BEARING ANGLE STRATEGY USE FOR LOCOMOTION TO AND INTERCEPTING A MOVING OBJECT

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The experiment investigates the effect of ball velocity and walking direction on the adherence to the Bearing Angle (BA) strategy in adults. A group of adult participants (N=12) approached a moving ball in order to manually intercept it at a predefined target area. Results revealed that during locomotion the BA strategy was implemented but on reaching the point of interception, this strategy broke down and the BA strategy of the wrist compensated movement requirements relative to ball velocity and approach angle. Larger deviations from the BA occurred when the angle of approach was decreased and when ball velocity increased. When the BA strategy was adhered to, postural involvement was reduced yet, increased movements occurred in a proximal-distal direction with increasing approach angle and faster ball velocity.

Introduction

Interception and object avoidance are complex perceptual-motor responses to external stimuli, in that movement is shaped to accommodate the future [1]. Everyday activities may involve coupling visual information with a particular action in order to successfully catch a ball, grasp a cup or on a larger scale cross a busy road or walk in a crowd. With respect to information about object position and orientation [2], optical variables have been formalised and evaluated empirically in the regulation of timing of grasping movements [3,4,5]. It is not clear however, which of these variables are exploited when the hand and arm are free to move for interception of a moving object.

In object interception BA is subtended at the point of observation by the current position of the ball and the direction of displacement [6]. Recent research in adults suggested that using the head as the angle centre, the angular position of the ball with respect to the interception point remains close to constant [7,8]. This strategy implies that only one information source is required in order to facilitate interception, and a person may maintain the Constant Bearing Angle (CBA) strategy on approach, in order to intercept at the right time [7]. Compliance to this strategy, however, has not been fully explored in relation to an actual interceptive action.

Participants adjust to horizontal properties of angular bearing during interception of a moving object along a V-shaped track whilst riding a tricycle [7,8]. The BA scarcely changed during approach and velocity adaptations were made in order to successfully complete the ‘catch’. It was therefore proposed that regulation is achieved through adherence to the CBA strategy. The present paper aims to analyse the manual interception of an object travelling at a constant velocity along a defined trajectory. It intends to investigate how participants regulate movement, in relation to ball velocity and angle of approach, in order to intercept at the right time.

A virtual reality interception study with the head [6] suggested larger angles of approach led to larger deviations in BA. Though studies have approached the area of interceptive tasks in search of a regulatory strategy, there is much indication that manipulation of task constraints leads to an accordingly regulated response [9]. Recently, it has been shown that constraining posture or movement during a prehension or interception task significantly affects perceptual-motor organisation [10,11,12]. For example, seating skilled and novice catchers affects their interceptive actions differently [12]. In previous bearing angle studies, when looking at extrinsic factors in relation to intercepting a moving object, most have neglected active prehensile action during or after self motion [6,9], some also controlling or stabilising the participants walking velocity using a treadmill. Stabilising walking velocity in such a way may artificially constrain the task and therefore restrict strategy implementation, making it difficult to relate results directly to everyday activities.

The present study looks to extend previous research [6,7,8] by allowing more strategy implementation by participants. Participants can freely adjust velocity on approach and adjust temporal parameters during the grasp of the object to be intercepted. Only the angle of approach and the interception point are defined. The CBA hypothesis is therefore applied to a real manual interceptive task as opposed to a virtual environment task. As participants are forced to decelerate at the point of interception to prevent collision with the track, in order to intercept successfully it is expected that the CBA strategy will transfer from central (head) during locomotion to the distal limb (wrist) in order to grasp.

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The present study looks at the role of the CBA strategy in a prehension task, and its effect on coupling manual movements with postural adjustments. It is expected that manipulations of walking direction and ball velocity give rise to different displacement kinematics [6,7,8]. In addition, the present paper looks to depict a relationship not only between BA strategy and change in ball velocity or a participant's angle of approach, but also between postural and temporal response in interceptive behaviour. It is anticipated that in accordance with previous research a larger BA will result in greater deviation from the CBA strategy [6,8]. It is also expected that increasing ball velocity will lead to greater deviation from the CBA strategy [6].

