

## The Negotiation of Stationary and Moving Obstructions During Walking: Anticipatory Locomotor Adaptations and Preservation of Personal Space

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This article introduces a novel, ecological, obstructed walking paradigm. Gait adaptations to circumvent obstacles undergoing uncertain displacements, and the effect of revealing the obstacle's action beforehand, were investigated in young adults. The personal space (PS) maintained during walking was quantified for the first time under different environmental factors including auditory distractions. Obstacle movement and its uncertainty resulted in gait adjustments aimed at gaining time to assess the situation. Early gait adaptations and constant clearances around the obstacle suggest that anticipation and preplanning are involved in such navigational tasks. Participants systematically maintained an elliptical PS during circumvention, but they adjusted its size according to different environmental factors. There was a relationship between the size of PS and level of attention, which suggests that the regulation of PS is used to control locomotion. This novel paradigm has important implications for the assessment and training of locomotor ability within real world environments.

**Key Words:** gait adaptations, anticipatory locomotor control, obstacle avoidance, moving obstacles

Bipedal locomotion in urban environments is often challenged by the need to navigate around stationary and moving obstacles such as other people in a shopping mall or on a street. In natural situations, the movement characteristics of such obstructions are not often immediately predictable, but at some point, anticipatory adaptations are necessary to avoid collision. Adapting gait to the environment not only has processing costs related to its very execution, but also in relation to the perception and integration of different sources of sensory information leading up to the adaptation. Obstructed gait paradigms to study locomotor adaptations have

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included different tasks such as stepping over obstacles or changing direction, but the circumvention of obstructions has received little attention. In particular, anticipatory locomotor adaptations used for the circumvention of stationary and moving human-shaped obstacles within contexts involving an element of uncertainty about their displacements have not been investigated.

When confronting an obstacle, people must control their center of mass (CM) displacement to either step over it (e.g., Patla, Prentice, Robinson, & Neufeld, 1991; McFadyen & Winter, 1991), change their direction (e.g., Patla et al., 1991; Grasso, Prevost, Ivanenko & Berthoz, 1998), or stop walking altogether (Patla, 1997). When enough preparation time is available, people preferentially use changes in foot placement as a strategy to control the CM, but when preparation time is restricted, a coordinated sequence of head yaw, trunk roll, and then trunk yaw is used if changing the walking direction is necessary (e.g., Patla et al., 1991; Patla, 1997; Patla, Adkin & Ballard, 1999). Circumventing an obstacle with the intention to continue in the initial direction, however, involves a lower body strategy with no stereotyped upper body coordination preceding the CM deviations (Vallis & McFadyen, 2003). Therefore, adaptive locomotor strategies for obstacle circumvention differ from those used for a single change in walking direction.

During obstructed walking, vision is an important sensory modality as it provides information to both foresee and react to physical hazards in the environment (Patla, 1997). For various interceptive tasks, time-to-contact (e.g., Lee, 1976; Lee, Lishman & Thomson, 1982) and bearing angle (e.g., Lenoir, Musch, Thiery & Savelsbergh, 2002) have been proposed as information used to regulate locomotion respectively to make contact with a stationary object and to intercept a moving object. When the goal is to avoid an obstacle, however, the specific aspects of visual information used for navigation are different (Cutting, Vishton & Braren, 1995). The relative motions of objects around the one to be avoided would be more relevant to predict whether collision will occur. Specifically, when fixating a stationary object, the perception of heading would rely on differential parallactic displacements, whereas changes in gaze-movement angle would be used for a moving obstacle (Cutting et al., 1995). Many experiments on perception of heading or collision judgment (e.g., Wann & Swapp, 2000; Warren, Kay, Zosh, Duchon & Sahuc, 2001; Wilkie & Wann, 2003a; Wilkie & Wann, 2003b; Cutting et al., 1995), however, either have not focused on gait patterns, or have simply not involved actual walking by the participants. The natural navigational behavior in terms of anticipatory locomotor adaptations used to circumvent obstacles is, therefore, still unknown. Nevertheless, taken together, the literature shows how information processing is crucial to navigating obstructed environments, in large part due to the perception and integration of visuospatial information.

In general, unobstructed walking requires more attention than maintaining static postures (Lajoie, Teasdale, Bard, & Fleury, 1993), while walking faster or slower (Kurosawa, 1994) and negotiating irregular paths (Lindenberger, Marsiske & Baltes, 2000) require greater attention than unobstructed walking at natural speeds. Evidence from a PET scan study (Malouin, Richards, Jackson, Dumas & Doyon, 2003) showed that higher brain centers were progressively more engaged with increasing cognitive and sensory information processing demands associ-

ated with imagined locomotor-related tasks. It has also been shown that judging a collision with a moving obstacle is more challenging than making such decisions about stationary obstacles (Cutting et al., 1995). Considering all of these findings, it would be expected that negotiating a moving obstacle, particularly when its displacement is initially uncertain, should involve increased mental processing demands that could affect gait performance.

When considering the mental processing involved during navigation of obstructed environments, it is not well understood how the information acquired is integrated and efficiently used to implement the necessary gait adjustments to safely navigate around obstacles. Fajen and Warren (2003) recently proposed a behavioral model for obstacle avoidance and route selection wherein walking trajectories towards goals and around obstacles were a function of the relative angles between the subject heading direction and the instantaneous relative positions of the goals and obstacles acting as attractors and repellers. Given that spatial parameters (angle and distance) could account for the observed trajectories around stationary obstacles, the authors proposed that a route is not preplanned, but emerges from environmental interactions. Do people, however, anticipate and plan obstacle avoidance in more complex and ecological obstruction scenarios involving moving obstacles with displacement characteristics that are initially uncertain? If so, what might be the basic control parameters underlying such anticipatory behavior?

One important control parameter might reside in the clearance one maintains when circumventing the obstruction. Over the last four decades, anthropologists and psychologists theorized that personal space was a zone maintained by individuals to keep others at a comfortable distance during different social interactions (Sommer, 1959; Horowitz, Duff & Stratton, 1964; Little, 1965; Hall, 1966; Dosey & Meisels, 1969; Rawdon & Willis, 1993; Webb & Weber, 2003). In the present work, the term personal space is used to describe a protective space surrounding the body during walking. Only a few authors (Fruin, 1970; Templer, 1992) have concentrated on personal space as a protective zone during locomotion that provides sufficient time to perceive environmental hazards, plan gait adaptations, and execute them (Templer, 1992). It has also been shown in primates, that neurons in the premotor cortex are able to encode the space near the body in arm-centered coordinates since these receptive fields move with the arm (not with the eyes), and are used to prepare and guide reaching movements in space (Graziano, Yap & Gross, 1994). The same authors believe that other body segments could have similar visuospatial representations. Such a somatotopic map could, therefore, also represent a personal space near the body of the pedestrian which would be anchored to the center of mass and which would displace with its movements. To date, however, no method has been reported for the calculation of PS during locomotion to provide a window on this otherwise abstract concept, particularly when navigating through obstructed environments. By studying this protective space, it should be possible to determine if its preservation follows a systematic behavior that might be used to control obstacle circumvention.

