 16 children with Down syndrome (aged between 5 and 14 years) over 2.5 years whilst they were taught using Numicon, and their performance was compared to archive data of children with Down syndrome who had not used Numicon[32]. A small but non-significant gain was seen in numerical performance (as measured by the BAS Basic Number Skills sub-test[33]) in the children who had used Numicon compared to those who had not. Qualitative analysis of the children's profiles, including data from observations of lessons and non-standardised detailed number assessments indicated that Numicon is of particular benefit to children for developing both early numerical concepts and those who are starting to work with arithmetical operations. Regular use of the materials and creative adaptation of the scheme to meet the needs of the individual children were both found to be critical in effective implementation of the scheme. Whilst the main finding from the standardised measure was non-significant statistically, it should be noted that the was a wide range of gains seen in the children, and the gains made may still make a considerable different to children's numbers skills and resulting quality of life.

In summary, individuals with Down syndrome find number skills very difficult in comparison to their ability to learn to read but respond positively to tuition. However, while studies investigating the cognitive correlates of general mathematic tests are a useful starting point, they give little insight into the underlying processes involved.

The cognitive bases of arithmetic in normal development and the origins of mathematical difficulties

In the last 20 years or so there has been a good deal of research concerned with understanding the cognitive bases and development of human numerical abilities. It appears from studies of animals and pre-verbal human infants that some basic numerical skills exist in the absence of language. This pre-verbal numerical system is probably somewhat imprecise and can only deal with small numbers of objects. Nevertheless, it has been suggested that such a preverbal "number sense" may form a foundation for more complex verbally elaborated number skills in humans [34,35]. The possible role of such a putative nonverbal number sense system in mature numerical processing remains controversial, but in one view, this nonverbal system provides the semantic underpinnings for understanding number since numbers, fundamentally, signify magnitudes.

One other important skill that also develops in the pre-school years is counting. By the time children go to school they are generally proficient at counting, at least for numbers up to ten, and these counting skills form a foundation for the development of arithmetic skills. Counting is fundamentally a form of measurement, and one that is more flexible and precise than the form revealed in studies of animals' and infants' preverbal numerical abilities. Learning to perform basic addition, which is the earliest arithmetical skill to be taught in school, can be seen as a natural extension of counting. At first, children use a simple 'count all' strategy to solve addition problems. By the age of 6, most are using a 'counting on' strategy in which they start with the smaller number and count on from this (the *min* strategy). Later, as they learn the number bonds, they can begin to retrieve these automatically. Development involves a change in the mix of strategies that are used. Importantly, the creation, in long-term memory, of an association between the problem integers (e.g. 3+4) and the answer that is generated (7) requires practice in the execution of basic computations. With each execution, the probability of direct retrieval of that number fact or bond increases. This direct retrieval strategy is rapid and highly efficient but only develops after the child has performed many less automatic computations of the relevant sums.

The possible cognitive bases of difficulties with arithmetic in children with Down syndrome

Such studies of arithmetic in typically developing children suggest it is important to understand the integrity (or otherwise) of the pre-verbal number system in children with Down syndrome, and the development of counting skills, as these two skills appear to provide two of the foundations for the development of arithmetic in typically developing children.

Preverbal numerical systems in children with Down syndrome

Magnitude comparison tasks have proved a very useful paradigm for investigating number skills and cardinal number understanding in typical development. Some authors interpret the ability to discriminate between magnitudes as a behavioural indicator of the operation of a basic "number sense" (e.g. REF 34) that underlies later number skills. It has been suggested that difficulty judging between magnitudes may underlie the difficulties that typical children with dyscalculia have with mathematics (e.g. REF 35).

In a typical numerical judgement task participants are presented with two stimuli (either digits, or arrays of dots differing in numerosity or squares differing in size) simultaneously on a computer screen and asked to indicate which is larger as quickly as possible. The simplicity and non-verbal requirements of the task make it ideal for individuals with Down syndrome. Findings from studies on numerical magnitude comparisons in typical adults and children have proved remarkably replicable. As Moyer and Landauer observed in their seminal study, the time required to compare the numerical magnitude of pairs of digits decreases as the numerical distance between stimuli increases (1 vs. 9 is a much easier judgement than 1 vs. 2)[36]. This is referred to as the symbolic distance effect (SDE). When the distance is held constant, discrimination of numbers becomes more difficult as their magnitude increases. This is referred to as the magnitude effect. This pattern of results mirrors that observed in comparison of physical magnitudes such as length and is the opposite pattern to that predicted if counting strategies were used. Recent work suggests that speed in making magnitude comparisons predicts individual differences in addition ability in typically developing children[37].

