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Perceptual-motor organization of children's catching behaviour under different postural constraints

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Abstract

The experiment investigates the perceptual-motor organization underlying children's catching performance when the demands on the postural system are varied. For this purpose, one-handed catching performance was observed under different postural constraints in children aged 9–10 years. Two groups of eleven participants, classified as either good or poor catchers, performed one-handed catches under three different postural conditions: standing, sitting, and standing while pressing a button positioned to a postural support aid (PSA). Results revealed, first, that when seated, poor catchers approached the level of the good catchers' performance. Second, poor catchers improved their performance by using the PSA, but not to the same performance as when sitting. Third, there was no effect of postural condition on the performance of the good catchers. The performance increase in the poor catchers is attributable to a combined change in functional postural sway and better timed movement of the catching hand, made possible by exploiting the extra surface support area afforded by sitting.

Keywords: Perceptual-motor organization; Timed movement; Postural constraints

Analysis of performance during dynamic interceptive actions, such as catching, provide valuable insights into how the perceptual-motor system is re-organized to conform to severe spatial and temporal constraints of the environment [1]. According to the theoretical paradigm espoused by Bernstein [2] and Newell [6], perceptual-motor organization in goal-directed behaviour is shaped by the constraints imposed upon the organism–environment system. Newell [6] ordered these constraints with respect to their origin, namely: organismic, environmental, and task constraints. In addition to subtly shaping movement co-ordination processes, particular constraints may often act as rate-limiters on the appearance and mastering of new behaviours. For instance, in the emergence of infant arm movements, it has been shown that postural position acts as a rate-limiting constraint on reaching behaviour. Savelsbergh and Van der Kamp [8] found that when infants were positioned in three different body orientations with respect to the ground surface, reaching patterns of 3–4-month-old infants in the vertical position were similar to those of 5–6-month-old infants. This was not the case in the supine position, resulting in fewer reaches in the 3–4-month-old infants.

With older children, Davids et al. [4] observed that posture may act as a rate limiting factor on one-handed catching performance. When good and poor catchers (9–10-year-olds) completed one-handed catches in both a seated and standing conditions, only poor catchers improved performance when seated compared to standing (i.e., the number of catches increased). There was no effect of changing postural requirements on the good catchers' performance. One possible explanation for these findings is that the sitting condition reduced the demand on postural control through a diminution in the number of motor system degrees of freedom to be

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regulated by the central nervous system (CNS). With fewer degrees of freedom to control, a reduction in postural sway per se was easier to accomplish, which may in turn have led to improved control of the catching arm during successful catching.

An alternative explanation for these findings is that a reduction in the motor system degrees of freedom to be regulated provided the CNS with the possibility to re-organize the remaining degrees of freedom in a more effective way. For instance, catching while seated may have afforded performers the opportunity to increase their upper trunk movements in an anterior–posterior direction because the support surface in sitting is larger than when standing. When standing upright and moving one arm quickly, the postural system has to compensate for a sudden shift in the centre of mass to keep it within the support surface in order to maintain equilibrium (e.g., [12]). Less skilled catchers may not be as competent in maintaining equilibrium under standing conditions, which would in turn influence positioning of the distal component (i.e., the catching hand). In other words, capacity to adapt to the postural demands of one-handed catching when standing upright could be the major rate-limiting factor on performance, and not the control of the distal component per se. This hypothesis was not directly tested in the study by Davids et al. [4]. In contrast, it was expected that the sitting condition might impede the capacity of more skilled catchers to use available motor system degrees of freedom in adjusting posture to align the catching hand in the correct line of flight of the ball.

Therefore, the objective of the present experiment was to examine changes in perceptual-motor organization in children when postural constraints, and hence available motor system degrees of freedom, were manipulated. To achieve this aim we examined effects of different postural constraints on children's control of the catching arm when sitting and standing. In addition, we introduced a third condition in which postural sway is reduced without substantially reducing the number of degrees of freedom involved. This additional task constraint was motivated by the study of Jeka et al. [5], which showed that postural sway is reduced significantly by lightly pressing (Force = 1 N) a wall-mounted button with one hand. In addition to kinematic analyses of the upper-trunk and catching arm, positioning of the hand and the timing of the grasp was also distinguished in order to determine the effect of the postural manipulations (cf. [4]).