Research demonstrates that attentional resources subserving audition, vision, and touch are shared and limited (Driver & Spence, 1998; Calvert, Brammer & Iversen, 1998; Just et al., 2001). Thus, paying attention to auditory information

while avoiding obstacles, as is commonly the case in public environments such as shopping malls, should compete for available attentional resources. If the role of the PS is to ensure that proper distance and time to perceive, process, and react to environmental obstructions are maintained at all times, then the size of this PS should be affected by the level of attention demanded by the obstacle context (e.g., its movement and the level of certainty about it). Allocating more attention to obstacles should allow one to safely decrease his or her PS. On the other hand, simultaneously attending to other environmental stimuli should result in the preservation of a larger PS for safe navigation.

Based on the background and rationale discussed above, two experiments are presented in this article. The objectives of Experiment 1 were to study the differences in anticipatory locomotor adaptations (ALAs) used by healthy young adults to circumvent stationary versus moving human-shaped obstacles with displacement characteristics that were initially uncertain; and to determine the specific effect of revealing the obstacle's action a priori on ALAs. Given that adapting gait has a processing cost, it was hypothesized that in the more realistic situation involving initial uncertainty about the obstacle's action, the greater online processing of information related to the moving obstacle would lead to delayed CM trajectory deviations, greater and more variable obstacle clearances as well as lower approach speeds. It was also hypothesized that making anticipation easier by revealing the action and final position of the obstacle ahead of time, thereby decreasing the online processing demands, would result in earlier (further away from the obstacle) execution of locomotor adaptations, smaller and less variable clearances as well as increased walking speeds.

Building on the knowledge of the natural locomotor behavior gained through the first experiment, the objectives of Experiment 2 were to quantify, for the first time, the protective space maintained by people as they walk around human-shaped obstructions; and to investigate the relationships of this personal space with different ecologically based environmental factors such as obstacle movement, the initial certainty about obstacle movement as well as simultaneous auditory distractions. It was hypothesized that the size of the preserved PS would be adjusted depending on the attention that is allocated to the obstacle to be avoided. Focusing attention on the obstruction would allow the use of a relatively smaller PS whereas diverting attention from the obstruction would result in the use of a larger PS. Specifically, with respect to the different environmental factors used in this experiment, people should unconsciously: use a smaller PS when circumventing a moving versus a stationary obstacle as well as when the obstacle's action is initially uncertain, and use a larger PS when some attention is directed towards a simultaneous auditory task.

## General Method

The ethics committee of the Quebec Rehabilitation Institute approved this project and all participants provided informed consent. Exclusion criteria included any self-reported neurological or musculoskeletal problems or the use of any medications that could have affected alertness or locomotion on the day of study. Normal, or corrected-to-normal, vision was assured by a minimum score of 20/20 on the Snellen vision test.

Three-dimensional segmental movements of the participants were measured during walking using three noncolinear infrared markers that were placed bilaterally on the feet, pelvis, trunk, arms, and head (legs, thighs, and forearms were also collected in Experiment 1). These markers were tracked (60 Hz in Experiment 1 and 75 Hz in Experiment 2) using the Optotrak 3020 system (Northern Digital Inc., Waterloo, ON). Certain anatomical points were also digitized to allow the creation of principal axes and the calculation of trajectories of the heels and left elbow where markers did not exist.

To mimic particular contexts of pedestrian-environment interactions similar to those found in public places, while preserving the required experimental control to consistently reproduce the obstruction scenarios, a moving obstacle system was designed and fabricated. The obstacle used was a full-sized department store mannequin, selected to simulate the contours of another pedestrian. This mannequin was mounted on an overhanging rail (3.66 m long) that crossed the walkway (respectively 8 and 10 m long in Experiment 1 and Experiment 2) at a 45° angle (Figure 1) at approximately 5 m (Experiment 1) to 6 m (Experiment 2) from the participant's starting location. A remotely controlled electric motor (0.25 hp, MDI, Canada) allowed mannequin movement between the different preprogrammed positions. Mannequin movement was also tracked using the Optotrak system.

### **Experiment 1: Context Specific Anticipatory Locomotor Adaptations During Obstacle Negotiation**

Circumventing stationary and moving obstacles within contexts involving an element of uncertainty about their displacements requires anticipatory locomotor adaptations. Although this is a common task in our activities of daily living, such ALAs used for the circumvention of stationary and moving human-shaped obstacles have not been investigated. In addition to providing the first description of such a locomotor task, this study introduces a novel obstructed walking paradigm that will lead to a better understanding and assessment of locomotor ability in real world environments.

#### *Methodology*

**Experimental Protocol.** Ten healthy young adults (4 female and 6 male; age  $24.5 \pm 3.1$  years, height  $1.77 \pm 0.13$  m, mass  $67.5 \pm 10.7$  kg) volunteered for Experiment 1. Initially, four trials of unobstructed walking at self-selected, natural speeds were recorded to synchronize the mannequin's movement in subsequent trials. Participants were then instructed to walk at their natural speed, without stopping, up to a table located 8 m straight ahead, and to avoid the mannequin whenever it obstructed their path, as they would do to avoid another pedestrian in a shopping mall. Obstacle contexts (see Table 1 and Figure 1) related to the human-shaped obstruction included no obstacle (NO; mannequin off to the side), a stationary obstacle (SO; mannequin stationary in the walking path), and a moving obstacle (MO; mannequin moving into the walking path from its initial position). Participants always started from the same location at the beginning of the walkway. Mannequin movement was triggered based on a theoretical point of interception calculated from

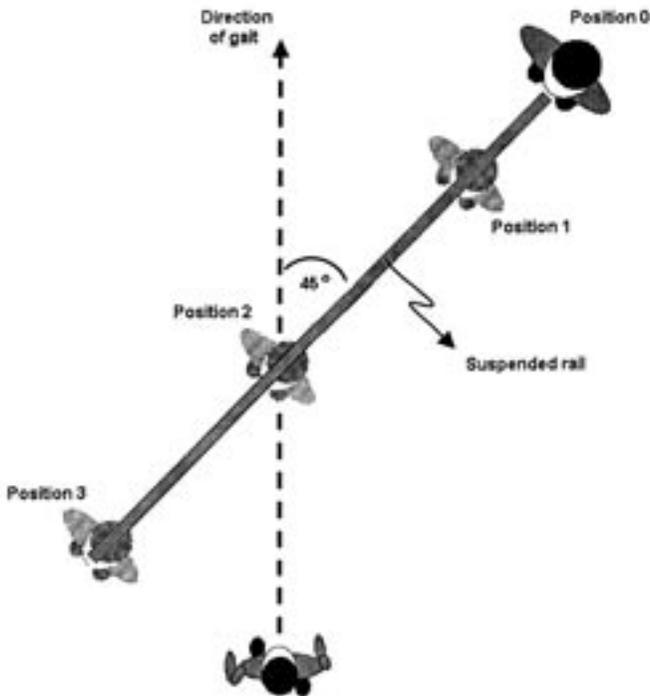
**Table 1** Obstacle Contexts as Defined by the Static Positions and Movements of the Mannequin

Label	Description	Mannequin positions	# of trials	
			Uncertain	Known
Analyzed conditions				
NO:	No obstacle (Mannequin stays stationary off to the side)	0	5	5
SO:	Stationary obstacle (Mannequin stays stationary within travel path)	2	5	5
MO:	Moving obstacle (Mannequin moves from 0 to 2)	0 to 2	5	5
Catch conditions				
MO_feint:	Mannequin feints start but stays out of the way	0 to 1	5	--
SO_move:	Mannequin starts at 2 as in SO but moves forward or backward	2 to 3/1	5	--
MO_cross:	Mannequin crosses the travel path	0 to 3	5	--
Total			45	

*Note.* The mannequin positions are illustrated in Figure 1.

the participant's unobstructed gait speed and the mannequin's travel time. Since it appears to be more natural to pass behind a moving obstacle (Cutting et al., 1995), rightward passes behind the mannequin were encouraged through a wider area to the right of the participant's initial line of progression, as well as the addition of a packaging box in the hands of the mannequin. After participants performed the four trials of unobstructed walking, a familiarization period including one trial of each obstacle context was performed prior to testing.

