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COGNITIVE EXPLANATIONS OF THE PLANNING AND ORGANISATION OF MOVEMENT

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Running head: Movement planning and organisation

By the time typical children reach infant school they have in place key movement skills such as running, hopping, jumping, throwing, kicking and writing (Gallahue & Ozmun, 1995; Haywood & Getchell, 2001). While these skills will continue to be refined throughout childhood, they reveal that children possess sophisticated movement planning, organisation and execution skills even at this young age. In this chapter the potential cognitive explanations for developmental coordination disorder, a disorder in which movement skill does not develop in the typical way, will be reviewed, and, where possible, studies will be considered in terms of their parallels to activities of daily living.

Typical development of skilled action

Movement is an essential ability which allows us to respond and interact adaptively with the environment. While we tend to take movement for granted, it is involved in everything we do. Many movements, such as postural adjustments and blinking occur automatically, while others are more obvious in everyday life (e.g., eating, dressing, writing). Furthermore, many human skills involve sequencing movements in new and unusual ways, playing the piano or doing gymnastics, for example.

Broadly speaking the development of movement skill has been shown to occur with age (e.g., Hay, 1979) and to show some degree of consistency over time. The fact that skilled action develops implies that the central nervous system stores information previously experienced and that this information expedites future behaviour. This is taken by many to imply that movements can be preprogrammed (by a feedforward, or open-loop mechanism) on the basis of prior experience. Schmidt (Schmidt, 1988 for example) has proposed the concept of a 'motor program', a set of preprogrammed muscle commands reducing the need for feedback control. Individual motor programs could be described as stored responses for specific movements which include information on the necessary conditions, speed and force for a movement as well as information concerning the sensory consequences of an intended movement. This general motor program will be adapted appropriately for each situation in parallel to the execution of the movement itself. In this way, developed movement skills can show variation, implying that on-line changes can be made to existing motor programs, adjustments which suggest that there is a role for feedback (or closed-loop) control in skilled action. Thus, evidence points to the use of open-loop (preprogrammed) as well as closed-loop (feedback) control in skilled movement (for an up-to-date model see for example Wolpert, Miall & Kawato, 1998). Imagine walking. It is easy to see how the initial, core response is preprogrammed in the healthy adult. But we constantly receive changing sensory information while walking which will alter the exact nature of our gait. Vision of objects in our path as well as visual and tactile information concerning the slope and stability of the ground (e.g., ice, heathland) are examples of environmental constraints which may cause us to alter our gait in order to maintain our stability. Incoming, changing information such as those just described is under closed-loop control, with on-line feedback being used to adjust the preprogrammed response so that it becomes efficient in a given situation.

As alluded to above, the development of skilled action is influenced by all sensory systems (Sugden, 1990). Vision and proprioception are key senses that interact to elicit skilled actions. Vision provides information both about the environment and the individual's place in it while proprioception contributes internal information concerning the movements of the body (Gibson, 1966). In the absence of vision, and consequent reliance upon proprioception, task performance has been reported to decrease (Sugden, 1990), thereby highlighting greater efficiency when the two systems interact.

Theoretical approaches to the question of how skilled action develops can be categorised broadly in terms of maturational theory (where development of skilled action is a consequence of unfolding structures in the nervous system; e.g., Gesell, 1946), information-processing theory (where action is viewed as taking place in discrete hierarchical stages, see Figure 1; e.g., Connolly, 1970) and the dynamic systems approach. In this latter account behaviour is described as arising from the interaction of multiple systems including the central and peripheral nervous systems, muscle-, joint- and limb systems, as well as external forces such as gravity and perceptual information, e.g., optic flow. According to this framework, motor skill development is an <u>emergent</u> process, where motor behaviour is <u>self-organised</u> rather than prescribed (see Smith & Thelen, 2003 for a review).

[Insert figure 1 about here]

<u>Developmental coordination disorder</u>

The development of motor coordination occurs gradually from birth but what happens in cases where this development does not occur in the typical manner? One example is seen in the condition 'developmental coordination disorder' (DCD). This condition has been recognised officially as a clinical entity only since the publication of the 3rd edition of the Diagnostic and Statistical Manual of the American Psychiatric Association in 1987. DCD is a neurodevelopmental disorder defined in terms of a child experiencing movement difficulties out of proportion with general development and in the absence of any medical condition (e.g., cerebral palsy) or identifiable neurological disease. For a diagnosis to be given, movement difficulties must interfere significantly with activities of daily living such as dressing, eating and walking or with academic achievement. An illustration of the level of difficulties experienced by children with DCD is shown in Figures 2-4 which give examples of the handwriting, copying and drawing abilities of children with DCD.

[Insert figures 2-4 about here]

Over the past three decades, a variety of labels have been coined to describe DCD. Descriptive terms such as clumsy child syndrome (Gubbay, 1975) have been used, in addition to terms such as developmental dyspraxia (Denckla, 1984) and specific developmental disorder of motor function (World Health Organisation, 1992). The term dyspraxia is now reasonably well-known by the general public, at least in the United Kingdom, with the national parent support group being known as the Dyspraxia Foundation. However strictly speaking dyspraxia relates to a specific type of motor difficulty. Thus in this chapter the term DCD will be used to refer to the general condition and the term dyspraxia to a specific type of deficit.

Developmental dyspraxia The use of the term ‘developmental dyspraxia’ has its roots in the adult neuropsychological literature and is used developmentally by some as an all-embracing term for movement difficulty. In contrast, others adhere to a strict definition of the term developmental dyspraxia, as it is used to define adult apraxia. Namely a very specific movement difficulty relating to the production of purposeful skilled movements in individuals whose motor effector and somatosensory systems are intact. Following this definition, it is clear that developmental dyspraxia could be one symptom of a DCD syndrome. Much of the literature has focused on whether specific developmental coordination disorders are synonymous with, or separate from dyspraxia (e.g., Dewey, 1995; Missiuna & Polatajko, 1995; Miyahara & Möbs, 1995), with no definite consensus emerging.

One particular problem has been the lack of an official operational definition of developmental dyspraxia in the literature. Dewey (1995) has attempted to provide such a definition that would distinguish developmental dyspraxia clearly from developmental disorders of motor function and control. She proposed that developmental dyspraxia should be defined as a disorder of gestural performance affecting both familiar and unfamiliar action sequences in children whose basic motor effector and somatosensory systems are intact. Dewey’s definition of developmental dyspraxia allows both for subtypes of gestural disorders to be identified and for different underlying mechanisms to cause these subtypes of the disorder. experimental studies of dyspraxia have provided some understanding of a subset of the motor coordination difficulties of those with DCD.

Experimental studies of dyspraxia Traditional tests of apraxia, and thus of dyspraxia, look at the production of meaningful (or representational) vs. meaningless gestures. A representational gestures task requires that the participant demonstrate familiar actions. These can be either transitive (requiring the use of an object, such as combing the hair with a comb, cutting paper with scissors) or intransitive (movements that do not require an object, such as salute, hitchhike, make a fist). Actions can be elicited in different response conditions, the predominant ones being to verbal command, imitation and using the object itself. In the verbal command condition, the participant is asked to demonstrate an action, which in the case of the transitive condition is done in the absence of the actual object. In the imitation condition, the experimenter mimes the action (again, in the absence of the object in the transitive condition), and the participant is required to copy this exactly. A typical performance profile sees transitive gestures performed more poorly than intransitive gestures, and all gestures performed more poorly to verbal command than to imitation. Most superior performance is seen, predictably, when demonstrating an action using the required object.