When manually intercepting a moving object, the BA of the head and reaching limb will be almost equal on approach. However, when reaching, the hand moves away from the body and adopts a different trajectory. When walking perpendicular to the object to be intercepted, more postural adjustments are possible and the immediate visual range is larger. When walking from a smaller approach angle, at a larger bearing angle with the object, large head movements are required to see the ball and the BA strategy is more likely to break down and fewer postural adjustment are possible.

CBA strategy may explain participant response when approaching an object to be intercepted; yet the effects of BA information on postural and reaching adjustment involved in manual interception of a ball have not yet been addressed. When approaching an object to be intercepted, it is suggested that more postural and reaching adjustments are made as the ball velocity increases to allow greater range of motion in order to successfully intercept [13]. Based on previous research it is also proposed that the peak velocity of the wrist will increase relative to the increase in ball velocity [14]. In the present study, the angle of approach should have no effect, as temporal variables are influenced by temporal-spatial information provided by the target to be intercepted.

Materials and Methods

Twelve healthy adults (8F, 4M; aged 22.2± 1.3 years) participated in this experiment on a voluntary basis. All participants intercepted a tennis ball (ø 60 mm) set on a small platform, moving along a motorised track (length 3m, height 0.79m), with their preferred (right) hand. Two OPTOTRAK™ camera units recorded movement (200Hz) of upper body and ball LED markers. Participants started walking from 4m away, at angles of 90º and 45º to the track. The ball approached at three different velocities (V_B) 0.45, 0.65 and 0.85m/s. The velocities remained constant along the movement trajectory. Running was not allowed in the task at anytime, but the participants were free to adjust their walking velocity should they require.

The OPTOTRAK™ data were used to calculate the BA between (1) the head and the ball and (2) the wrist and the ball in order to determine the strategy used relative to change in walking direction and V_B. As participants were instructed to start walking when the ball started to move and the ball had a constant velocity after that, constant BA strategy is defined by sustaining the initial BA throughout the trial. In order to analyse dissimilarity between CBA and the measured BA ($\delta CBA_{H,W}$), the CBA was calculated as the average starting bearing angle from each walking direction. For walking direction 90º the BA of the head and wrist was 55º and for approach angle 45º it was 88º.

The bearing angles of the head (H) and wrist (W) were calculated using the following formulae at each time interval of 0.05s;

$$BA_H = Tan^{-1}\left[\frac{head_y - ball_y}{head_x - ball_x}\right] \quad (1)$$

$$BA_W = Tan^{-1}\left[\frac{wrist_y - ball_y}{wrist_x - ball_x}\right] \quad (2)$$

*x= direction of the ball along track
y= perpendicular to the track and ball

Duration of the trials varied with ball velocity, so deviation from the CBA (δCBA) was also analysed by dividing the trajectory into quartiles and looking at the deviation that occurred at each comparable point in a trajectory. In the deviation from the CBA the course of the movement analysis was divided into quartiles and the δCBA at 25%, 50% & 75% were analysed as the start and endpoints (0 and 100%) of the movement trajectory were pre-defined by the task conditions (ball movement initiation and grasp).

Time to contact denoted the time taken from start of reach to interception (grasp). The start of the reach was determined by appearance of the hip marker. The time of grasp was indicated by the disappearance of the ball marker.

Calculated as the maximum incremental displacement of the wrist marker during the reach, the peak velocity of the wrist (PV_W) occurred during the reach and was preceded by an acceleration phase (TA) from the start of reach to PV_W. This was followed by a deceleration phase (TD) as the hand moved into closer proximity of the target object and decelerates in order to accomplish precision in interception.

Data from the LED markers were also used to determine possible postural adjustment strategies employed. Elbow, shoulder and trunk angles at the start and end of the reach phase were calculated , after which the difference between the calculated angle at the start and end of the interceptive action were determined as an indication of elbow movement, shoulder movement and approximation of trunk movement

Data were collected at 200Hz and filtered using a 2nd order Butterworth filter with a cut off frequency of 10Hz. Statistical analysis was done, using repeated measures analysis of variance (3 way ANOVA for δCBA; 2 way ANOVA for other dependent variables). Post hoc pairwise comparisons proceeded with Bonferroni corrections. The significance level was set to $\alpha = 0.05$.