Information related to the movement and end position of the mannequin was either not initially available (uncertain condition; UN) or revealed ahead of time (known condition; KN). For the known condition, the investigator told the participant what the movement of the mannequin would be for the upcoming trial whereas for the uncertain condition, the participant was told that the mannequin's action would be from among the possibilities experienced during the familiarization



**Figure 1—Top view of the experimental environment. The different predetermined locations of the mannequin’s final positions are shown across conditions for no obstacle (mannequin stationary off to the side at position 0), a stationary obstacle (mannequin stationary within the walking path at position 2), and a moving obstacle (mannequin moving from position 0 to position 2). During uncertain trials, participants were also randomly exposed to catch trials with different mannequin displacements (position 0 to 1, position 2 to 1, position 2 to 3, and position 0 to 3) rendering the initial prediction of the mannequin’s action difficult.**

period. Additional catch trials with different mannequin displacements were also used (see Table 1 and Figure 1), but not analyzed. Participants had the opportunity to both see and experience all possible mannequin displacements (analyzed and catch trials) during the familiarization period. The fact that no discrepancy between the announced movement and the actual movement ever occurred helped the participant to rapidly trust the given information during the familiarization period. Each participant performed a total of 30 trials in which the action of the mannequin was uncertain including 15 trials for the analyzed obstacle conditions (i.e., NO, SO, and MO) and 15 trials for the catch conditions (i.e., MO\_feint, SO\_move, and MO\_cross). The exposure to such catch trials helped to make the initial prediction of the mannequin’s action difficult for the uncertain condition. The participants verbally confirmed this during both pilot and experimental studies. The same soft,

instrumental music was played through headphones to mask auditory cues from the motor controlling the mannequin. Five trials were performed for each of the six conditions as well as for each of the three catch conditions. Following the familiarization period, all trials were randomly presented.

### *Data Analyses*

The 3D kinematic data processing and analyses were performed using custom programs written in Pascal and in MatLab. Dependent variables (Table 2) included initial path deviation, obstacle clearance, obstacle clearance variability, gait speed, step width, step length, and step duration. The total body CM was estimated using a weighted sum of the CM positions of the individual segments. Initial path deviation was calculated as the point where the CM exceeded the straight walking CM trajectory found by tracking backward in time from the maximum lateral deviation to the right until the point when the CM lateral velocity component was zero indicating the transition from a leftward to a rightward deviation. Clearance data were normalized to participants' step length to account for the natural variability in walking and anthropometrical characteristics of the participants. Foot placement modulations (in step width, step length, and step duration) were calculated as the change from control foot placement (average of all steps during the NO condition) normalized to control foot placement. Foot placement modulations were averaged over seven bins of equal distance corresponding to a typical step length of 75 cm based on the CM position at successive heel contacts (from 4.75 m before and up to 0.5 m after the intersection point with the obstacle).

**Table 2 List of Definitions for the Dependent Variables**

Dependent variables	Definitions
CM trajectory	—CM trace in the transverse plane
Initial path deviation	—Distance before the mannequin where CM trajectory departs from the average of the control NO condition (at point of inflection $VCM_z = 0$ )
Clearance	—Minimum transverse distance between the left elbow of the mannequin and the left arm of the subject
Clearance variability	—Standard deviation in clearance data
Gait speed	—Mean navigational speed with initiation and second steps removed from calculation
Step width	—Lateral distance between 2 consecutive heel contact locations
Step length	—Longitudinal distance between 2 consecutive heel contact locations
Step duration	—Time between 2 consecutive heel contacts

*Note.* CM, center of mass;  $VCM_z$ , lateral component of the CM velocity.

The statistical model consisted of a two-factor randomized block design (obstacle context  $\times$  certainty, levels:  $3 \times 2$  or  $2 \times 2$ , depending on the variable tested) with Tukey post hoc tests (SPSS version 10.0.0, SPSS, Inc., Chicago, IL). Results were blocked by participant since each participant was exposed to all conditions in the model, and the participant mean across the five trials for each condition was entered into the corresponding cell of the model. The significance level was set at 0.05. For simplicity, a pairwise comparison between two conditions of the two-factor model in which one factor was held constant and one varied was called the “direct comparison,” whereas such a comparison in which two or more factors varied was called the “indirect comparison.”

## Results

### *Medio-lateral Control of the Center of Mass*

When the obstacle context was uncertain, the global CM trajectory used to avoid the mannequin was similar for both the SO and the MO (Figure 2A), remaining close to unobstructed walking for the first portion of the approach and then showing a pronounced lateral deviation at about 1.50 m before the obstacle. The CM trajectory then kept moving rightward with a medio-lateral deviation at obstacle crossing that was similar for both SO and MO conditions. When mannequin movement was revealed a priori (known condition), the global CM trajectory of the participants for the avoidance of the MO-KN (Figure 2D) appeared to be similar in shape but slightly shifted to the right versus the MO-UN condition (Figure 2A). For the SO-KN condition, however, participants gradually deviated their CM trajectory from start to obstacle crossing. The certainty factor did not influence the gait trajectory used during the unobstructed (NO) situation.

**Initial Path Deviation.** With respect to the global CM trajectories described above, there was no significant difference in the point where initial path deviation occurred for the SO versus the MO (Figures 2B and 2E) although there was a tendency for participants to deviate from their unobstructed path earlier for the SO. A main effect for the certainty factor,  $F(1, 27) = 12.60$ ,  $p = .001$ , however, was shown for path deviation. Knowing the mannequin movement a priori resulted in an initial path deviation that occurred earlier (further away from the obstacle, Figure 2E). No interaction effects were observed between the obstacle context and certainty factors for initial path deviation.

**Step Width Modulation.** Under uncertain conditions, the pattern of step width modulation for the SO was similar to that of the MO (Figure 2C). Revealing the mannequin’s action a priori resulted in a redistribution of the step width modulation (Figure 2F). The CM was displaced laterally with a tendency for greater step widening early in the approach. This led to a smaller modulation amplitude later in the approach, especially for the SO condition where steps were wider than control steps from the start, removing the need for a wide crossing step. In the MO condition, there was only a tendency for such redistribution and the modulation was still greater in the last stride preceding obstacle crossing and the crossing step as in the uncertain conditions.