Pre-testing of (30 one-handed catching trials) of a sample of 36 children from a local primary school (Excalibur Primary School, Cheshire UK) resulted in classification of groups of relatively 'poor' or 'good' catchers. On the basis of the pretest, 22 children ($M = 9.33$ years, S.D. = 0.71) were invited to participate in the experiment. The 'Poor' catchers ($n = 11$: 7 boys and 4 girls) caught less than 50% of the balls, while the 'Good' catchers ($n = 11$: 6 boys and 5 girls) caught more than 70% of the balls. This method of participant selection was essentially the same as Davids et al., therefore, permitting a comparison between the results of these studies. Ethical clearance was provided by a local University committee and informed consent was obtained from the children and their parents/guardians after written and verbal explanation of the purposes and nature of the study.

A ball-projection machine (BOLA, Stuart and Williams, UK) delivered yellow tennis balls with an initial velocity of $9.8\,\mathrm{ms}^{-1}$ from a distance of 7 m and a height of 1 m above the ground, resulting in an average flight time of 970 ms. The projection angle was adjusted for each participant so that the ball arrived at a distance of around 30 cm from the shoulder of the catching arm. All balls fell within a 30-cm diameter of the desired location. The accuracy of the ball machine enabled us to project the balls away from the face and torso of the children.

The postural stability aid (PSA; see Fig. 1) consisted of a metal triangle base (60 cm × 40 cm) with a metal pole attached to the base that extended vertically by 200 cm. The triangular base was stabilized on the ground by a 50 kg weight. In the PSA condition, participants were asked to apply a light touch to a switch (6 cm × 6 cm) attached to the vertical pole at shoulder height above the floor, enabling experimenters to determine whether participants kept in touch with the PSA during the experimental trials. In the sitting condition, participants were seated on a chair without an armrest, which was taken from their classroom to ensure a comfortable sitting position.

A video camera was positioned in such a way that catchers' movements could be recorded from the front (Fig. 2), enabling a clear view of the ball position relative to the catching hand. A slow-motion video playback monitor (GR-DVL 9700, JVC, Matsushita, Japan) was used after the testing session to determine the outcome of each trial. An ELITE on-line motion analysis system (Milan, Italy) was used to collect data on arm and head movements at a sampling rate of 100 Hz. Two infra-red detecting cameras recorded the two-dimensional coordinates of reflective markers placed on the temple of the head, shoulder, elbow, wrist and pelvis. Each marker consisted of a half-spherical piece of plastic (diameter = 8 mm) covered with reflecting material. Reflective tape (8 mm circular disks) was also placed on the tennis ball to ensure adequate tracking. The cameras were situated 5.5 m from the participant in the sagittal plane, at a height of 2.1 m and with a 45 degrees intra-camera angle (Fig. 2). A volume of 1.25 m × 1.70 m × 0.4 m was calibrated prior to testing. An infrared beam was placed at the projection mouth of the ball machine so that it was interrupted by ball release, providing a signal used to synchronize the moment of ball projection with the video and ELITE recordings.

Participants faced the ball machine with their catching (right) hand positioned on the front of the ipsilateral thigh, while their non-catching hand was rested on the other thigh. When they caught a ball, they placed it into a bucket that was situated by their right hand side. Eight one-handed catching trials were performed in three experimental conditions ($n = 24$) imposing different postural constraints on participants: standing, sitting and standing while holding the PSA.