Results

The BA_H displayed a relatively horizontal trajectory, deviating in accordance to walking direction and ball velocity as the target came into closer proximity (Fig.1).

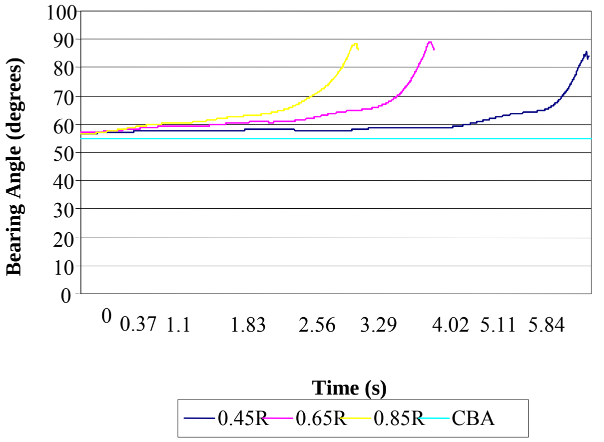

Figure 1: Bearing Angle of the Head from start of locomotion to grasp. Results of a typical subject's BA_H for varying ball velocities when walking from 90°. *CBA* indicates the required BA; other trajectories display the actual BA.

A significant effect of ball velocity on δCBA_H $\{F(2,18)=5.97;\ p<0.01\}$ was found. Post hoc pair wise comparisons revealed that δCBA_H was significantly different for the lowest than for the highest velocity ($p<0.01$). A further significant effect of direction on δCBA_H $\{F(1,9)=42.26;\ p<0.001\}$ indicated that the deviation from CBA was significantly larger in the 45° walking condition (Fig. 2). This was the case especially at 75% of the approach, as indicated by the significant interaction between walking direction and quartile $\{F(2,18)=5.23;\ p<0.05\}$.

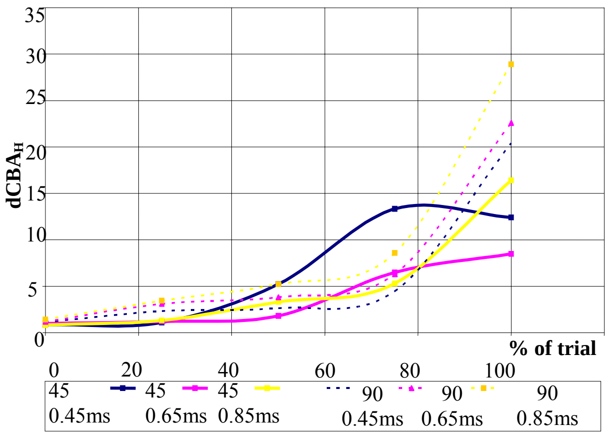

Figure 2: Percentage course of the deviation of the head from the constant bearing angle (δCBA_H), at quartile points (0%, 25%, 50% and 75%, 100%) of the trajectory. Differences between the CBA and the actual BA_H from start of locomotion to grasp of target ball are indicated.

On examination of the BA strategy of the wrist at grasping (100%), where δCBA_H increased, δCBA_W decreased and vice versa (Fig. 2 and 3). Both direction $\{F(1,9)=8.57;p<0.05\}$ and ball velocity $\{F(2,18)=6.426;\ p<0.01\}$ had a significant effect on δCBA_W. Post hoc analysis indicated a significant difference between the slower 0.45m/s ball and the two faster balls ($p<0.05$), confirming the hypothesis that an increase in ball velocity leads to increasing deviation from the CBA strategy.

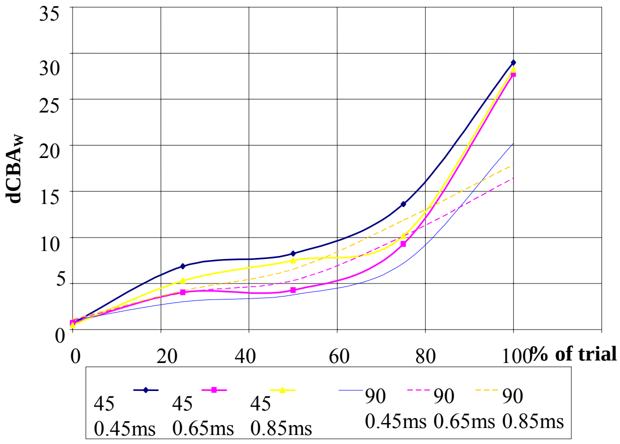

Figure 3: Percentage course of δCBA_W at quartile points (0%, 25%, 50% and 75%, 100%) of the trajectory, indicating difference between the constant bearing angle and the actual bearing angle of the wrist from start of locomotion to grasp of target ball.