One argument is that poor performance on a representational gestures test in patients could arise from a comprehension deficit. To assess gesture production independently of this, participants can be asked to imitate meaningless (unfamiliar) single hand postures and sequences of these postures. Such a task has the advantage of using gestures that cannot be ascribed a verbal label, thereby removing an explanation of poor performance in terms of a comprehension deficit rather than a movement difficulty. Thus, a comprehensive apraxic battery allows a number of effects to be considered, including the effect of input modality (verbal command vs. imitation), movement complexity (single posture vs. sequence), type of limb gesture (transitive vs. intransitive), representational nature of gestures (meaningful vs. meaningless), and gesture performance vs. actual object use. Examples of these are shown in Table 1.

[Insert table 1 about here]

A small number of studies have investigated praxis errors in tests of meaningful gestures in typically developing children. The quantitative pattern of performance on tests of representational gestures seen in adults, with transitive gestures performed more poorly than intransitive gestures and gestures to verbal command more poorly than to imitation, is also observed in healthy children (Kools & Tweedie, 1975; Overton & Jackson, 1973). Age-related changes have been reported in the qualitative nature of the responses produced by children when completing a task of representational gestures (Kaplan, 1968). Thus accurate performance on a task of representational gestures has been shown to increase with age in typically developing children.

Children with DCD and developmental motor deficits perform significantly more poorly than their typically developing peers on tasks of representational gestures but show the same hierarchy of performance difficulty; namely, transitive gestures are performed more poorly than intransitive actions, and gestures to verbal command more poorly than to imitation (Dewey, 1993; Dewey & Kaplan, 1992; Hill, 1998). This pattern of performance has also been reported in those with sensorimotor dysfunction (Dewey, 1991), specific language impairment (Hill, 1998) and learning disabilities (Cermak, Coster & Drake, 1980), and is true in both quantitative and qualitative analysis of task performance (Hill, Bishop & Nimmo-Smith, 1998).

To complete the assessment of dyspraxia in DCD, Hill (1998) assessed the production of single and multiple meaningless posutres in children with DCD. These children had no difficulty copying single hand postures such as those shown in Figure 5 in relation to their typically developing peers, although in some instances they were significantly slower to produce an accurate posture. Furthermore, these same children showed no difficulty in the copying of short, meaningless hand sequences, although Dewey and Kaplan (1992) reported that their sample of children with DCD did have difficulty copying meaningless hand sequences, in comparison to their typically developing peers. Zoia, Pelamatti, Cuttini, Casotto and Scabar (2002) assessed limb gesture performance using a variety of input modalities (imitation, visual+tactile, visual, verbal) in a group of children with DCD in relation to typically developing children aged 5-6, 7-8 and 9-10 years. The performance of the children with DCD in relation to typically developing children throughout the four input modalities was suggestive of a maturational delay, with the difference increasing with age. This finding is supported by Hill's (1998) study in which a younger control group – who acted as a motor match for the DCD group – was included as well as an age matched control group. Taken together, these studies indicate that developmental dyspraxia – a difficulty in the production of gestures – is a component of the symptomatology seen in DCD.

[Insert Figure 5 about here]

Cognitive explanations of DCD

Various hypotheses have been suggested in an attempt to identify the underlying mechanism(s) whose impairment contributes to DCD. A brief overview of the main approaches is presented below. This covers descriptive approaches, explanations of DCD in terms of motor programming ability and perceptual accounts of DCD. It should be noted that most of the published research has investigated children, rather than adults, with DCD, hence the use of the term 'children' to refer to research participants. This does not by any means deny the longitudinal nature of the disorder (Losse, Henderson, Elliman, Hall, Knight & Jongmans, 1991; Cantell, Smyth & Ahonen, 1994). Furthermore, it stresses the need for adult studies investigating the cognitive causes of DCD.

Descriptive studies of DCD In this area of research functional everyday tasks with which the child with DCD has difficulty (e.g., buttoning; Barnett & Henderson, 1994) are investigated systematically. Such work can highlight the precise output problems that such children experience daily with a specified task. Barnett and Henderson (1992), for example, investigated drawing ability in children with DCD, finding that the more uncoordinated a child was, the poorer their drawing ability. Whereas drawing skill tended to remain stable or improve in well-coordinated children, it fell further behind chronological age norms with time in those with DCD.

The findings of descriptive research can help to increase awareness of the actual output difficulties of the child with DCD, as well as to help teachers and other professionals to identify children with DCD who have not yet been diagnosed officially. Thus while the descriptive approach cannot tell us why DCD occurs or how it is mediated, it can point to the problems encountered by the child with DCD and raise awareness of their difficulties.

Motor programming explanations of DCD A second research approach investigates the problems of children with DCD using chronometric techniques such as aiming, interception and tracking tasks. Much of this work focuses on: (i) the preparation and organisation of motor responses, and (ii) timing control as studied through tapping tasks.

Response Selection In a simple reaction time aiming task, children with DCD have been found to have significantly prolonged movement latency and movement duration, as well as increased variability of these compared to age-matched controls (Henderson, Rose & Henderson, 1992). Performance on the Test of Motor Impairment (TOMI; Stott, Moyes & Henderson, 1984) was a powerful indicator of movement duration, suggesting that the greater the degree of impairment shown by a child with DCD, the longer the time taken to complete a movement.

By evaluating their reaction time data with reference to that of typical adults and patients with Parkinson's Disease, Henderson et al. suggested that the prolonged response latencies seen in children with DCD reflect problems in the search for and retrieval of stimulus-response (S-R) mapping from working memory, but only when there is little S-R compatibility along with responses that are demanding to produce. This compatibility effect may therefore be an indicator of general resource depletion in the planning and control of action, rather than a direct reflection of a specific processing deficit underlying poor coordination.

Henderson et al. (1992) also presented the same children with a 'coincidence timing' task in which a series of auditory tones were presented at regular intervals and children were required to synchronise the arrival of their finger at a target with the presentation of the fifth tone. In this task, absolute timing error was found to be significantly greater in the children with DCD. Increasing the time between each tone presented in the countdown resulted in equally poor performance for children in both the DCD and control groups, suggesting that the problems of children with DCD arise from an inability to generate responses with reliable timing rather than to a poor cognitive process of time estimation. This finding lends support to the suggestion that a general deficit in planning and action control influences the behaviour of children with DCD.

In a number of studies, researchers in The Netherlands have investigated the perceptual anticipation of children with DCD and age-matched controls through the medium of choice reaction time tasks (e.g., Geuze & Van Dellen, 1990; Van Dellen & Geuze, 1988). Perceptual anticipation is measured as a decrease in reaction time when children have received a precue indicating to which target they will be expected to move. While children with DCD had significantly slower reaction and movement times, along with increased variability on these tasks, these children profited from precuing in the same way as their typically developing peers. This finding may indicate that children with DCD have more problems translating a stimulus code into a response code when this translation requires more transformations (Van Dellen & Geuze, 1988). Following this account, response selection is a cognitive decision process that is likely to be involved in any adequate explanation of perceptual-motor deficits. It is suggested that an impairment in the cognitive decision process of response selection may, at least in part, contribute to the slow performance of children with DCD on these tasks. However, in a follow-up to the Van Dellen and Geuze (1988) response selection study, Geuze & Börger (1994) found that although 50-70% of the 12-year-olds with DCD studied five years previously (those reported in 1988) were still performing poorly on the TOMI, the differences of response selection between the children with DCD and their typically developing peers had disappeared. Thus the role of response selection in DCD remains unclear.