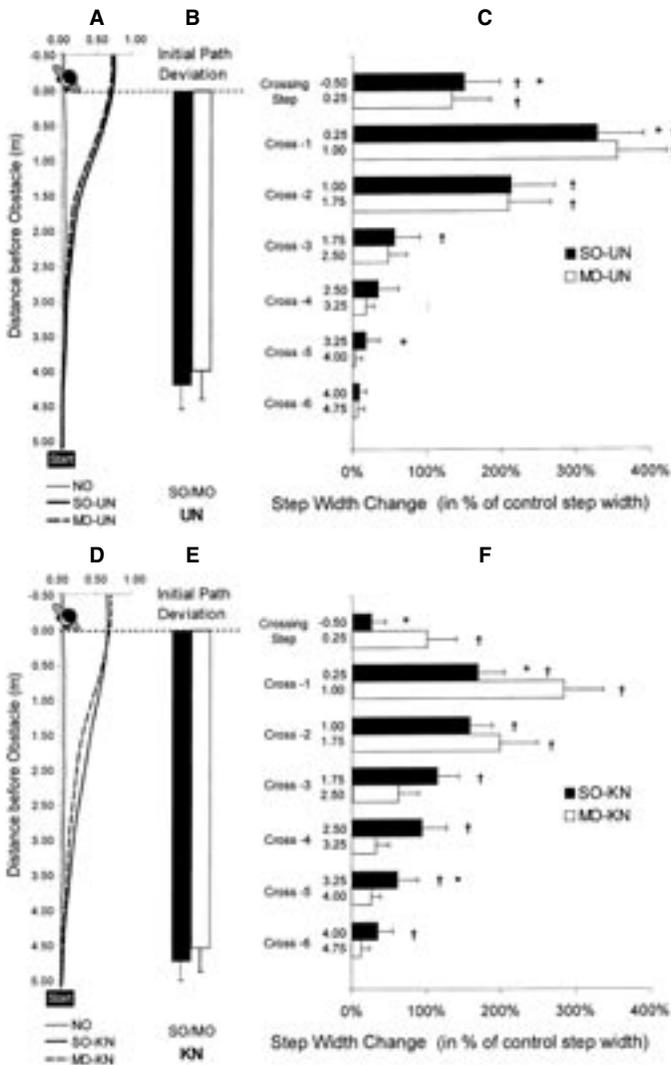
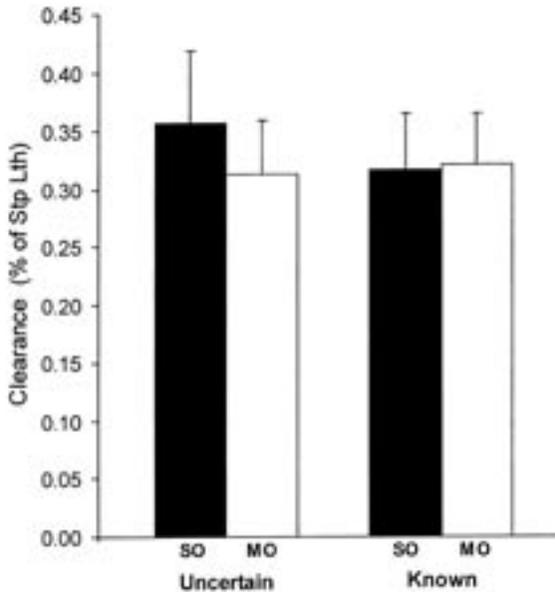


Figure 2— Average anticipatory locomotor adaptations including CM trajectories in the transverse plane (A & D); distance from the obstacle at which initial path deviations occurred (B & E); and step width modulation during the approach (C & F) for no obstacle (NO), stationary obstacle (SO), and moving obstacle (MO) conditions when mannequin movement is uncertain (UN; A-C) and known (KN; D-F). Significant direct pairwise comparisons ( $p < .05$ ) are shown between the SO and MO conditions ( † ), between the SO and MO conditions respectively, with unobstructed walking ( ‡ ) and between the UN and KN mannequin’s action ( \* ) conditions. Error bars represent standard errors of the mean.

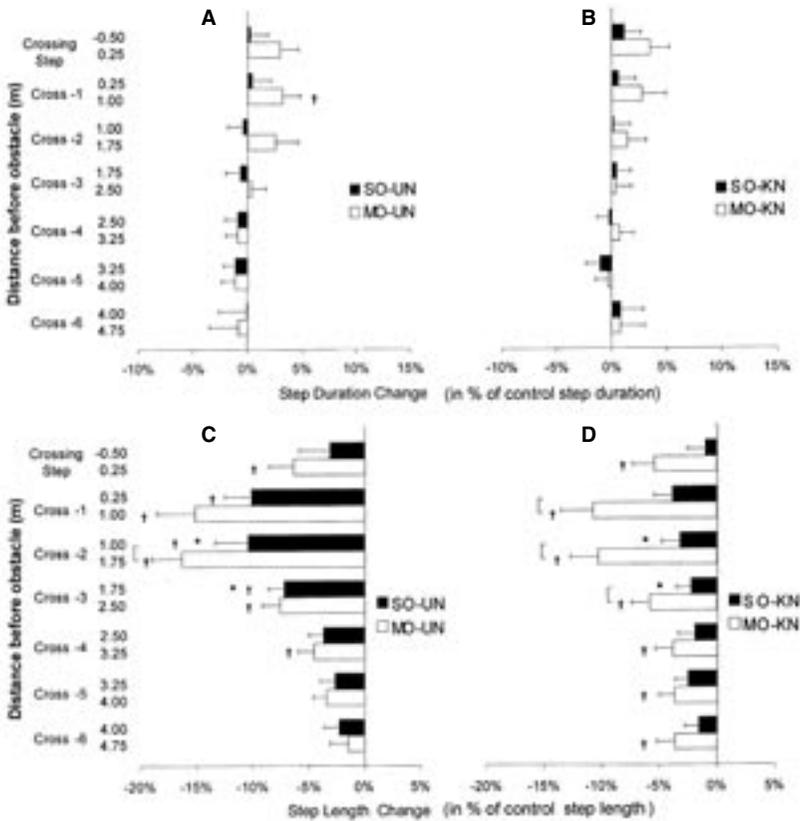
**Clearance.** The obstacle context did not affect clearance,  $F(1, 27) = 1.30, p = .265$ , (Figure 3) and there were no differences in clearance variability,  $F(1, 27) = 1.25, p = .274$ , between the SO ( $M = 7.49\%$ ) and the MO ( $M = 6.58\%$ ) conditions. Certainty about the obstacle context also had no effect on clearance,  $F(1, 27) = 0.89, p = .354$  (Figure 3), or on clearance variability,  $F(1, 27) = 0.29, p = .597$ , between the KN ( $M = 6.82\%$ ) and the UN ( $M = 7.25\%$ ) conditions. Clearance was kept constant at about one-third of the participant's step length regardless of the condition.



**Figure 3—Average obstacle clearance normalized to step length across the stationary (SO) and moving (MO) obstacle conditions when the mannequin's action was uncertain or known. None of the direct pairwise comparisons were significant. Error bars represent standard errors of the mean.**

### *Antero-posterior Control of the Center of Mass*

**Step Duration Modulation.** In Figures 4A and 4B, a negative change indicates a shorter step duration, while a positive change signifies a longer step duration than during unobstructed walking. With the exception of step Cross-1 for the MO-UN, where a significant, but small, increase in step duration was observed, this variable was not significantly altered during the circumvention of either the SO or MO for both the uncertain and known conditions when compared to unobstructed walking. Certainty about the obstacle context did not affect step duration for either the SO or MO. Step duration, therefore, was similar between the obstructed contexts throughout the approach.