The time taken from reach to grasp (time to contact: ttc) decreased significantly as ball velocity increased (Table 1; $F(2,18)=8.04;\ p<0.01$}. Post hoc pair-wise comparisons revealed a significant difference between ball velocities 0.45m/s, and 0.85m/s. No significant effect of direction or interaction between direction and ball velocity was found for ttc.

Ball velocity had a highly significant effect on peak wrist velocity (PV_W) $\{F(2,18)=185.17;\ p<0.001\}$. Increasing ball velocity led to increasing peak velocity of the wrist (Table 1). Post hoc tests indicated all differences between ball velocities were highly significant {all $p<0.001$}. No significant effect was found for direction and no significant interactions were revealed. Results indicated no significant effects of ball velocity or direction of travel (Table 1) on acceleration and deceleration time of the wrist. No significant interactions were present.

Postural involvement during interceptive action could explain the strategy used by participants in accordance to defined task constraints such as ball velocity and the direction of approach. Elbow movement increased significantly with increasing ball velocity $\{F(2,18)=3.63;\ p<0.05\}$. Post hoc comparisons however showed no significant differences. The effect of direction was significant $\{F(1,9)=8.18;\ p<0.05\}$. When walking from 90° participants adopted an elbow extension strategy from reach to interception, whereas when walking from 45°, elbow angle was reduced significantly from reach initiation to interception (Table 1). No significant interactions were found.

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Table 1: Mean and standard deviation *(between brackets)* data for calculated dependent variables for each combination of walking direction and respective ball velocity.

Dependent Variable	**Walking direction 90º**			**Walking direction 45º**		
	0.45 m/s	**0.65 m/s**	**0.85 m/s**	**0.45 m/s**	**0.65 m/s**	**0.85 m/s**
(Units = Degrees)						
δCBA_H: 25%	6.86*(1.1)*	4.05*(1.1)*	5.29 *(1.1)*	1.098*(0.5)*	1.208*(0.8)*	1.32 *(0.68)*
50%	8.26 *(1.3)*	4.29 (1.3)	7.52*(1.5)*	5.24 *(1.3)*	1.807*(2.4)*	3.30 *(2.62)*
75%	13.64*(1.4)*	9.29 *(2.2)*	10.17*(1.9)*	13.35*(8.2)*	6.49 *(3.8)*	5.3 *(4.63)*
δCBA_W: 25%	3.*03 (0.8)*	3.99 *(0.8)*	4.20 *(0.8)*	2.33 *(0.9)*	3.13*(0.94)*	3.45 *(0.99)*
50%	3.78 *(1.6)*	5.32 *(1.4)*	6.55 *(1.7)*	2.64*(16.0)*	3.82 *(5.1)*	5.33 *(5.44)*
75%	7.22*(1.7)*	10.13*(2.4)*	11.87*(1.9)*	4.46*(15.4)*	6.31 *(7.3)*	8.59 *(7.75)*
Elbow Movement (E_M)	6.34 *(13)*	8.07 *(20)*	13.8 *(14)*	-4.69 *(11)*	-6.75 *(9)*	-0.46 *(5)*
Shoulder Movement (S_M)	48.28 *(13)*	56.*46(16)*	66.05 *(14)*	46.51 *(14)*	54.66 *(14)*	63.8 *(18)*
Trunk Movement (T_M)	5.98 *(4)*	9.33 *(4)*	12 *(5)*	5.18 *(2)*	7.24 *(3)*	7.15 *(3)*
Total Movement	60.59	73.86	91.85	46.99	55.15	70.49
(Units = ms)						
Time to Contact (TTC)	500 *(133)*	459 *(81)*	439 *(88)*	525 *(121)*	426 *(75)*	404 *(116)*
Acceleration Time (TA)	127 *(109)*	35 *(200)*	41 *(255)*	86 *(431)*	-38 *(376)*	118 *(148)*
Deceleration Time (TD)	373 *(106)*	424 *(201)*	398 *(216)*	439 *(509)*	464 *(347)*	286 *(150)*
(Units = m/s)						
Peak wrist velocity (PV_W)	1390*(147)*	1870*(264)*	2400*(251)*	1260*(256)*	1770*(233)*	2280 *(246)*