These simple and choice reaction time studies suggest that it is a central deficit in the planning and control of action, rather than a specific processing deficit, that contributes to the poor coordination of the child with DCD. Such findings are consistent with studies adopting the descriptive approach which have revealed that slowness is a major characteristic of the performance of children with DCD on everyday tasks such as drawing (Barnett & Henderson, 1992) and buttoning (Barnett & Henderson, 1994).

Timing Control Studies of timing control have investigated movement coordination by considering the stability of the intervals between taps when required to tap regularly. If a lack of ability to adapt to specific constraints is found in children with DCD when tapping, this may point to nonoptimal functioning of the central nervous system in these children. Williams, Woollacott and Ivry (1992) investigated timing control in children with DCD on a tapping continuation task (children were required to tap in time with a tone and to continue tapping once the tone had ceased). The Wing-Kristofferson model of repetitive movements (Wing & Kristofferson, 1973) was used to identify the locus of the timing control difficulties seen in the children with DCD.

The Wing-Kristofferson model is a linear model that looks at the nature of the representation of a movement sequence by focusing on order errors in the execution of sequences during regular tapping tasks. When tapping out regular sequences using one finger, the variability of interresponse intervals (the length of time between consecutive taps) can be measured. Two sources may be responsible for the variability of interresponse intervals, the first being a timekeeper process which triggers the response at the required interval, and the second a motor delay, the mechanism that intervenes between the trigger and the response. This two-component model predicts that successive interresponse intervals will be negatively correlated: If an interresponse interval is longer than the average, this will be followed by one shorter than the average more often than would be predicted purely by chance. Research has shown that the timekeeper process and motor delay are independent, suggesting that these two mechanisms have distinct physiological representations (Wing, Keele & Margolin, 1984).

Applying the Wing-Kristofferson model to their data, Williams et al. (1992) found that children with DCD had significant difficulty with timing control when compared to their well coordinated peers. Variability in the timed, rhythmic responses of those in the DCD group could, for the most part, be explained by the Wing-Kristofferson model in terms of a problem in the central timing mechanism (the timekeeper process) rather than in a peripheral mechanism involved in response implementation (the motor delay component). This finding ties in with that of the continuation tapping task reported by Henderson et al. (1992) as well as with other studies of continuous tapping in DCD (e.g., Geuze & Kalverboer, 1987; 1994; Hill & Wing 1999).

Overall the findings of tapping studies point to evidence for a general timing difficulty in children with DCD. The consequences of this for everyday activities and learning are not difficult to imagine.

The evidence from timing control studies relates also to the reaction time literature. Both sets of findings suggest that some kind of central planning deficit is related to DCD, rather than a problem arising at the peripheral level of response implementation. If this is the case then the difficulties of a child with DCD could lie in organising certain timing dimensions of central motor programs. A likely source of such central timekeeping problems could be the cerebellum. Indeed, some evidence for at least a subgroup of DCD showing cerebellar-type difficulties has been postulated by Lundy-Ekman, Ivry, Keele and Woollacott (1991).

If it is the case that impairment in a central timing mechanism contributes to the problems of children with DCD, then this would have consequences for learning: If you are unable to map successfully the temporal aspects of a task onto its spatial component when catching a ball, for example, then inaccurate feedback will be incorporated into the existing schema for ball catching. Inevitably, this would impair the ability to make appropriate adaptations to the task and performance would never be improved adequately. Timing is an intrinsic component of any everyday task, thus an explanation of DCD in terms of a deficit in a central timekeeping component of the motor system may be a valid one. Future work needs to investigate further the underlying temporal components of functional everyday tasks in naturalistic settings (see Barnett & Henderson, 1994 for a study which does this). Such an approach can provide an indication of the extent of the temporal dysfunction that the child with DCD faces on a daily basis in activities of daily living and academic tasks.

Microscopic movement planning A further approach to understanding the nature of difficulties in the planning and organisation of movement in DCD comes from studies investigating the coordination of the timing of microscopic aspects of movement such as the coordination of the start or end of a movement with grip force (the amount of squeeze exerted by the fingers when holding and moving an object). When adults hold an object while making vertical movements there are differences in the coordination of grip force with movement onset (see Figure 6). Specifically, when making upward movements adults increase their grip force at the onset of movement (in the acceleration phase). In contrast, when making downard movements adults increase their grip force only towards the end of the movement (in the deceleration phase). These differing patterns of anticipatory grip force adjustments indicate acquired knowledge about environmental effects on movements (Flanagan & Wing, 1993; see Wing 1996 for a review). Arguably this task acts as an analogue for moving a cup to and from the mouth to drink. While there have been no studies charting the developmental course of coordination between grip force and movement phase when making vertical movements with objects, Forssberg and colleagues have documented developing coordination of the grip force and movement onset in infants, children and young adults when simply lifting an object to hold it steady above a table top (Forssberg, Eliasson, Kinoshita, Johansson & Westling, 1991; Forssberg, Kinoshita, Eliasson, Johansson, Westling & Gordon, 1992). They have shown that anticipatory grip force adjustments in lifting an object develop until approximately eight years of age, with some refinement continuing after this point. In two case studies, Hill and Wing (1998, 1999) have investigated how the developmental curve in lifting and making vertical movements while holding an object might be altered in impaired development, and specifically in boys with DCD in comparison to their peers. In their first study, vertical upward and downward movements were made while holding an object, while in the second study different children repeated this task, but also undertook a lifting task, a time production (tapping) task and holding an object subject to unpredictable perturbation (a test of reflexes). By combining performance on this series of tasks, it was possible to postulate the locus of motion planning difficulties seen in DCD. A number of differences were observed between the child with DCD and control child. In the first study, Hill and Wing (1998) showed that a 11-year-old child with DCD increased his grip force earlier when making downward, but not upward, movements in comparison to a typically developing control child. In the second study, the child with DCD showed an earlier rise in grip force when making both upwards and downward movements (Hill & Wing, 1999). This was seen in parallel to greater variability in the timing of voluntary actions in the child with DCD when undertaking the tapping task and longer grip reflexes in the child with DCD in comparison to his typically developing peer. However, no differences were seen between the two children in the coordination of grip force and movement onset when lifting an object to hold it a short distance above the table top. These findings suggest that the difficulty in this particular child with DCD relates to the timing of movement execution. The authors speculate that at least part of the observed deficits might be explained in terms of inaccurate prediction, fitting in with the model of Wolpert, Miall and Kawato (1998) that planning any particular movement involves selecting appropriate feedforward (and inverse) models from a larger set that spans all possible movements. These models will be selected according to context, something that may not be used to an individual’s advantage in those with DCD. Wolpert et al. identify this function with the cerebellum, which ties in with the findings cited by Williams et al. (1992) above. Furthermore, Kooistra, Snijders, Schellekens, Kalverboer and Geuze (1997) have shown that the motor problems of children with congenital hypothyroidism, a condition believed to affect the cerebellum, are likely to be related to peripheral processes associated with motor execution rather than to central cerebellar processes associated with motor timing.