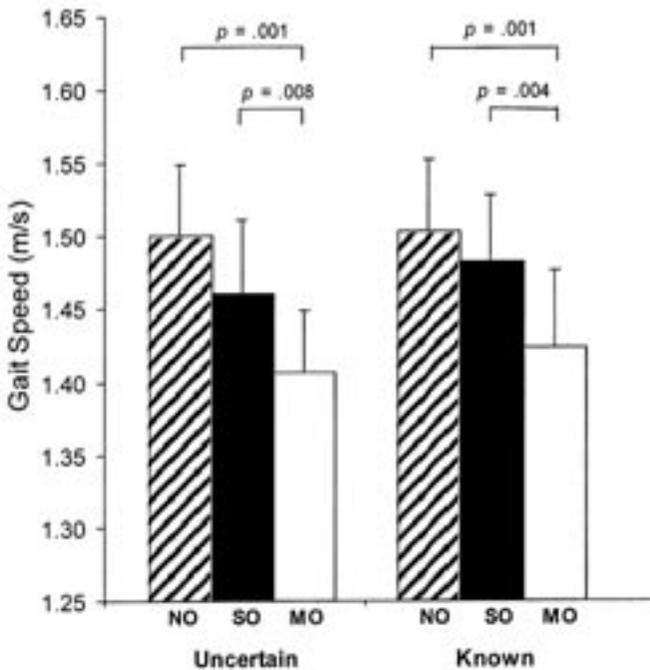


**Figure 4—**Average step duration (A & B) and step length (C & D) modulations during the approach to the stationary (SO) and moving (MO) obstacles for uncertain (UN) and known (KN) mannequin action conditions. Significant differences ( $p < .05$ ) are shown between the SO and MO ( ), between the SO and MO conditions respectively, with unobstructed walking (†) and the UN and KN (\*) conditions. Error bars represent standard errors of the mean.

**Step Length Modulation.** Only step shortening strategies (negative changes in Figures 4C and 4D) were observed during the avoidance of both the SO and MO. Under uncertain circumstances, the global shape of the step length modulation pattern was similar for both the SO and MO conditions. In both obstacle contexts, the two steps preceding the obstacle were the shortest, and this step length reduction was greatest for the moving obstacle (tendency for Cross-1 but significant for Cross-2). Revealing the mannequin’s action a priori resulted in a general decrease of the amplitude of the step shortening strategy (Figure 4D). This diminution was significant ( $p < .05$ ) for the steps preceding obstacle crossing for the SO (Cross-3 and Cross-2). For the MO, there was only a tendency towards a reduction of the step

shortening strategy in the stride preceding obstacle crossing so that the overall shape of the step modulation pattern was maintained. The conservation of this pattern led to significant differences between SO-KN and MO-KN (Cross-3 to Cross-1). Step length modulation during the SO-KN condition did not significantly differ from unobstructed walking whereas all steps in the MO-KN did. The crossing step for the MO-KN condition was, on average, shorter than the average control step length ( $p = .013$ ), but was not different in the SO-KN condition ( $p = .990$ ).

**Gait Speed.** On average, participants walked at a speed of 1.50 m/s ( $SE = 0.02$  m/s) during the unobstructed condition, but their gait speed was affected by the obstacle context,  $F(2, 45) = 35.47, p = .001$ . Specifically, Figure 5 shows that gait speed was significantly slower for the MO as compared to either the SO or the NO conditions. Gait speed during the SO condition only showed a tendency to be slower than the unobstructed condition. Gait speed across known conditions ( $M = 1.470$  m/s,  $SE = 0.006$  m/s) only showed a tendency to be greater than during uncertain conditions ( $M = 1.456$  m/s,  $SE = 0.006$  m/s). There was no interaction effect between obstacle context and certainty about its movement for gait speed.



**Figure 5**—Average gait speed across the “no” (NO) stationary (SO), and moving (MO) obstacle conditions when the mannequin’s action was uncertain (UN) or known (KN). Significant direct pairwise comparisons ( $p < .05$ ) are shown using square brackets ( ). Error bars represent standard errors of the mean.

## *Discussion*

**Global Strategy for the Control of the CM During Avoidance.** The global avoidance strategy can be separated into an anticipatory locomotor phase and a clearance phase. The anticipatory locomotor phase includes an initial path deviation that occurs about 4.5 m (i.e., approximately 6 steps) from the obstacle as well as a readjustment with two wider and shorter steps just preceding obstacle crossing. A generally wider and shorter crossing step and a constant distance from the mannequin characterize the clearance phase that follows.

Although adjustments for obstacle avoidance can be made within one stride from an obstacle (Patla, 1997), the initial adaptive behavior for the circumvention of the present human-shaped obstruction involved earlier adjustments. The section of the approach beginning with initial path deviation can be labeled the early planning stage, while the final adjustments during the last stride preceding obstacle crossing can be labeled the late planning stage. Final decision-making, based on the evaluation of the mannequin's movement and end position, appears to occur during the late planning stage where the greatest step adjustments took place. The trajectory of the CM is controlled using a lower body strategy, in agreement with previous work (Vallis & McFadyen, 2003), through step width modulation for the medio-lateral control of the CM and step length modulation for gait speed reduction while the walking rhythmicity is maintained.

**Uncertain Obstacle Context.** The first objective of this study was to determine whether the same ALAs are used to avoid stationary versus moving obstacles. In the most natural situation where the mannequin's action was not known a priori, participants appear to have used the same ALAs for both the SO and MO when considering the medio-lateral control of the CM. In both conditions, participants used similar global CM trajectories with initial path deviation occurring at the same distance from the obstacle. Step width modulation was also the same for both the stationary and moving obstacles and clearance distances were equivalent.

When considering antero-posterior control of the CM, however, it is clear that gait adaptations are different for moving obstacles versus stationary obstacles. Although participants maintained their natural cadence, average gait speed during the anticipatory locomotor phase was, as expected, significantly decreased for the moving obstacle. Such a reduction in walking speed probably reflects the greater time needed to evaluate the obstacle's movement and its final position in this dynamic scenario. Participants also further reduced their step length in the last stride before crossing the moving obstacle, indicating a fine-tuning during this late planning stage that suggests a final estimation of the mannequin's action and end position. These gait adaptations in the antero-posterior direction are most likely a result of the increased information processing needed to monitor the moving obstacle (Cutting et al., 1995) and to execute appropriate motor changes.

**Known Obstacle Context.** As expected, ALAs were performed earlier when the obstacle movement and its final position were known ahead of time. Step width modulation to displace the CM laterally was redistributed over all steps, with a tendency for greater modulation in the early planning stage, and smaller modulation

in the late planning stage, especially for the SO condition where a wider crossing step was no longer needed. When the obstacle was moving, there was a tendency towards such adaptations, but the step modulation was still more concentrated in the late planning and clearance stages because of the dynamic nature of the environment and the related online information processing. The step shortening strategy associated with the presence of the obstacle was generally reduced resulting in nonsignificant changes across all steps for the SO condition when compared to unobstructed walking. For the MO situation, however, the shape of the step modulation pattern was preserved. Therefore, even if the obstacle displacement was revealed a priori, participants seem to have waited, during steps Cross-6 to Cross-4, most likely to collect environmental cues to confirm such information for themselves before making significant CM adjustments.

The lack of effects of the certainty factor on average gait speed is likely a consequence of the high level of confidence in young adults about performing this common, simple task at their natural speed even in uncertain conditions. It remains to be seen whether a greater level of uncertainty would affect gait speed. The tendency for a slower speed in the uncertain conditions suggests, nevertheless, that less predictable obstacle movements should lead to a further decrease in gait speed. It also remains to be seen how uncertainty, even at the level used in this experiment, will affect gait speed in populations with diminished motor and processing capacities such as older persons. Thus, revealing the movement of the mannequin and its final position a priori, facilitates, as expected, anticipatory locomotor adaptations. When the obstacle's action is initially known, it is possible that anticipation relies more on internal models (e.g., Kawato, 1999; Flanagan et al., 1999). These accurate representations of the physical properties of the environment, built from previous experience, could reduce the amount of online processing required thereby allowing earlier execution of ALAs.