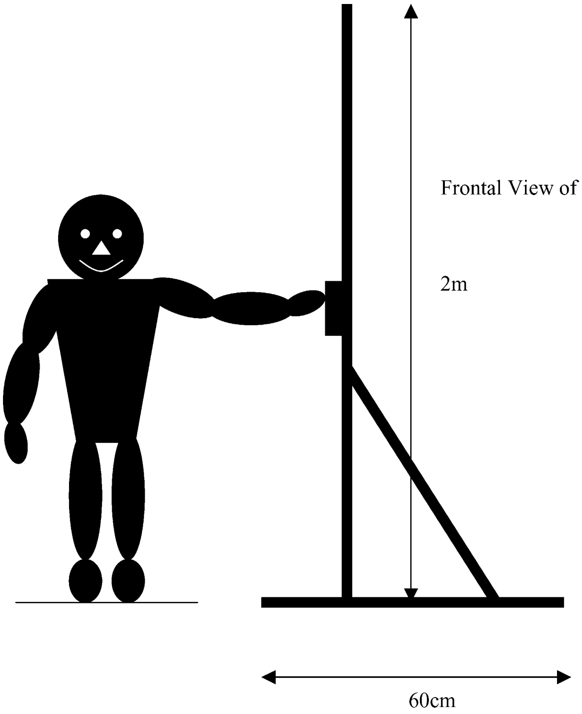

Fig. 1. The postural stability aid device. See text for explanation.

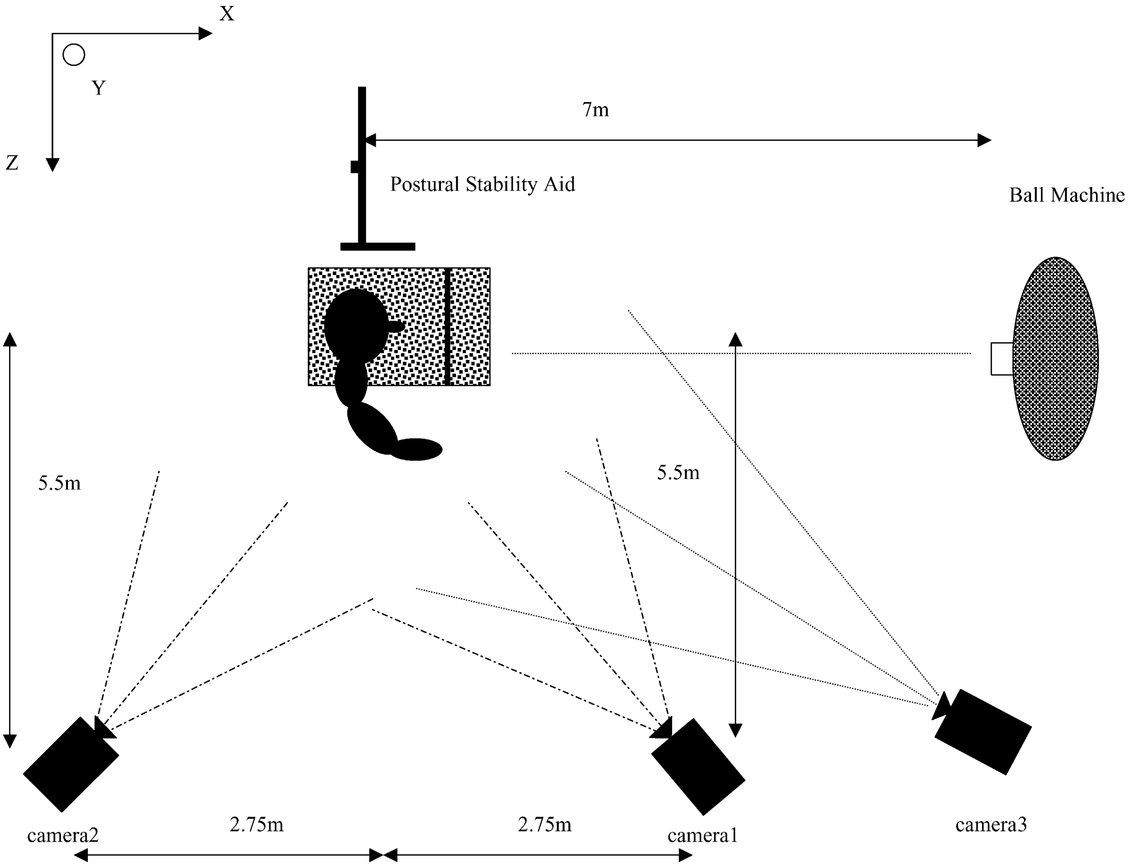

Fig. 2. A bird eye view of the experimental set-up. Camera 1 and 2 is the ELITE system, camera 3 is the video camera. See text for explanation.

In each condition the feet were placed on markers located on the floor at a distance of 0.3 m apart. The order of condition presentation was counterbalanced across participants. In order to familiarize the child with the equipment two catches in each condition were carried out before the experimental trials. At this time, participants were asked to report any discomfort with the apparatus and signal their willingness to continue.