[Insert Figure 6 about here]

In their studies, Hill and Wing showed that two children with DCD experienced certain significant diffficulties in their planning and/or execution of movements at the microscopic level (at a time scale of half a second or less). In the future, clearer understanding of the planning, organisation and execution of children with DCD at the microscopic level of motion may have far-reaching implications for therapeutic training methods to help these children maximise the efficiency of their movements and consequently to minimise the difficulties that they experience with the manipulation of objects in daily living, such as when eating. This detailed approach offers a positive new methodology for investigating the planning and execution of movement in both typical and atypical development although clearly further larger and more detailed studies are essential before the total value of the methodology can be evaluated.

In sum, a number of classic as well as more novel techniques have been used to investigate the movement production problems of childen with DCD. These studies suggest that a crucial deficit exists in the planning and control of action, and that this contributes to poor coordination. Furthermore, children with DCD have significant difficulty with the timing of both individual movements, and sequences of movements, when compared to their well coordinated peers. Taken together, such findings suggest that the difficulties of an individual with DCD could lie in the organisation of certain timing dimensions of movement, with the cerebellum being a possible source of such problems.

Perceptual Explanations A third approach to the understanding of DCD has focused on the links between problems of perception and impairment of movement in an attempt to identify the specific information-processing deficits that might underlie the movement problems seen in the individual with DCD. In particular, specific deficits of visual and kinaesthetic perception have been suggested.

Visual Perception Adequate visual-perceptual input is crucial for accurate skilled movement. Visual perception is important so that distance and spatial relationships are perceived correctly and movements are guided accurately. Charles Hulme and his colleagues have considered the issue of a deficit of visual-perceptual processing in children with DCD in order to assess the role that perceptual impairments may play in the difficulties of those with DCD. If it is the case that children with DCD cannot perceive a situation accurately, then their movement plan and its execution will be based on 'misinformation'. Indeed, the work of

Hulme and his colleagues has shown evidence of wide-ranging deficits in the perceptual processing of visuospatial information in children with DCD.

Hulme and his colleagues (Hulme, Biggerstaff, Moran & McKinlay, 1982; Hulme, Smart & Moran, 1982) based their research on the premise that there are three distinct perceptual systems which must each function appropriately before successful interaction can occur between the systems. Specifically, these three systems are: (i) a visual-perceptual system, (ii) a kinaesthetic-perceptual system, and (iii) an inter-sensory system linking vision and kinaesthesis[1]. Hulme, Biggerstaff et al. (1982) showed that children with DCD had significantly poorer visual and kinaesthetic perception than their typically developing peers when children were required to match the length of lines presented successively both within and between the visual (V) and kinaesthetic (K) modalities. Line matching occurred in four conditions: V-V, K-K, V-K, K-V. In the visual modality the child saw a line, while in the kinaesthetic modality the child felt the length of a rod. The initial stimulus was then removed from vision/touch prior to matching. Motor skill correlated significantly with accuracy of line length matching in the visual, but not in the kinaesthetic only or cross-modality matching conditions. This finding suggested that difficulties in the visual perception of distance and spatial relationships may be an important determinant of the poor motor coordination experienced by children with DCD. Alteratively visual-perceptual deficits and motor performance may be linked because they depend upon the same cause, rather than being linked directly themselves.

Before proceeding with further details of later studies conducted by Hulme and his colleagues, it is necessary to draw attention to two issues arising from the study described above. First, the experimental design fails to rule out the possibility of a memory impairment leading to the observed performance, though this explanation has been eliminated by a later study in which children were required to match lines presented simultaneously (Hulme, Smart & Moran, 1982). In addition, visual acuity difficulties were not investigated in the Hulme, Biggerstaff, Moran and McKinlay (1982) study, though again these were ruled out in a later study (Lord & Hulme, 1987b), as well as by Mon-Williams, Pascal and Wann (1994) and Mon-Williams, Mackie, McCulloch and Pascal (1996) using a different paradigm.

In a later study, Lord and Hulme (1987b) examined the range of the visual-spatial perception deficits that had been reported previously in children with DCD. In this study size constancy judgments, visual discrimination of shape, area and slope were made by children with DCD and their typically developing controls to visually presented stimuli. Children with DCD performed significantly worse than controls on all but the shape discrimination measure. As a result, Lord and Hulme proposed that visuospatial deficits

[1] Kinaesthesis provides us with information concerning our body schema through internal information.

contribute to serious problems of motor control. They place this deficit within an information-processing framework of motor control suggesting that visual-perceptual ability is involved in most motor skills and that dysfunction at this level of the motor control hierarchy has a knock-on effect: If initial perceptual input is poor then accurate decision making about movement cannot occur. Furthermore a visuospatial deficit is likely to decrease the chances of error detection and correction during a motor activity, leading to inefficient or inaccurate output being executed.

In a study that focused on how children with abnormalities in motor development remember movements, Skorji and McKenzie (1997) reported that the memory of children with DCD when imitating movements modelled by the experimenter was more dependent upon visuospatial rehearsal than the memory of typically developing children, providing further evidence for the involvement of a visuospatial impairment in DCD. Inevitably the process between visual-perceptual input and motor output is a complex one, making it difficult to untangle the exact level at which the system breaks down.

The probable complexity of the route between visual-perceptual input and motor effector output is highlighted further in a study by Lord and Hulme (1988). In this study, the role of visual-perceptual ability in drawing was assessed in relation to the issue of whether a visual-perceptual deficit is the cause of DCD. Children with DCD and controls completed tasks of visual discrimination (identifying two stimuli as ‘same’ or ‘different’), tracing and drawing with and without vision. Visual-perceptual ability correlated with drawing ability *only* in the DCD group, a finding which the authors explained in terms of visual-perceptual function influencing motor performance only if the former skill is poor, hence the significant correlation between visual-perceptual and drawing abilities in the DCD, but not the control children.

To summarise the work on visual-perceptual ability and its relation to motor output in children with DCD, the findings are difficult to interpret convincingly, perhaps owing to the probable complexity of the processing stages occurring between the visual-perceptual modality and motor output assessed in these studies. In a recent meta-analysis to identify information processing factors that characterise DCD, Wilson and McKenzie (1998) analysed 50 studies, reporting that the greatest observed deficit was in visual-spatial processing, irrespective of whether or not tasks involved a motor component. It is also possible that the problems of children with DCD may arise from an abstract problem of understanding spatial coordinates, which is not tied to any one modality. This would lead to problems with visuospatial tasks, although the problem is not actually in the visual system, it is equally present in other sensory systems, e.g., tactile or vestibular. A valuable focus for future research will be to consider cross sensory interactions in individuals with DCD.

Kinaesthetic Perception An alternative perceptual explanation of the difficulties experienced by children with DCD has focused on kinaesthetic sensitivity. Like vision, kinaesthetic perception (our sense of position in space and movement of the body and limbs) is a crucial source of movement activity[2]. Imagine yourself catching a ball. An important aspect of this task is an appreciation of the fact that the environment is constantly changing as the ball moves closer to you. Movements of the eyes, head, arms and hands must be coordinated and synchronised with the movement of the ball, if it is to be caught. To be successful at this task it is critical that you have an intact and accurate sense of kinaesthesis. If this is inadequate or nonexistent then you will fail the task, the ball will be missed and, doubtless, you will experience a certain degree of embarrassment.