Circumventing the MO resulted, as expected, in the use of different ALAs even if its final position was known and the same as during the stationary condition. Why would participants delay their avoidance strategies when the mannequin was moving, especially with prior knowledge of the obstacle's final position? Vision is of prime importance in goal-directed gait as it allows one to plan and monitor the walking trajectory to reach the end point (Patla, 1997). During visually guided locomotion, participants tend to face their goal (Warren et al., 2001). In the present experiment, the need to continuously face the spatial goal (i.e., the table) could partly explain the predominance of the side stepping strategy observed throughout the approach. Perhaps participants walked towards the goal with relatively little adaptations until the moving obstacle caused, or threatened, visual interference of the table. Given that the movement of the mannequin was synchronized to the participant's gait speed, such visual interference would become imminent around 1.5 m before the intersection point. Alternatively, at this very point, gaze-movement angle changes (Cutting et al., 1995) could have specified the occurrence of a collision if no evasive action was taken. This point thus marked the beginning of the late planning stage, where wider steps were taken to avoid the obstacle and possibly to regain vision of the end goal. In contrast, for the SO condition, where the mannequin prevented vision of the table before beginning the trial, step width

modulation increased almost immediately as the participants started to walk. Differential parallax displacement information (Cutting et al., 1995), which is readily available as soon as the participant moves, could explain, in this case, the early and gradual deviation of the CM as an action ensuring obstacle avoidance.

Contrary to expectations, participants cleared the mannequin by the same distance of approximately one-third of their step length across all conditions. In addition, the variability in normalized clearance remained constant across conditions. These results suggest that the observed clearance distance represents the standard safety margin for the avoidance of this particular obstacle. A reason for the observed preferred clearance could be related to the concept of personal space. Templer (1992) used the term “sensory zone” to describe the amount of space a pedestrian tries to keep between the body and other objects of the environment, so that sufficient time is provided “to perceive, evaluate, and react to approaching hazards” (Templer, 1992, p. 61). To date, no method has been reported for the quantification of such a personal space, but this issue is addressed in Experiment 2. During the clearance phase for MO-KN, the crossing step was wider, shorter, and tended to last longer than control steps whereas it was similar to control steps in the case of SO-KN. This might be interpreted as a more “cautious” avoidance strategy. Yet, waiting to take a wider step to the side during actual obstacle crossing is in fact somewhat riskier than the earlier adjustments observed in the SO-KN situation since it provides less time for avoidance. Although young adults were still successful despite the use of this riskier strategy, it would be interesting to see in the future whether other populations such as older persons and people who had a brain injury, would plan their avoidance strategies differently.

**Anticipation and Locomotor Adaptations.** As previously mentioned, locomotor adaptations have a mental processing cost, and judging collision when monitoring a moving obstacle is more challenging than when looking at a stationary obstacle (Cutting et al., 1995). The present study involved further challenges on the information processing system by introducing uncertainty about the mannequin’s displacements. When the mannequin’s action was revealed ahead of time, however, anticipation was greatly facilitated. For instance, CM trajectories slightly drifted laterally in uncertain obstructed situations compared to unobstructed walking in anticipation of the most natural strategy of passing behind the moving obstacle. This behavior was augmented when participants knew the mannequin’s displacements a priori, i.e., when anticipation was facilitated. This facilitation of anticipation perhaps allowed participants to use a more efficient processing mechanism for known conditions as compared to uncertain obstacle contexts. It is known that intermittent visual sampling is sufficient for safe locomotion over various terrains, but that steering and obstacle avoidance increase the visual sampling demands (Patla, Adkin, Martin, Holden & Prentice, 1996). In the present study, participants would most likely sample the known mannequin’s movement at a relatively lower frequency, filling in the gaps with predictions between samples to track movement with less data than would be otherwise necessary (Cavanagh, Labianca & Thornton, 2001), thereby minimizing information processing costs related to comparing the desired CM trajectory with the integrated visual signals (Berthoz & Viaud-Delmon, 1999).

On the other hand, when the movement of the mannequin was uncertain, more time was needed during the anticipatory locomotor phase to collect sufficient cues before committing to a locomotor strategy. Under uncertain circumstances, anticipating the obstacle's movement was more challenging and most likely required a higher visual sampling frequency as well as increased online processing to continuously assess the situation. This could explain the delayed CM medio-lateral deviations, the tendency for a reduction in gait speed, and the step shortening strategy in the last stride before obstacle crossing in the more natural, uncertain, situation.

**Anticipatory Locomotor Control and Path Planning.** Fajen and Warren (2003) argued that the navigational path around obstacles toward a goal is not explicitly planned but rather evolves online based on the angle and distance between the walker and the surrounding obstacles and goals. The authors have presented an interesting dynamical model that has been able to simulate the behavior observed when participants avoided simple virtual obstacles appearing at a given distance while walking. If the route through obstacles in the direction of a goal, however, were to be strictly a function of spatial parameters, then knowledge or uncertainty of obstacles movements should not result in different behavior. As shown above, this was not the case. In addition, if attractor points, as discussed by Fajen and Warren (2003), evolve online according to the relative position of the walker in space, then we might expect the inherent variability related to human walking to translate into more variations in obstacle clearances. This experiment, however, showed a constant clearance distance and clearance variability across all conditions, suggesting that the locomotor control system might take into consideration a specific distance around the body when navigating cluttered environments. In the model proposed by Fajen and Warren (2003), the repulsion strength of obstacles decreases to near zero at a distance of greater than 4 m. The early planning stage discussed in the present study, however, showed that people can initiate modifications to their CM trajectories (path deviation) up to almost 5 m before the mannequin. The present results, therefore, suggest that there is some anticipation involved in navigational tasks, as well as some preplanning related to the space that is required to safely clear obstacles.

Nevertheless, the behavioral model of Fajen and Warren (2003) is able to predict global navigational paths around obstacles in the direction of a goal, using angles and distances between the walker, obstacles, and goal. For more complex, ecological environments, however, the locomotor system might need additional parameters to completely define a navigational path through a given obstacle course. Given the observation in the present study of the stages of early planning, late planning, and clearance related to a stereotypic path deviation, preferred step modulation pattern, constant clearance distance, and systematic changes in walking speeds, it is possible that a more general avoidance variable is used to set such parameters. The preservation of a personal space could be one such mechanism used to parameterize avoidance behavior. The second experiment explores whether such a personal space is preserved for successful navigation through complex, ecological, obstructed environments.

## Experiment 2: The Preservation of a Personal Space During Obstacle Circumvention in Contexts Involving Different Information Processing Demands

Few authors have concentrated on PS as a protective zone during locomotion that provides sufficient time to perceive hazards, plan locomotor adaptations, and execute them. Both the medio-lateral and the antero-posterior control of the CM observed in Experiment 1 provided clues as to the existence of such a PS which seemed to be consistent with the rare estimates of this protective zone (Fruin, 1970; Templer, 1992). To date, however, no method has been reported to calculate PS when navigating through realistic, obstructed, environments. Assuming that people do maintain a PS when walking through obstructed environments, then it should be possible to determine if its preservation follows a systematic behavior for obstacle circumvention and if it is affected by different environmental factors.