Video analysis resulted in extraction of the following variables: (i) number of successful catches; (ii) proportion of grasp errors (i.e., balls that made contact with the hand but were subsequently dropped) relative to number of trials in which there was no position error (i.e., eight possible catches minus the position errors); and (iii), number of position errors (i.e., no contact between the hand and the ball).

An interactive routine was developed to determine variables on postural sway and movement of the catching arm. For postural sway, we plotted the excursion of head movement in the *X*, *Y* and *Z* axes. Excursion was calculated by summing all movement in these axes from the moment of ball release to ball/hand contact. When there was a position error, and hence no ball/hand contact, the end of the trial was deemed as the moment the ball passed beyond the hand in the *x*-axis. For the movement of the catching arm, we calculated: (i) movement time (time between movement initiation and ball/hand contact); (ii) peak velocity in the *x*- and *y*-axis; (iii) acceleration time (i.e., time between movement initiation and the moment of peak velocity); and (iv), deceleration time (i.e., time between the moment of peak velocity and ball/hand contact). Finally, in order to check whether there was any change to the movement profile, the ratio between acceleration time and deceleration time was plotted.

The raw data were submitted to separate 2 (Group: good versus poor catchers) × 3 (Posture: standing versus sitting versus standing with PSA) analyses of variance with repeated measures on the last factor. One participant from the poor catcher's group could not be included in the analyses because of technical problems that restricted the extraction of the kinematic measures.

For the number of catches, there were significant main effects of Group, ($F(1,19) = 10.9$, $p = .0037$) and Posture ($F(2,38) = 4.01$, $p = .026$; Table 1), and a significant interaction between Group and Posture ($F(2,38) = 5.47$, $p = .0081$) (see Table 1). Post hoc analyses of the interaction effect (Newman–Keuls, $p < .05$) revealed that poor catchers made significantly more catches in the sitting condition compared to the standing and PSA, and in the PSA compared to the standing condition. In fact, in the sitting condition the poor catchers reached the same level as the good catchers. No significant effects were found for the good catchers. They performed to an equally high level in each condition.

Analysis of the proportion of Grasp errors, revealed a significant main effect of group $F(1,19) = 19.6$, $p = .0003$, and posture ($F(2,38) = 3.56$, $p = .038$, and a significant interaction between group and posture, $F(2,38) = 6.68$, $p = .003$. Post hoc analysis showed a significant reduction in the proportion of grasp errors in the sitting condition compared to the standing condition, and between PSA and the standing condition for the poor catchers. No difference was found between PSA and sitting.

Table 1
The mean and standard deviation (in parentheses) for the dependent variables Catches, Position errors and proportion of Grasp errors as function of Postural condition and Group

Dependent variable	Posture condition				
	Group	Stand	PSA	Sitting	ANOVA
Catches	Poor	2.0	3.4	5.1	
	Good	5.5	5.0	5.3	
		3.9 (2.2)	4.2 (2.2)	5.2 (2.0)	$p = .026$
Position errors	Poor	0.6	1.0	0.1	
	Good	0.5	0.6	0.4	
		0.5 (0.6)	0.8 (1.1)	0.2 (0.4)	$p = .004$
Proportion of Grasp errors	Poor	68	45	31	
	Good	24	27	30	
		45 (26)	36 (22)	30 (20)	$p = .038$

With respect to Position errors, there was only a significant effect for posture, $F(2,38) = 3.4$, $p = .044$. The main effect of group ($F(1,19) = 0.13$, $p = .71$) and the interaction between group and posture $F(2,38) = 1.0$, $p = .37$) did not reach statistical significance. Post hoc analysis showed a significant reduction in the position errors in the sitting condition compared to the PSA.

There was a main effect of Posture in the anterior–posterior (*X*) direction ($F(2,38) = 10.1$, $p = .003$), and lateral (*Z*) direction ($F(2,38) = 10.4$, $p = .0002$; Table 2). Post hoc testing indicated that sitting led to increased movement in line with ball approach and less perpendicular movement, while PSA resulted in less perpendicular movement.