We do not tackle the task of catching a ball as a novice each time that we come back to it. In fact, preparation for catching is essential. We learn quickly that we can anticipate the stance and position that we must adopt in advance of the ball arriving into our hands. An experienced catcher will take up this position for both body and hands before the ball has been thrown, adapting these once the trajectory of the ball becomes evident. This latter task requires an understanding of time and space so that the eye can be coordinated with the trajectory of the ball. The catcher must be sensitive to time in order that the hands will be opened, not only in the right part of space, but also at the right moment in order to catch the ball accurately.

We can see that a task such as catching a ball seems fairly simple to a person with intact kinaesthetic perception (provided conditions such as the size or visibility of the ball are adequate), but that it may be a task of extreme difficulty for somebody who has a deficit of kinaesthetic perception: Such an individual would have great difficulty predicting where to place their hands in order to catch the ball successfully.

Kinaesthesis is an internal source of information, being compiled from information collated from the four classes of kinaesthetic receptors (joint receptors, tendon organs, muscle spindles and skin receptors). This process produces a global perception of movement and position by indicating the relative position of body parts and by providing sensory information about the extent, direction, speed and force of movements. Consequently kinaesthesis is involved in the efficient acquisition and performance of motor skills (Laszlo & Bairstow, 1983). DCD may, then, be related to a deficit in the kinaesthetic receptors or in the processing of

[2] One point of difference between some researchers is the use of the words 'kinaesthesis' and 'proprioception'. Strictly speaking, proprioception is a broader term used to cover all sensory systems involved in providing information about position, location, orientation and movement of the body and its parts. Certain authors use the two terms somewhat interchangeably. In the current paper the term kinaesthesis is preferred, but where authors have used the term proprioception, their definition of the term will be described.

information from these receptors. This could give rise to the motor difficulties of children with DCD since they may be basing their movements on inaccurate cues, leading to less accurate motor plans being formulated, muscles being activated inappropriately and inaccurate feedback being provided. Inevitably this becomes a circular problem with poor motor input leading to inaccurate feedback and vice versa.

Judith Laszlo and her colleagues have investigated their suggestion of a deficit of kinaesthetic perception through the development of their ‘Kinaesthetic Sensitivity Test’ (KST; Laszlo & Bairstow, 1985). The KST is divided into two parts; the first, a test of kinaesthetic acuity and the second a test of kinaesthetic perception and memory. The equipment for the Kinaesthetic Acuity Test is placed on a tabletop in front of the child and involves two ramps, which can be positioned at angles from the horizontal. On each ramp is a peg which can be slid up and down the ramp. A masking box is placed over the equipment. Each trial proceeds in the following way: The slope of each ramp is altered, with the slopes of the two ramps differing for each trial, ensuring that one slope is steeper (termed ‘higher’ in the test instructions) than the other. Children place a hand on each peg (under the masking box). The experimenter moves a child’s hands simultaneously up the ramps and down again, after which the child indicates which hand was ‘higher’. Thus the child is required to discriminate the heights of two inclined runways and the test is described as measuring the ability to discriminate limb position following passive movement, something which Laszlo and Bairstow claim to be dependent upon kinaesthetic sensitivity.

The test of Kinaesthetic Perception and Memory is a pattern representation task, in which a child must restore a displayed pattern to the orientation the pattern had when previously traced. Children’s hands are guided (in the absence of vision) around an arbitrary shape, after which the experimenter alters the orientation of that shape. Vision is restored to the child who must then return the shape it its original configuration. Thus, the child must integrate kinaesthetic and visual information (a cross-modal task) in order to complete the task correctly, a requirement that makes the test of kinaesthetic perception and memory a test of higher kinaesthetic processes. For both the tests of Kinaesthetic Acuity and of Kinaesthetic Perception and Memory, Laszlo and Bairstow (1985) provide normative data derived from the study of British and Australian children as well as of Australian and Canadian adults. Performance improves with age with children aged 12 years performing approximately similarly to adults on Kinaesthetic Acuity. On the Kinaesthetic Perception and Memory test the performance of children aged 12 years is superior to that of younger children but substantially poorer than that of the adult normative sample. Laszlo, Bairstow, Bartrip and Rolfe (1988) reported that children with DCD perform worse than their typically developing peers on both tests.

Unfortunately, while the results of Laszlo's work with the KST have been replicated at least partially (see Piek & Coleman-Carman, 1995), many others have failed to find significant difficulties on either part of the KST (Hoare & Larkin, 1991; Lord & Hulme, 1987a). Using this particular kinaesthetic test, it is therefore difficult to ascertain whether a difficulty with kinaesthetic perception is related to DCD. As Wann (1991) has argued, there are certain flaws present in many tests claiming to measure kinaesthesis, for example, most are based around a series of static judgements and therefore measure proprioception rather than kinaesthesis, many impose a memory load, and those where the limbs are not placed in matched orientations measure the egocentric mapping of proprioceptive cues, rather than proprioceptive sensitivity per se. However, some form of kinaesthetic deficit may account for the uncomfortable and inefficient postures and actions generally adopted by children with DCD, who may not be able to 'feel' that a posture is awkward (because of some dysfunction in the kinaesthetic system; Cantell, Smyth & Ahonen, 1994; Hill, 1998; Smyth & Mason, 1997; 1998). It is a possibility of course that a posture which looks and would be uncomfortable for the motorically unimpaired person does not feel uncomfortable to an individual with DCD.

A number of researchers have attempted to investigate the issue of a kinaesthetic deficit in DCD in other ways. T.R. Smyth has conducted a series of studies using chronometric techniques in order to investigate the visual and kinaesthetic processing of children with DCD. In a reaction time study which investigated the processing of visual and kinaesthetic information, Smyth and Glencross (1986) found that abnormal coordination was associated with difficulty processing kinaesthetic but not visual information, providing evidence for a specific deficit in DCD. Later studies in the same series have also identified a kinaesthetic deficit in DCD (T.R. Smyth, 1994; T.R. Smyth, 1996). In addition, these two studies manipulated the experimental set-up further in order to investigate the nature of the kinaesthetic deficit. The results of these simple and choice reaction time tasks provided evidence to suggest that abnormal motor coordination was not the result of poor motor programming (T.R. Smyth, 1994). A possible explanation lies in a difficulty in the cross-modal translation of information (T.R. Smyth, 1996), a finding supported by Piek and Coleman-Carman (1995) who reported that Laszlo and Bairstow's test of Kinaesthetic Acuity discriminated between children with DCD and controls only when administered actively, and not when administered passively as stated in the test manual.

Further evidence of a kinaesthetic, or proprioceptive deficit in DCD has come from studies adopting a target location and pointing task reported initially by von Hofsten and Rösblad (1988). These authors use the term proprioception to mean information about the body obtained from receptors located most noticeably in the joints, muscles and tendons. This test assesses the use of visual, proprioceptive and visual+proprioceptive information. The child sits at a table, on which is placed a circle made of a number of points marked with pins. The task is to place a pin under the table at the correct point which 'matches' the location of a specified pin on the tabletop. In this way proprioception is measured as the ability to use information obtained through touch. The child either sees (intramodal), feels (intermodal) or sees and feels the pin on the tabletop before sticking a pin under the table in the corresponding location. Studies by Smyth and Mason (1998) and Sigmundsson and colleagues (e.g., Sigmundsson, 1999; Sigmundsson, Ingvaldsen & Whiting, 1997) have shown that children with DCD perform more poorly in terms of absolute error on both inter- and intra-modal matching. In the case of the Sigmundsson studies this result was explained as arising from the particularly poor performance of the children with DCD when performing with the nonpreferred hand. Smyth and Mason focused more on a comparison between the matching conditions, reporting that when the conditions were analysed together, performance in the proprioceptive-only condition was significantly worse than that observed in the visual and visual-proprioceptive conditions, which themselves were not different from one another. This result, like those reported in the series of studies by T.R. Smyth suggest that it is when kinaesthetic (or proprioceptive) processing is required in isolation from visual processing that performance difficulties in this domain occur for children with DCD. Mon-Williams, Wann and Pascal (1999) conducted a series of cross-modal matching tasks, finding that the particular difficulty of those with DCD was in making cross-modal judgements that required the use of visual information to guide proprioceptive judgements of limb position, providing further evidence that proprioceptive skill may be a problem for those with DCD.

