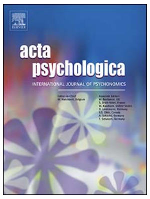
Acta Psychologica 182 (2018) 100–106

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/locate/actpsy



Action strategies for walking through multiple, misaligned apertures

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ARTICLE INFO

Keywords:
Obstacle avoidance
Aperture crossing
Gait
Visual control of locomotion
Goal-directed locomotion

ABSTRACT

When avoiding obstacles, path selection is thought to be determined by the attraction of the end-goal. However for aperture crossing, it is unclear whether the attraction point originates in the center of the aperture or at the end-goal, as previous experiments align the aperture with the end-goal. The purpose of the current study was to decipher the possible location of the attraction point, by evaluating crossing behaviour for multiple, misaligned apertures. Participants were instructed to walk through three separate apertures while en route to an end-goal. The first and last apertures were fixed such that they were both either 0.9 × or 1.7 × shoulder width (SW) while the second aperture was either 0.9, 1.3 or 1.7 × SW and shifted 25, 50 or 75 cm off the midline. Findings revealed that the attraction of the end-goal, and not the middle of the aperture, guided crossing behaviour. The *spatial margin* decreased as the size of the shift increased. Furthermore, the *frequency of rotation* increased as the aperture was shifted away from midline, regardless of the aperture size. Since rotations would not normally occur for all of these aperture sizes when aligned with the end-goal, these results suggest that rotations were produced in an attempt to keep one's trajectory as close to the midline as possible. Therefore, not only does the attraction of the goal guide path trajectory, but individuals will choose to reduce the *spatial margin* and rotate the shoulders when walking through misaligned apertures, likely in attempt to maintain the straightest possible path.

1. Introduction

The behavioural strategies involved for successfully walking through an aperture on the travel path are well documented. Individuals initiate a shoulder rotation for apertures deemed too small for straight passage and scale the size of the rotation to the size of the aperture (Franchak, van der Zalm, & Adolph, 2010; Hackney & Cinelli, 2013; Warren & Whang, 1987; Wilmut & Barnett, 2010). Furthermore, the amount of rotation produced at time-to-contact is controlled by the desire to maintain a minimal spatial margin between the shoulders and the obstacles (Higuchi, Cinelli, & Patla, 2009). Lastly, adjustments to both the path trajectory and walking speed are made in order to approach an aperture head-on and pass through the center of it, likely in an attempt to equalize the size of the spatial margin for both shoulders (Cinelli, Patla, & Allard, 2008; Higuchi, Cinelli, Greig, & Patla, 2006).

The fact that individuals adjust their actions in order to cross through the center of an aperture supports the visual equalization strategy (i.e., maintaining the same optic flow speed on the left and the right visual fields). Srinivasan, Lehrer, Kirchner, and Zhang (1991) first introduced the idea of visual equalization by observing that honeybees fly along a corridor in a location where the speed of optic flow from each wall reaches the lateral portion of the eyes at equal rates. The honeybee therefore aims to fly along the optic flow balance point. Moreover, if artificial motion is added to one wall, the bee will adjust its position in order to fly down the path in a location that is perceived as having equal optic flow speeds (Srinivasan et al., 1991). The idea of a visual equalization control law has also been implemented as a means of guiding robots through cluttered environments. By following such a control law, the mobile robots were able to traverse down passageways, through openings, and around obstacles with considerable success (Coombs, Herman, Hong, & Nashman, 1998; Duchon & Warren, 1994; Duchon, Warren, & Kaelbling, 1998; Weber, Venkatesh, & Srinivasan, 1997). More current research has extended these findings by demonstrating that humans also employ a similar behaviour when walking down corridors (Duchon & Warren, 2002; Dyre & Andersen, 1996). In addition to equalizing the speed of optic flow, Fajen and Warren (2003) argue that path trajectory towards a goal and around obstacles is a function of the relative angles between the heading and the instantaneous relative positions of the goals and obstacles, which act as attractors and repellers. In other words, where and how an individual

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https://doi.org/10.1016/j.actpsy.2017.11.006
Received 28 July 2016; Received in revised form 11 September 2017; Accepted 5 November 2017
0001-6918/

chooses to walk on a path is determined by the location of goals and obstacles: goals attract the individual to walk towards them on the shortest possible path, while obstacles repel the individual away from the shortest path. Although obstacles push an individual off the straight walking trajectory, the attraction of the goal quickly pulls them back so that a walker can reach his or her goal by walking the straightest path possible (Warren, 2006). Thus, when traversing a corridor or walking through narrow passageways, the attraction of the goal and the flow equalization strategy are both likely to guide an individual down the center of the passage way. However, since previous studies involve experimental designs where the aperture is located in direct line with the goal, it is unclear the extent to which these approaches guide aperture crossing behaviours. One cannot decipher whether individuals are equalizing the spatial margin of the shoulders at time-of-crossing because the attraction point is first located at the aperture itself or because they are aligning themselves with the attraction of the end-goal. In other words, do individuals treat aperture crossing as a two-step process whereby the center of the aperture is the first goal or is the end-goal the sole attraction point?