Table 2
The mean and standard deviation (in parentheses) for the dependent variables reflecting head displacement in *X* (anterior–posterior), *Y* (vertical) and *Z* (lateral) direction as a function of Group and Postural condition

Dependent variable	Posture condition				
	Group	Stand	PSA	Sitting	ANOVA
Head *X*	Poor	45	47	81	
	Good	61	44	88	
		53 (27)	45 (21)	84 (47)	$p = .003$
Head *Y*	Poor	26	38	44	
	Good	34	24	35	
		30 (15)	30 (24)	39 (15)	ns
Head Z	Poor	67	44	38	
	Good	66	42	49	
		66 (27)	43 (18)	44 (19)	$p = .0002$

Head *X*, *Y* and *Z* displacement is in mm. The mean of the two groups is also presented for comparison.

Table 3
The mean and standard deviation (in parentheses) for the dependent variables of the arm kinematics as function of Postural condition in *X* (anterior–posterior) and *Y* (vertical) direction: Movement time (MT), Acceleration time (ACCT), Deceleration time (DECT), ACCT/DECT ratio, Peak velocity

Dependent variable	Posture condition			
	Stand	PSA	Sitting	ANOVA
MT	602 (64)	586 (99)	659 (109)	$p = .010$
ACCT				
y	312 (95)	309 (168)	336 (207)	ns
x	268 (95)	262 (76)	279 (89)	ns
DECT				
y	290 (61)	277 (69)	321 (98)	$p = .05$
x	334 (81)	323 (98)	389 (75)	$p = .009$
ACCT/DECT				
y	1.8	2.2	2.1	ns
x	1.4	1.6	1.0	ns
PV				
y	131 (45)	110 (58)	137 (75)	$p = .005$
x	91 (30)	86 (29)	75 (34)	$p = .013$

MT, ACCT and DECT data are reported in ms; PV is in cm/s.

There was a significant main effect of Posture for peak velocity ($F(2,38) = 4.8$, $p = .013$), and deceleration time ($F(2,38) = 5.3$, $p = .009$) in the anterior–posterior direction (X), movement time ($F(2,38) = 5.1$, $p = .010$), and peak velocity ($F(2,38) = 5.9$, $p = .0057$) in the vertical direction (Y) (see Table 3). The main effect of Posture for deceleration time in the vertical direction was also significant ($F(2,38) = 3.1$, $p = .05$). There were no significant group, or group by condition effects. Post hoc testing of the significant main effect of Posture revealed that both groups exhibited a longer movement time, accompanied by a longer deceleration time and reduced peak velocity in anterior–posterior direction (X) in the Sitting condition compared to the Stand and Stand PSA conditions.

The purpose of the experiment was to examine children's perceptual-motor organization of catching actions under different postural constraints. Specifically, we sought to determine whether the previously reported finding of improved performance of poor catchers when sitting compared to standing was attributable to a reduction in postural sway per se, or the more effective use by the CNS of the remaining degrees of freedom. Analysis of outcome performance showed no significant effect of the postural manipulations in the group of good catchers. However, the poor catchers' performance was influenced by the experimental manipulation, enabling them to make significantly more catches and less grasp errors when sitting or using the PSA. Consistent with the findings of Davids et al. [4], the poor catchers achieved the same high level of performance as the good catchers in the seated condition. By including analysis of the type of errors made, we also found that unsuccessful attempts at catching were due to errors in timing the closure of the catching hand. Both the skilled and unskilled catchers made very few position errors (see Table 1), indicating that in general the accuracy of the gross orientation of the catching movements was not strongly affected by the postural manipulations. Using the excursion of head movement as a measure of postural control, we found significant effects of postural constraints on sway in anterior–posterior and lateral directions (see Table 2). Both groups exhibited significantly more anterior–posterior sway in the sitting condition compared to the two other conditions, and more lateral sway in the standing condition compared to the sitting and PSA conditions. The change in sway direction as a function of postural condition was generally well reflected in the arm kinematics. In the sitting condition, both groups exhibited an overall lengthening of motor response time while maintaining the ratio between accelerative and decelerative phases. In other words, participants responded with a reduced peak velocity, which occurred at a relatively constant time, but then decelerated towards ball/hand contact for a longer duration, subsequently extending movement time. The deceleration of the catching hand prevented the perturbation of the sensitive grasp phase of catching in the seated condition. Similar changes in the arm kinematics were observable in the PSA condition, but did not reach statistical significance.