This symbolic distance effect (SDE) has been observed across all ages from 6 years upwards, supporting the idea that the effect is relatively independent of educational influences and cognitive ability[38,39,40]. The hypothesis that it is independent of language and does not rely on counting is supported by findings that children with specific language impairment who have significant difficulties with the verbal count sequence demonstrate typical performance in numerical comparison tasks[9]. Since individuals with Down syndrome are observed to have relatively preserved visuo-spatial abilities, and numerosity judgments are independent of language and general cognitive ability, this suggests that they will demonstrate normal performance on numerosity comparison tasks, provided they are sufficiently familiar with the count sequence and digits.

Paterson, Girelli, Butterworth and Karmiloff-Smith investigated the distance effect in infants and older individuals with Down syndrome and Williams syndrome[41]. They also administered a battery of number tasks hypothesised to rely on verbal abilities to the older groups. Eleven infants with Williams syndrome and 18 infants with Down syndrome, matched on chronological and mental age plus 16 mental age and 14 chronological age typically developing controls were tested on a preferential looking paradigm. Infants were familiarised with arrays of 2 objects. In the test phase they were presented simultaneously with one card displaying new objects but the familiar numerosity and one card with three objects i.e. a new numerosity. Cumulative looking times were measured. It was found that there was a significant difference in mean looking time between the familiar and novel numerosity in all groups except the Down syndrome group. This suggests that the infants with Down syndrome were unable to distinguish between 2 and 3 items.

However performance in a numerosity comparison task with older individuals showed the reverse pattern. Eight older children and adults with William's syndrome, 7 with Down syndrome, 8 typically developing controls matched for mental age using the British Abilities Scales, and 8 typically developing controls matched for chronological age to the clinical groups took part in the experiment. Participants were asked to indicate the larger of two dot arrays presented simultaneously on a computer screen. Reaction times and accuracy were measured. The numerosity of the arrays varied from 2 to 9 and the numerical distance between the arrays was classified as small (a difference of 1 to 3) or large (a difference of 5 to 7). Although reaction times were slow in the Down syndrome group, individuals responded more quickly and more accurately to arrays that had a large difference between them than those that had a small distance between them. A significant effect in the same direction was noted in the control groups but this distance effect was not observed in the William's syndrome group. Analysis of errors revealed that the Williams syndrome group was the least accurate of all the groups. The results of this study support the conclusion that language skills do not support performance in magnitude comparison tasks.

Participants also took part in a detailed battery of number tasks that assessed rote counting, dot and numeral seriation, matching dots to numerals and reading numerals aloud as well as single digit addition, subtraction and multiplication. Performance in the clinical groups was below that of the control participants who performed near ceiling. The William's syndrome group displayed considerable difficulties when compared to the Down syndrome group on all the tasks except rote counting from 1 to 20 and reading single digits where performance was good in both groups. Both groups found matching numerosities to Arabic numerals difficult.

No correlations were found between performance in the dot comparison task and the number battery task except in the performance of the Down syndrome group on the matching dots to Arabic numerals task. This could suggest a link between the ability to discriminate numerosities and the ability to associate Arabic digits with their underlying quantity representation[41].

An unpublished study conducted at York investigated the pattern of reaction times obtained by 16 children with Down syndrome, with a mean age of 13; 2 years (SD 24.44 months) and a receptive vocabulary level of above 5 years, on three computerised comparison tasks and a timed pencil and paper single digit addition task[7]. Each computerised task comprised 54 trials and required participants to identify the larger of two simultaneously presented stimuli. There were three sets of stimuli: dot arrays (matched for surface area), Arabic digits and horizontal lines. The order in which these stimulus types were presented was counterbalanced between participants.

Performance of the individuals with Down syndrome was compared to that obtained by typically developing children in Year 1 and Reception classes matched for receptive vocabulary level. The children in Year 1 demonstrated typical distance and magnitude effects in all tasks. The speed with which they made magnitude comparisons using line and digit stimuli correlated with their performance in the addition tasks (r=. 49). This correlation between comparison speed for numeric and physical stimuli and addition skills suggests numeric representations in this group are underpinned by analogue magnitudes representations, which in turn support addition skills. The children with Down syndrome and children in Reception also demonstrated typical distance and magnitude effects in all tasks, although five children with

Down syndrome had to be excluded from RT analysis of the numeric comparison task because of high error rates on the task. Although group sizes were too small to make firm interpretations of the pattern of correlations achieved in these groups, intriguingly, speed in making magnitude comparisons using dot arrays was the only correlate with addition performance (reception: *r*=. 72; Down syndrome: *r*=. 69). This pattern suggests that children with Down syndrome may have typical representations of numerosity but raises the possibility that the ability to link digit representations to magnitudes may be immature in children with Down syndrome (as in much younger typically developing reception year children).