To summarise, although it does seem that there is at least some kind of kinaesthetic processing difficulty in DCD, no clear picture has transpired. Taking the studies together, the only clear point that emerges is summarised neatly by Hoare and Larkin (1991) who state that kinaesthesis is a "...global, multi-modal construct, and task specifics may dictate many of the relationships between this and motor ability in both clumsy and normal children..." (Hoare & Larkin, 1991, p. 677). It is clear that more detailed, theory-driven experimental manipulations are needed before reliable conclusions can be drawn.

Evaluation of Perceptual Explanations Unfortunately neither the visual-perceptual or the kinaesthetic explanations of DCD have withstood fully the test of time. Replication of both the work of Charles Hulme and particularly of Judith Laszlo has failed frequently to repeat their results (e.g., Barnett & Henderson, 1992; Henderson, Barnett & Henderson, 1994; Hoare & Larkin, 1991). Owing to the diverse methodologies adopted in the visual and kinaesthetic literatures, it would be useful in a future study to assess the effect of visual vs. kinaesthetic training in an intervention study, to investigate whether training in one modality has a beneficial effect compared to the other. Laszlo's kinaesthetic training could be given to one group, while another could be given visual-perceptual training, using a visual spot-the-difference task, for example.

It is unlikely that either a visual or kinaesthetic deficit is the single contributing factor to DCD. An alternative explanation is that the sensory systems (e.g., visual, vestibular, kinaesthetic) may be interlinked in order to provide us with accurate spatial information, and that without each component of the system being intact, the system cannot operate accurately (Henderson, 1993).

Summary

Undoubtedly children with DCD experience significant difficulties with fine and gross motor control, the planning and execution of movement and visuospatial skill. Unfortunately the question of why children with movement difficulties have such problems remains unanswered. One drawback of the research to date is that it assumes that the functional architecture of the motor system is invariant across typically developing children and those with DCD. It would seem more likely that this is not the case, owing to the possible abnormality of processes such as visual-perceptual development from birth. This would have long-term consequences for motor development. Such a deficit would have implications for development from infancy onwards because acquisition of function must depend at least in part on the adequate development of skills which have developed earlier in the developmental process. In this case, poor perceptual-motor skills may be related to mild perceptual-motor dysfunction early in development which has interfered with the development of more complex motor skills. If this is the case, the relationship between perceptual-motor difficulty and DCD may arise not only from impaired perceptual-motor difficulty at the time of assessment, but also from the impaired acquisition of perceptual-motor skills during development. Furthermore, little research has been conducted investigating aspects of postural control in those with DCD (see Johnston, Burns, Brauer & Richardson, 2002, for an exception).

Considering the prevalence of motor difficulties in a range of developmental disorders, with estimates of DCD alone ranging from 6% to 10% (American Psychiatric Association, 1994 and World Health Organisation, 1992 respectively), it is imperative that further understanding of the motor difficulties seen in these disorders must be obtained. The greatest challenge and avenue for progression in understanding DCD will be to identify and develop a theoretical and functional cognitive framework. Causal modelling of the links between behaviour, cognition and biology (cf. Morton, 2004) will be invaluable to this end (see Figure 7). Without such a framework, intervention studies and practical day-to-day management of DCD will continue to be variable in its success and the problems of self-esteem will continue to be felt more fully than is optimal. Despite the difficulties associated with the investigation of motor skill development, the development of such an understanding must not be ignored.

[Insert figure 7 about here]

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FIGURE LEGENDS

Figure 1. Basic diagram of Roy's (1983) model of the action system (adapted from Roy & Square, 1985, p. 113). In this model, the developed action system plans and controls actions through two interacting functional systems, the conceptual and production systems. The conceptual system integrates incoming sensory information about task context with a stored knowledge base for action which may include knowledge about the properties of an object as well as of task-specific actions. The conceptual system provides an abstract representation of action. The production system uses information from the conceptual system to develop or access a set of production rules that will help to guide limbs in time and space. Generalised action programs are integrated with the necessary perceptual-motor processes for organising and executing actions, actions which are acted out through muscular activity. According to this model, action production is dependent upon first having a conceptual representation of an action.

Figure 2 Example of the free handwriting of a 10-year-old child with DCD.

Figure 3 Example of a passage copied by a 10-year-old child with DCD.

Figure 4 Example of the drawing of a 10-year-old child with DCD (Fig.1a) vs. other typically developing 10-year-old children (Figs. 1b and 1c).

Figure 5 Examples of the meaningless single hand postures used by Hill (1998). Hand postures were taken from Kimura & Archibald (1974).

Figure 6a Moving an object: participants move the force transducer up or down using a precision grip, as shown (redrawn from Wing, 1996).

Figure 6b Example of an upward and downward movement trace showing the coordination between onset of grip force increase and movement onset/end.

Figure 7 Illustration of the causal modelling approach.

Table 1

Examples of tests used to assess apraxia, showing a breakdown of task components including movement complexity (single posture vs. sequences), type of limb gestures (transitive vs. intransitive) and the representational nature of gestures (meaningful vs. meaningless). The transitive and intransitive pantomimed gestures can be performed both to verbal command and imitation

Type of Apraxia Test	Example
MEANINGFUL MOVEMENTS:	
Transitive Gestures:	
Action with single object	Comb hair, stir coffee with spoon, saw wood.
Action with multiple objects	Make tea or toast, bake cake, look up a number in phone book and dial it.
Simple pantomimes	Mime brushing teeth with toothbrush, or cutting paper with scissors.
Complex, narrative pantomimes	Mime act of making a cup of tea, or writing letter and posting it.
Intransitive Gestures:	
Symbolic gestures	Blow a kiss, hitchhike, cross fingers for good luck.
Natural, expressive gestures	Wave goodbye, indicate anger towards somebody.
MEANINGLESS MOVEMENTS:	
Single movements	For examples see Figure 5

Sequences	Close fist, thump sideways on table; fingers and thumb extended, but closed on table-top. Back of hand slaps the table across other arm, rotates, palm slaps back at the start position