The central question in this paper concerns the relationship between postural constraints, amount and direction of postural sway and arm kinematics. How might this relationship have influenced performance of the poor catchers? Taken together the data suggest that children were able to adapt perceptual-motor organization of the upper limb and the postural sub-system in a functional manner as task constraints changed. The modification to the arm kinematics resulted in better temporal control and improved catching performance, and was facilitated by functional changes in postural sway in the sitting condition. When standing and extending the arm rapidly, as in one-handed catching, the postural sub-system has to compensate in order to avoid too much sway and keep the centre of mass within the support surface, maintaining equilibrium (e.g., [12]). This control problem for the CNS is reduced in the sitting condition because of the increased surface support area, allowing participants to produce more functional anterior–posterior movement of the upper body, providing improved regulation of upper limb degrees of freedom in this direction. The resultant perceptual-motor re-organization reduced peak velocity and increased deceleration time of the catching arm leading to functional performance improvements. In addition, the sitting condition restricted the opportunity to make perturbing lateral movements, facilitating postural stability. Given that the ball approached the shoulder of the catching arm with a highly consistent trajectory, such lateral displacements were not necessary under the task constraints of the current study. This constraint on lateral movement was less obvious in the standing condition, enabling greater lateral sway, requiring the CNS to regulate more degrees of freedom, thereby increasing the complexity of postural organization. In other words, the nested nature of the degrees of freedom within the human movement system, enabled a complimentary response between proximal (posture) and distal (arm) sub-systems in the sitting condition, that acted together to reduce timing errors and improve catching performance in the poor catchers. Good catchers consistently demonstrated this functional level of perceptual-motor organization, with complementary changes in postural sway and arm kinematics in all postural conditions. In other words, skilled catchers are capable of exploiting the available degrees of freedom to achieve a functional perceptual-motor re-organization in order to perform successfully [9].

Alternatively, from a dynamic systems perspective (e.g., [7]), one could argue that all the postural conditions provided a stable solution for the skilled catchers. That is, they have 'access' to a range of stable solutions for a specific perceptual-motor problem, and could functionally vary perceptual-motor organization to suit contextual changes in the performance environment. In contrast, for the poor catchers, it seemed that only the sitting condition provided a stable solution, whereas the other conditions did not.

An interesting finding was that the poor catchers caught more balls in the PSA condition than the standing condition, although performance did not attain the same level as when sitting, confirming the importance of movement in the anterior–posterior direction in the current study. In the PSA condition, it was observed that a small increase in support surface (attributable to the light pressure applied to the PSA) did not lead to reduced postural sway in the anterior–posterior direction (see Table 2), and was not accompanied by a significant change in arm kinematics. There was, however, a significant reduction in lateral sway, and an improvement in catching performance compared to the standing condition. The implication is that in order for poor catchers to reach the level of good catchers, it is necessary that the support surface facilitates a perceptual-motor re-organization of postural sway (in both anterior–posterior and lateral directions) and upper limb movements allowing them to overcome the rate-limiting effect of posture in the standing condition.

It is worth noting that enhanced catching performance could also have been facilitated by improved perception of regulatory information following a change of postural sway. Stoffregen and colleagues showed that a reduction in postural sway facilitates visual search [10] and is closely coupled to environmental objects and events [11]. Our data are consistent with these findings since the improved timing of the catch could have resulted from a reduced lateral sway and an increase in lateral steadiness of the retinal image of the approaching ball, and/or an increase in anterior–posterior sway which facilitates more effective use of visual information on the looming object (see [3]). Further specific experimentation is needed to confirm this suggestion.

In conclusion, data reported in this paper suggest that adapting the task constraints of performance can facilitate the functional perceptual-motor re-organization needed for successful interceptive actions. A combination of lateral sway reduction, a decrease in motor system degrees of freedom to be regulated by the CNS (only control needed with respect to upper trunk movements) and the opportunity to increase anterior–posterior movements (exploiting the support surface) together, were responsible for the significant improvement of the poor catchers up to the level of the good catchers. Further work is needed to tease out how perceptual and motor factors contribute to performance adaptation under changing task constraints.

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