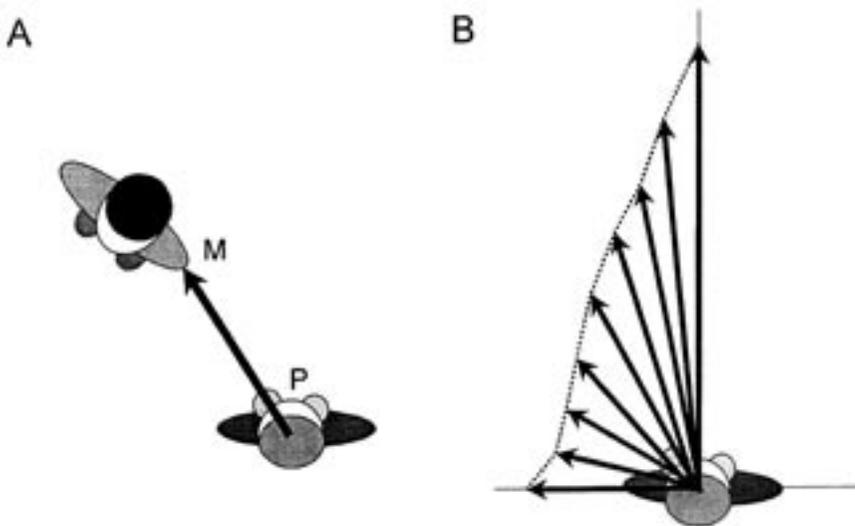
### *Methodology*

**Experimental Protocol.** The protocol of Experiment 1 was replicated in a new laboratory with the addition of an auditory distraction manipulation. Nine additional healthy young adults (6 female and 3 male; age  $24.6 \pm 4.1$  years, height  $1.71 \pm 0.10$  m, mass  $69.9 \pm 16.1$  kg) were tested. The auditory distraction manipulation consisted of messages, designed to mimic department store announcements that were played at random through headphones for half of the trials over the area of the walkway corresponding to the approach to and clearance of the mannequin (or the same floor when the mannequin did not obstruct the path). These messages contained three elements of information (numerical, such as prices; nominal, such as an item name; and spatial, such as a department section). On arriving at the end of the walkway, participants were questioned on any one of the elements, randomly preselected, to test whether they had paid sufficient attention to the messages. When there was no message, the same soft, instrumental music was played to mask any auditory cues from the motor controlling the mannequin. Following a familiarization period, participants randomly performed a total of 90 trials including 45 trials without the auditory message (OFF condition) as in Experiment 1 (Table 1) and a repeat of these trials where participants were required to listen to the messages (ON condition).

**Data Analyses.** Processing of the motion data through custom programs written in Pascal and in MatLab allowed the calculation of both the person's center of mass (CM) and the mannequin elbow trajectories. A scanning window was created within the transverse plane in front of the participant by defining a quarter circle composed of 90 vectors in the upper left quadrant of a circle centered at the estimated body CM position. These vectors had polar coordinates incremented at intervals of  $1^\circ$  and amplitudes (i.e., the radii of the circle) equal to three times the average step length of the participant (mean of all steps during unobstructed walking). Given that personal space during the circumvention of obstacles has not been quantified yet, the

scanning window was purposely made large enough to exceed both the clearances observed during similar obstacle circumvention tasks (Vallis & McFadyen, 2003; Gérin-Lajoie, McFadyen & Richards, 2003) and the sensory zone (approximately 1.06 m wide by 1.52 m deep) described by Fruin (1970). The premise was that if a personal space is maintained in the vicinity of the obstacle, the use of such a large scanning window would ensure that its boundaries would be captured.

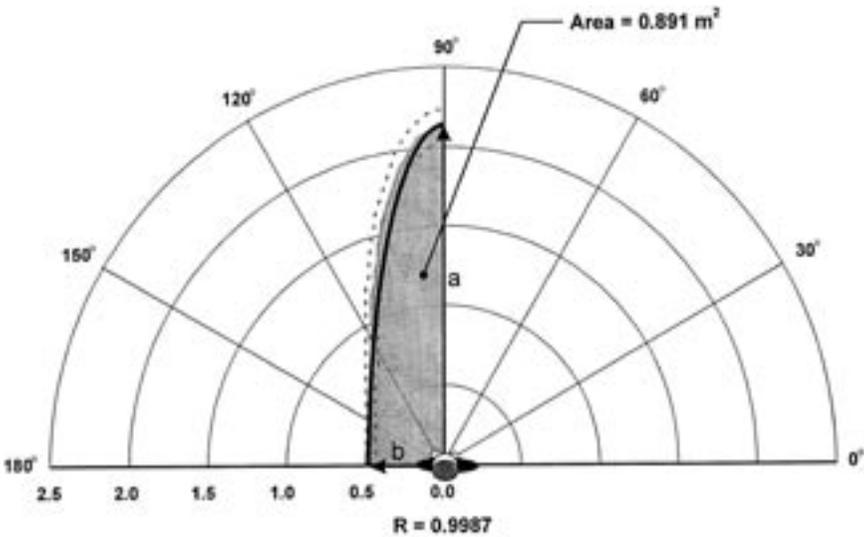
The distance within the transverse plane between the CM of the pedestrian and the elbow of the mannequin (P - M distance, Figure 6A) was calculated during avoidance and used to determine the shortest distance encountered for each corresponding vector within the scanning window. The contour of the resulting pattern of vectors determined, for each trial, a transversal cross-section of the person's preserved personal space within the upper left quadrant (Figure 6B), and the area under that curve was then computed as the main dependent variable. The statistical model consisted of a three-factor randomized block design (obstacle context  $\times$  certainty  $\times$  auditory message, with two levels each). Results were blocked by participant since each participant was exposed to all conditions in the model, and the participant mean across the five trials for each condition was entered into the corresponding cell of the model. The significance level was set at 0.05 for all statistical tests which were performed using SPSS (v. 11.0.0).



**Figure 6—Distance within the transverse plane between the center of mass of the pedestrian and the elbow of the mannequin (P - M distance) (A); contour of preserved personal space within the upper left quadrant created by joining the tips of vectors representing the shortest P - M distances encountered for each of the 90 vectors composing the scanning window (B).**

## Results

**Determination of Personal Space During Obstacle Circumvention.** Figure 7 shows the global average personal space maintained across all conditions and participants within the upper left quadrant of a circle centered at the CM of the participant. The area under the contour of this average personal space was  $0.891 \text{ m}^2$ . Fitting the average personal space preserved by the participants using the equation of an ellipse with longitudinal and lateral axes equal to  $2.11 \text{ m}$  and  $0.48 \text{ m}$ , respectively, achieved an almost perfect correlation ( $R = 0.9987$ ).



**Figure 7—Global average of the preserved personal space (shaded area) plus or minus one standard error (dotted lines) across all conditions and participants. The superimposed solid line is defined by the equation of an ellipse with parameters  $a = 2.11 \text{ m}$  and  $b = 0.48 \text{ m}$  that achieves an almost perfect fit with the average curve.**

**Personal Space Across Environmental Factors.** The cross-section areas of the preserved personal space across the different conditions are shown in Figure 8. Obstacle movement decreased the preserved personal space, on average, by about 22%, i.e., from  $1.002 \text{ m}^2$  in static conditions to  $0.779 \text{ m}^2$  when the mannequin was moving,  $F(1, 56) = 30.30$ ,  $p < .001$ .