FIGURE 1

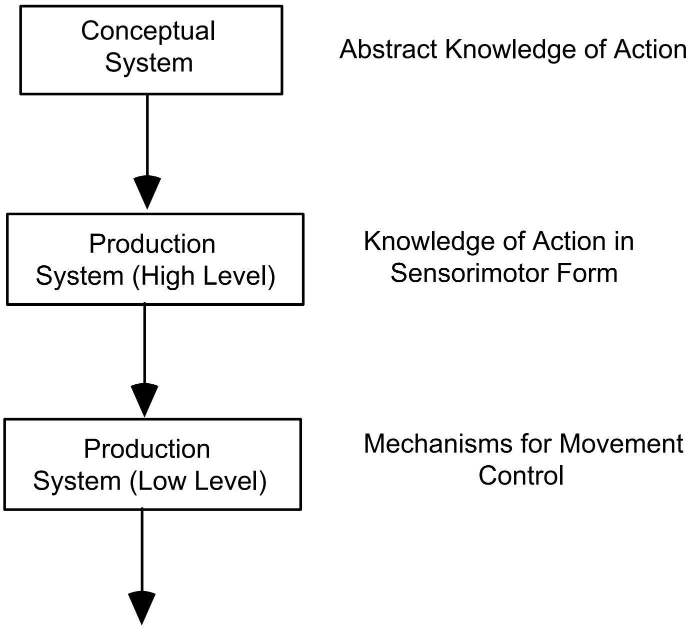

Conceptual System
Abstract Knowledge of Action
Production System (High Level)
Knowledge of Action in Sensorimotor Form
Production System (Low Level)
Mechanisms for Movement Control

FIGURE 2

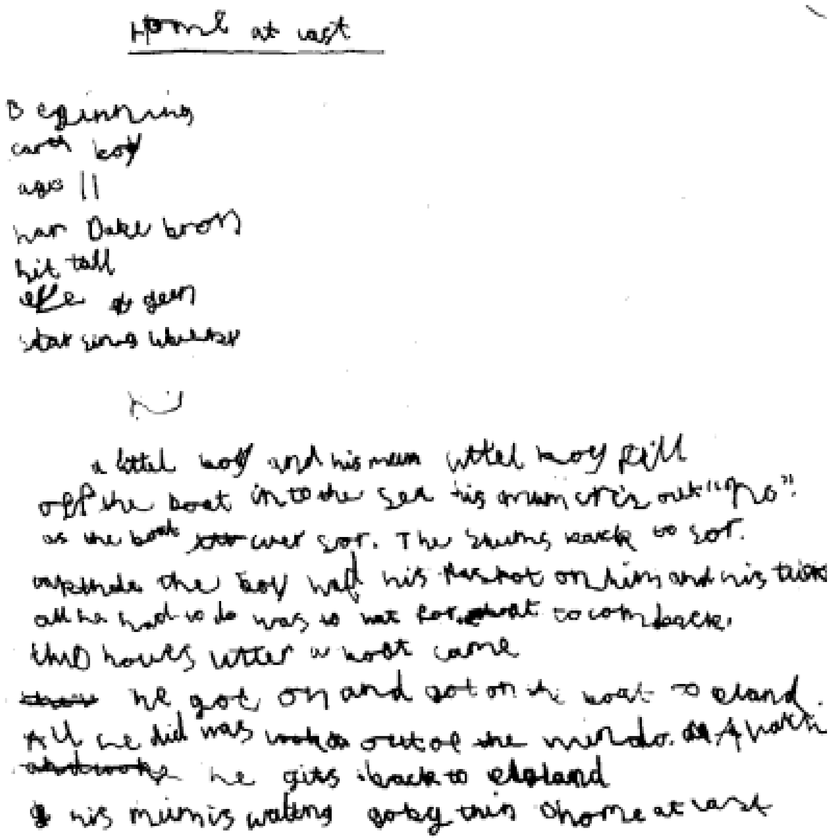

Home at last
Beginning
he got on and got on the boat to eland.
he gits back to england

FIGURE 3

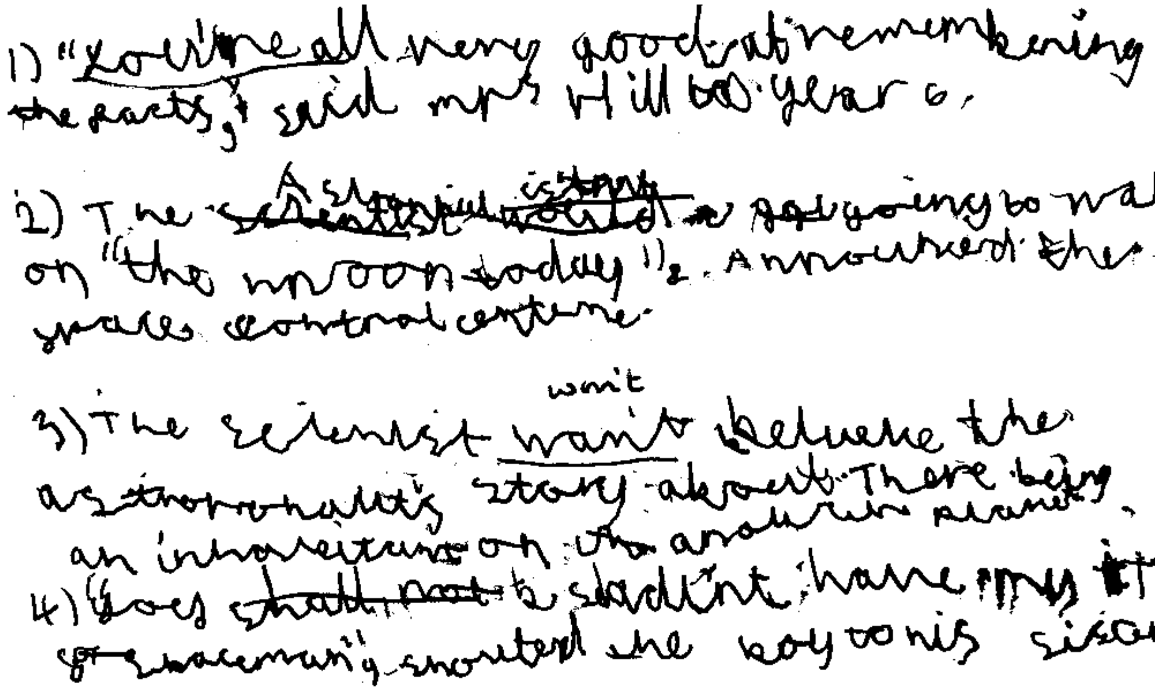
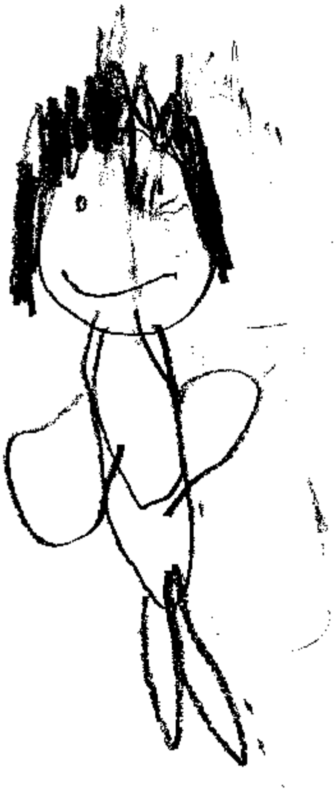


FIGURE 4

(1a)



(1b)

(1c)