Although a substantial body of literature exists to explain how individuals adjust their actions to walk through single apertures, the examination of multiple aperture crossing is far less common despite the fact that navigating through crowds of people encompasses a series of various-sized, and potentially misaligned, apertures. Not only is research needed to determine the action strategies employed for multiple aperture crossing, but these scenarios can also help determine what aspect of the travel path acts as the attraction point. Therefore the current study set out to explore how individuals walk through a series of apertures that vary in both their size and their position on the walking path.

If the attraction point is first located at the aperture (before moving to the end-goal once the individual arrives at the aperture), then individuals will be attracted to the center of the aperture and act to equalize the spatial margin between the shoulders and the obstacles at TOC. As observed with single aperture crossing, this equalization will be achieved by deviating away from the straight walking path and approaching the aperture head-on (Cinelli & Patla, 2007). If the equalization strategy is the dominant control strategy also used for misaligned aperture crossing, then one would also anticipate that as the size of the off-set increases, the path deviations will move away from midline in order for the position of the center of mass (COM) of the body to always pass through the center of the aperture. However, if the final end-goal acts as the only attraction point, then the multiple apertures may be treated as a steering task where the individual guides behaviour through a winding path while circumventing obstacles. As such, individuals may opt to maintain the straightest possible path through the apertures by walking closer to the obstacle nearest the midline rather than walking to the center of each aperture. As the size of the offset increases, one would expect that the position of the COM relative to the center of the aperture to increase and the size of the spatial margin to decrease. In some instances, this may result in individuals choosing to rotate their shoulders for apertures shifted off midline for spaces where a shoulder rotation may not normally be necessary.

The purpose of the current study was to decipher whether multiple aperture crossing is perceived as having the attraction point be the center of the aperture or the final end-goal. To do this, participants were asked to walk through three separate apertures of various sizes, with the second aperture shifted away from the midline of the path. It was hypothesized that behaviour would be similar to that predicted from a single end-goal attraction point, whereby the desire to maintain the straightest possible walking path would override the desire to walk through the center of the aperture, and that walking speed would be adjusted to maintain this goal. Therefore, it was anticipated that the medial-lateral (M-L) COM position relative to the center of the aperture would increase and the spatial margin would decrease as the size of the off-set increased. Additionally, we anticipated that participants would rotate their shoulders more frequently as the size of the shift increased, even at aperture widths that would not normally induce a shoulder rotation, and would have an overall slower walking speed when the aperture was shifted farther from the midline.

2. Methods

2.1. Participants

Nineteen healthy young adults ($\bar{x}_{\text{age}} = 23.31 \pm 2.67$ years; $\bar{x}_{\text{shoulder width}} = 44.5 \pm 3.18$ cm; 9 males and 10 females) volunteered to participate in the study. Participants were included in the study if they were free of deficits or disorders that could affect postural control, balance and locomotion; they conveyed no self-reported history of hip, knee, or ankle injury; had normal or corrected-to-normal vision; and could understand English instructions. Upon arrival, participants completed a screening questionnaire to confirm eligibility.

Once informed and written consent was obtained, the researchers recorded the shoulder width of each participant (the horizontal distance between the greater tuberosity of the left humerus to the same landmark on the right shoulder) using a measuring tape. Ethics approval was obtained from the University of Waterloo's Office of Research Ethics and the Wilfrid Laurier University Research Ethics Board.

2.2. Apparatus

The experiment was conducted on an 11 m long path with three sets of pole obstacles (0.23 m wide × 2.4 m height) located 3.5 m, 5.5 m and 7.5 m from the starting location (Fig. 1). Each set of poles created an aperture for the participants to walk through, which could be manually adjusted by the researchers. For all trials, participants were instructed to walk to the goal located at the end of the path and pass through all three apertures without colliding with the obstacles. Furthermore, participants were instructed to rotate their shoulders when passing through spaces they felt were too narrow for straight passage. Avoiding the apertures all together by walking around them was not permitted. Between experimental trials, participants faced away from the path while the researchers manually adjusted the size of the three apertures.

Kinematic data was measured using the OptoTrak camera system (Northern Digital Inc., Waterloo, ON. Canada) at a sampling frequency of 60 Hz. IRED markers were placed on the left and right posterior-lateral (acromion) aspects of the spinous process of the scapula and tenth thoracic vertebrae.

2.3. Experimental design

On all experimental trials, both the first and the last aperture were located directly in line with the goal such that the center of the aperture aligned with the midline of the path. Throughout the experiment, the size of these two apertures were presented as a pair (i.e., both aperture

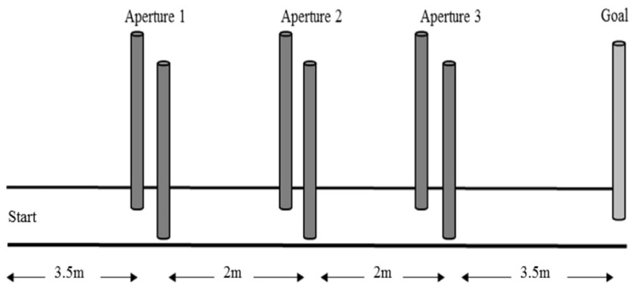

Fig. 1. A sagittal view of the experimental set-up, including the three apertures which were located 3.5, 5.5 and 7.5 m from the starting locations.