The development of counting skills in children with Down syndrome

The development of counting has been examined in some detail in individuals with Down syndrome. Counting is an important skill that is often claimed to underpin a number of later mathematic skills (e.g. REF 42) such as children's early attempts at addition. Counting involves not only learning the number words, their sequence and how to tag number words to individual objects, but also requires understanding of the cardinality principle. This refers to the fact that the final count word refers to an exact quantity – the cardinal value or magnitude of the set. The cardinality principle means that the order in which items are tagged is irrelevant to the cardinal value of the set. Understanding of the order-irrelevance principle is used to assess whether children understand the purpose as well as the procedure of counting.

Gelman and Cohen reported the first detailed study of count production and understanding in ten children with Down syndrome with a mean chronological age of 10:06 years and mental ages ranging from 3:06 to 6:08years compared with younger typically developing children broadly matched for social economic status[20]. All of the children with Down syndrome attended special school. Children were assessed on rote counting and object counting knowledge as well as a task designed to test knowledge of the order-irrelevant principle. Children were presented with a line of objects and asked to count them in a non-linear order. For example, they might be asked to label the middle object, "the one". The children with Down syndrome performed better than controls on rote counting and object counting but worse on the order irrelevance counting task. On this basis, the authors concluded that the children with Down syndrome performed rote counting with no conceptual understanding of number. However, the instructions for the order-irrelevant counting task and the feedback involved very complex language. In contrast, Caycho, Gunn and Siegel found no difference between 15 children with Down syndrome (mean chronological age of 9:07 years) and 15 typically developing children (mean age of 4:06 years) matched for receptive vocabulary level[23], on a simplified version of the Gelman and Cohen task[20]. In this task the children presented with a row of items and asked to count them in a non-linear fashion but their finger was guided to the start item and they were told it was "one". The language and feedback used in the task were simplified. Caycho et al. concluded that conceptual understanding of counting is related to receptive vocabulary levels[23].

A longitudinal study by Nye investigated performance of a group of children with Down syndrome and typically developing children matched for non-verbal mental age on a variety of counting tasks [43]. A striking similarity was found between the counting skills of the Down syndrome group and the typically developing group matched for non-verbal mental age, both in terms of object counting and understanding of cardinality. While counting skills have not been found to be a particular problem for children with Down syndrome in previous research, what was particularly surprising here was how these skills developed in line with non-verbal mental ability (see REF 23). Even more surprising was the lack of a difference between the Down syndrome and typically developing groups in terms of their cardinal understanding; this would not have been predicted from previous research[20,23]. The only difference between the two matched groups was in count word vocabulary and sequence production, which were both significantly greater in the typically developing group, though by no means lacking in the Down syndrome group. However, any limitations that the children with Down syndrome had in production of the count word sequence did not seem to impact on their ability to count or give sets of objects, as evidenced by the lack of a difference between them and the typically developing children on these tasks. These seemingly positive findings of fledgling number skills in young children contrast strongly with the poor levels of achievement reported in older children although success was limited in these studies to very small arrays of objects (up to 18 items) so these positive results only extend to very basic skills, typically achieved by pre-school children.

Conservation

In order to progress to any form of number skills without the use of concrete props, understanding of the relative value of number and conceptual understanding of the number system that goes beyond the perceptual characteristics of a given array of items is essential. Conservation tasks that manipulate the surface characteristics of an array but keep the underlying value the same are often used to test this in typical development. The only studies to use traditional conservation tasks in Down syndrome were conducted by Lister and Lee and Lister, Leach and Riley[44,45]. They studied number and length understanding in 48 individuals with Down syndrome between 5 and 26 years. The tasks involved the subject creating or agreeing the initial equality of two stimuli. One of the stimuli was then transformed and the individual asked to judge whether the remaining quantities were still equal. None of the participants succeeded on all the conservation of length tasks, although five succeeded on all of the number conservation tasks. This is the pattern of development observed in typically developing children[40]. No information is provided on the counting ability of the participants. Given the wide age range of the sample it is likely that this is a significant factor in performance. Consequently, no clear conclusions can be drawn about the understanding of conservation in Down syndrome without further research.

Conclusions

It is clear that children with Down syndrome show severe difficulties in mastering basic number skills as assessed by tasks that include size and numerosity judgements, counting and simple arithmetic. There are suggestions that a pre-verbal "number sense" system may show atypical development in Down syndrome, but so far the group sizes studied preclude strong conclusions. It is clear that learning to count is difficult for children with Down syndrome, though there is no evidence that the development of counting follows a qualitatively different path to that seen in younger typically developing children. It appears that problems in the sphere of arithmetic show strong correlations with language skills in the Down syndrome population though such correlations may in part reflect limitations in children's ability to understand the arithmetic tasks they are required to complete. It would seem that studies of larger samples of children with Down syndrome that assess their pre-verbal number sense skills as well as counting and basic addition skills are badly needed.

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