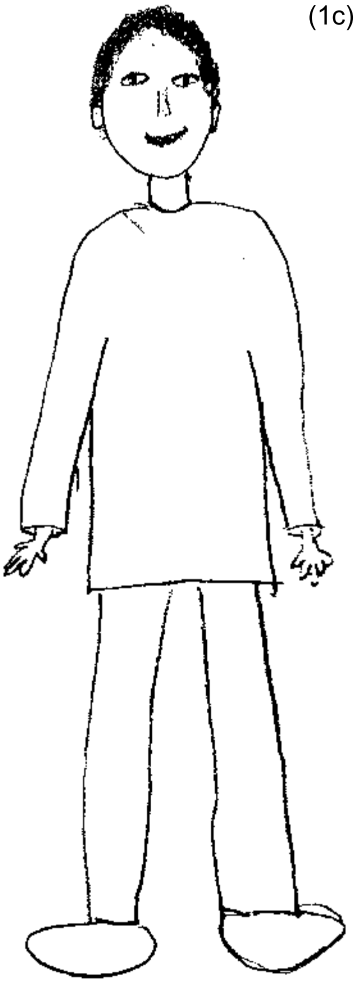


FIGURE 5

FIGURE 6A

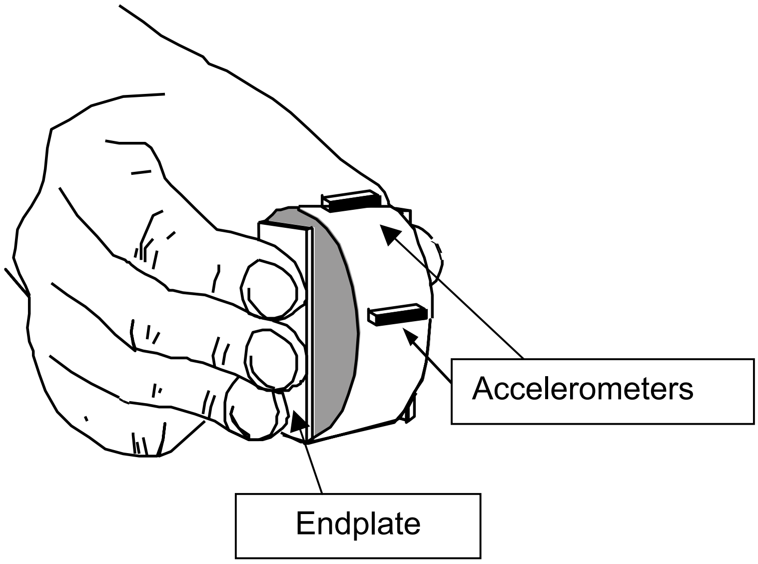
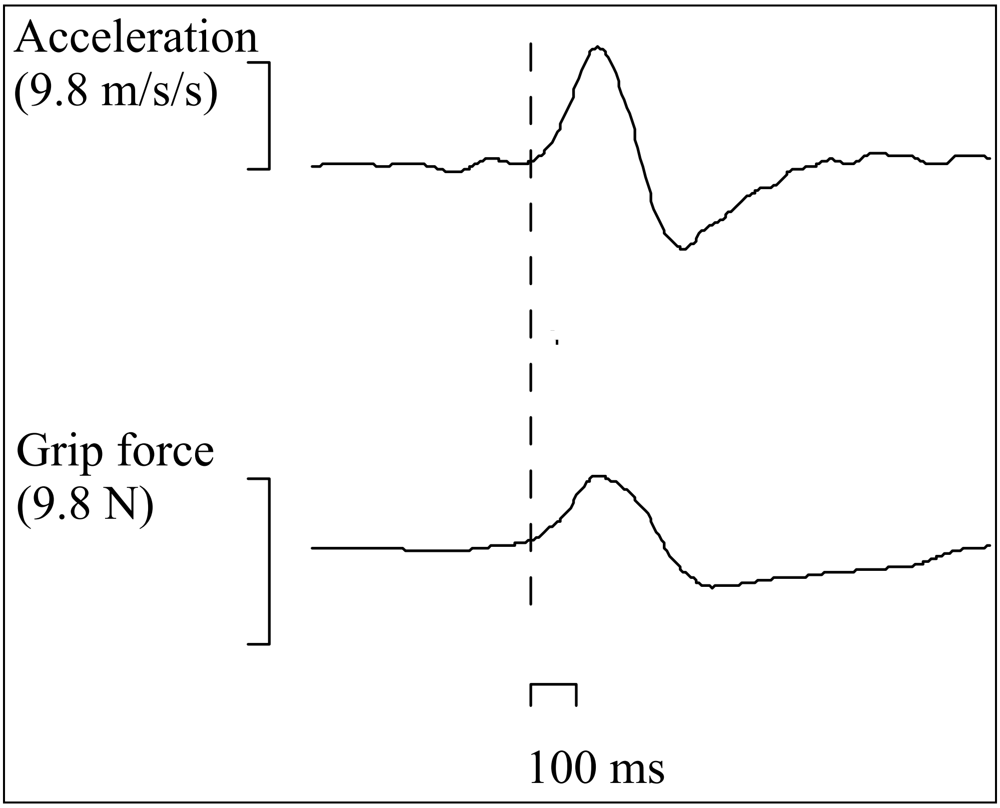


FIGURE 6B

Upward movement



Downward movement

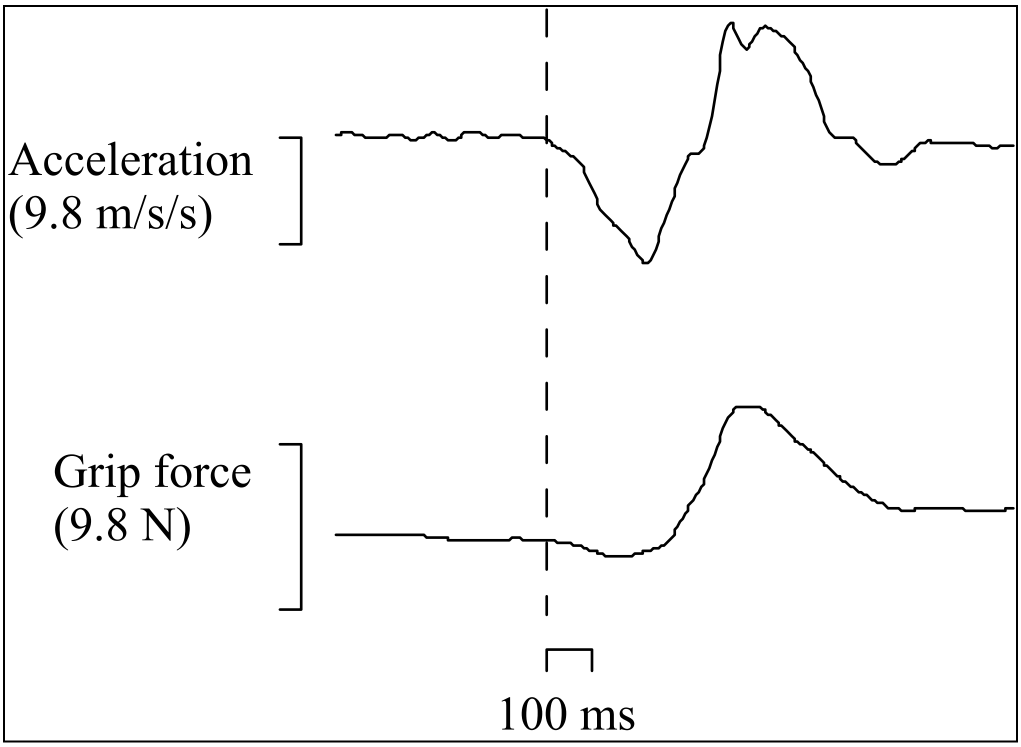


FIGURE 7