Participants displayed increasing shoulder movement for increasing ball velocity {Table 1; $F(2,18)=13.15$; $p<0.001$}. Significant differences with the fastest ball (i.e. between 0.85 and 0.45 m/s and between 0.85 and 0.65m/s) were visible through post hoc pairwise comparisons (both $p<0.05$). This suggests shoulder movement was recruited significantly more when intercepting the fastest balls than when intercepting slower balls. Walking direction did not affect shoulder movement during interception. No significant interaction between ball velocities and walking direction was found.

Trunk movement increased as ball velocity increased and when walking from 90° compared to walking from 45° (Table 1). Statistical analysis indicated that both direction {$F(1,9)=9.38$; $p<0.05$} and ball velocity {$F(2,18)=8.39$; $p<0.01$} had a significant effect on trunk movement, though there was no significant interaction between the two. Post hoc tests indicate significant differences ($p<0.05$) in trunk movement between the slow ball and the two faster balls when intercepting the slowest ball compared to the two faster balls.

The total movement was defined as the combined movement of the elbow, shoulder and trunk, i.e. a simple addition of the above mentioned movement ranges, so as to combine the movement in the action system as a whole. This technique was used order to establish the extent to which joints are held more rigidly during interception. Postural rigidity was indicated by a lower value for total movement and freeing of postural involvement was essentially indicated through more postural adjustments.

The effect of walking direction was clearly visible through looking at the total movement in either direction for increasing ball velocity (Table 1). This indicated more postural adjustments were made with increasing ball velocity for the larger angle of approach. Statistical analysis indicated a significant effect of ball velocity {$F(2, 18)=18.14$; $p<0.001$}. Post hoc pairwise comparison indicated significant differences between the three ball velocities ($p<0.05$). A significant effect of walking direction {$F(1,9)=9.64$; $p<0.05$} on total postural involvement was also noted.

Discussion

The primary theoretical framework of this study focused on postural and timing adjustments made when applying the CBA strategy to a real interceptive task, whilst manipulating ball velocity and participant walking direction.

In summary, it may be drawn from this experiment that in an interceptive task, when approaching from an angle, individuals comply with the bearing angle strategy up until the point of interception, at which point the bearing angle of the wrist essentially takes over. A larger approach angle coincided with a greater deviation of the head from the CBA at interception, but a lower deviation from the CBA strategy for the wrist. A smaller angle of approach caused greater compliance to the CBA strategy during locomotion but greater deviation on interception.

In concordance with current theory [11], it seemed that the smaller angle of approach does lead to greater deviation from CBA strategy. The extent of this deviation was related to an increase in ball velocity; where a higher ball velocity led to greater deviation. There was a significant difference between the slowest and fastest ball velocity. Though previous literature has addressed the degree of CBA compliance during the approach phase in interceptive actions, the strategy employed during the actual interceptive action has not been clearly established. For this reason the bearing angle strategy of the wrist was analysed.

The experiment proposed to extend previous research [6, 7, 8] by analysing the effects of manual interception of a real target following locomotion rather than use of a treadmill, tricycle or the head. Results indicated a clear difference in BA strategy used by participants walking from the two prescribed directions that may be explained by the visual information being received. Although this has not been experimentally verified, it could be that walking perpendicular to the moving object, participants used their peripheral vision and hence the target remained in sight at all times. Head movements may have been largely unnecessary to maximize spatial and temporal precision in grasping at the given interception point; preserving energy [15]. A decision could have been instantly formed and adhered to, relative to visual information. Walking from 45º, various hand trajectories may be implemented in order to successfully intercept at the right time and place. This may not be entirely based on the visual information provided by target displacement rate however, as the ball velocity and direction of approach have no significant interaction with the δCBA_H quartile.

It was hypothesised that the CBA strategy broke down or essentially transferred to the wrist on reach initiation; accounting for the larger deviation at interception, previously documented [7, 8, 11]. The results of this experiment suggest that in comparison to the δCBA_H, the deviation of the wrist had a somewhat opposing effect, in that a larger approach angle led to the deviation of the wrist to be lower. This suggests a combined bearing angle strategy in both head and wrist. This indicated that when the BA_H adhered more to the CBA strategy, δCBA_W increased relative to ball velocity and vice versa.

In accordance with previous literature [13, 14] wrist velocity appeared to be coupled to ball velocity in that a higher wrist velocity was used for faster balls in order to successfully intercept. Reaching time decreased with increasing ball velocity, possibly suggesting that individuals used the visual information provided by optical displacement of the ball along the trajectory. Participants therefore, visually distinguished the ball speeds and adjusted timing of interception accordingly; the direction of walk had no effect.

The results for trunk movement suggest that trunk flexion was the first adjustment made during interceptive behaviour in each trial. Since of the three (elbow, shoulder and trunk), the trunk is the largest in mass, it defines postural stability; its low range of motion making overall movement more energy efficient. This is due to the related stability defined by skeletal structure of the spine. As the trunk has limited movement sequences available in this task, it was easily controlled in order to provide energy efficiency and control. The extent of trunk movement is related to the velocity of the ball, increasing relative to increase in ball velocity, displacing the centre of mass in order to reduce the amount of work involved in bringing the hand in close proximity to the ball.

In synchronisation with trunk movement, shoulder and elbow movement also increased with increasing ball velocity, indicating freeing of movement [15] in the reaching limb as the velocity of the target object increases. It remains probable that this energy efficient strategy [16] could be seen to increase the success in task outcome, as the range of possible movement trajectories of the arm increased. Results suggest elbow, trunk and shoulder angles increase relative to ball velocity; their extent of involvement appears to adhere to a proximal-distal control strategy. The strategy indicates control is achieved by first freezing movement closest to the centre of mass and freeing those more distal, in order to control movement stability and goal outcome.

The control of elbow movement was the most variable between participants as there was a greater range of trajectories possible in order to achieve the goal of the task successfully. The difference in movement patterns shown between travelling directions of the participants, indicated a different strategy to that used when walking from 90°. When walking from 45° the participant may have perceived the track and ball to be closer and require fewer trunks and elbow movement. This was not seen in the shoulder, possibly because the range of motion of the shoulder essentially influenced that of the elbow (significant correlation $p<0.05$).

As there was no combined effect of direction of approach and ball velocity on the BA strategy employed, it may be suggested in line with previous literature that indeed on approach individuals only require one information source in order to intercept successfully [7]. This source of information is indicated by the degree of compliance to the bearing angle strategy. Though this is not entirely verified experimentally, where immediate visual information is reduced, when approaching from a smaller angle, the CBA strategy is adhered to, to a larger extent up until the point of interception or reach initiation.

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It is this point where the BA of the wrist takes over in order to complete the interception successfully compensating by deviating more from the CBA strategy.

The emergence of this proposed strategy suggests an immediate link with postural involvement in movement, in that the direction of approach dictates the degree of postural adjustments involved in interception. When the individuals adhered more to the CBA strategy on approach, the postural adjustments involved in interception were reduced. This indicates an effect of visual information provided through direction of locomotion, where greater use of peripheral visual information essentially allows for more postural involvement and freeing of possible movement patterns during interception.

With respect to the regulation of the CBA strategy, the distinct difference in response to slow and fast balls may govern locomotion and the combined hand and ball involvement during interception. The tight coupling of perception and action facilitates such a behavioural response, as adults are able to predict the success of using a particular strategy against another.

Conclusions

In a manual interceptive task the BA strategy is largely implemented during locomotion but on reaching the point of interception this strategy breaks down and the wrist compensates movement requirements relative to V_B and approach angle, deviating more from the CBA strategy. The information provided by change in ball velocity (e.g: the looming angle), may act as the perceptual key to effective interception, as its greatest effects occur on interceptive timing and postural involvement. As ball velocity increases, there is more postural involvement and hence less restriction to possible hand trajectories on approach.

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