Certainty about the mannequin's movements had a small but significant effect,  $F(1, 56) = 4.12$ ,  $p = .047$ . When the action of the mannequin was revealed ahead of time, participants opted to maintain, on average, a personal space ( $0.932 \text{ m}^2$ ) that was about 9% larger versus the most natural situation involving initial uncertainty ( $0.849 \text{ m}^2$ ).

The auditory message factor also had a significant effect  $F(1, 56) = 8.94$ ,  $p = .004$ . Participants, on average, maintained a personal space that was about 15%

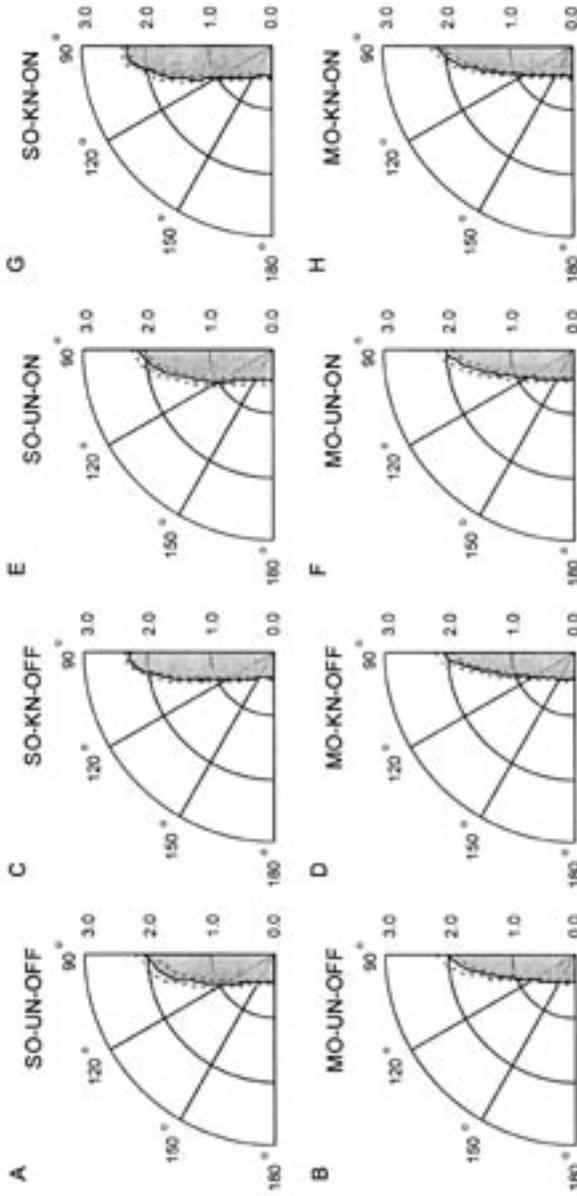


Figure 8—Cross-section of the personal space that was preserved across the different environmental conditions including: stationary obstacle (SO, on first row i.e., A, C, E, & G), moving obstacle (MO, on second row i.e., B, D, F, & H), uncertain (UN, on first and third column i.e., A, B, E, & F), known (KN, on second and fourth column i.e., C, D, G, & H), message off (OFF, on first two columns i.e., A-D) and message on (ON, on last two columns i.e., E-H). The respective averages of preserved personal space plus or minus one standard error are shown for each curve. The corresponding values for the area under these curves are shown on panel I. Error bars represent standard errors of the mean.

(continued)

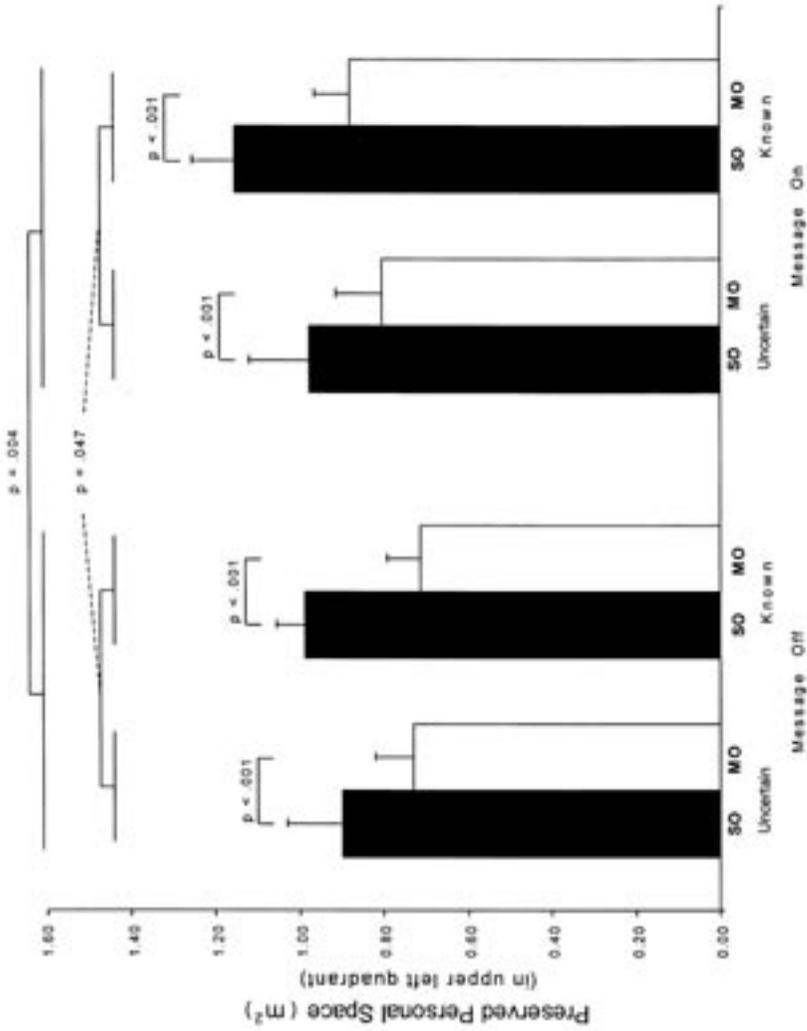


Figure 8—(continued)

larger when paying attention to the simultaneous auditory message ( $0.951 \text{ m}^2$ ) than during the absence of auditory distraction ( $0.830 \text{ m}^2$ ).

## Discussion

In his work related to designing public places for proper pedestrian ambulation, Fruin (1970) calculated that 1.48 m is the minimum longitudinal spacing required between people at normal walking speeds. A later description of such a sensory zone (Templer, 1992) estimated that, at a natural walking speed of about 1.3 m/s, one might maintain an area of approximately 1.06 m wide by 1.52 m deep. The dimensions of the personal space determined in the present study ( $2 \times 0.48 = 0.96 \text{ m}$  wide by 2.11 m deep) are generally in agreement with these dimensions. The longitudinal axis of the personal space measured in our study is slightly longer, but the average walking speed of our participants (1.58 m/s,  $SE = 0.05 \text{ m/s}$ ) was also higher. This could explain the slight difference in the amplitude of the longitudinal axis since the faster people walk, the larger the distance they need in front of them to perceive, anticipate, and react to, potential obstructions.

In addition, the present results showed that the personal space preserved by young adults during obstacle circumvention has an elliptical shape. The preservation of this elliptical protective zone shows that the passage of the CM around the obstacle is not performed at random, but rather with systematic, gradual, transitions. Had the task been more reactive in nature, we might have expected more abrupt changes in the contour of the personal space. Given that participants could anticipate obstacle circumvention at some level, the smooth elliptical shape seems like a logical choice for the control of the CM trajectory. The fact that the longitudinal axis of the personal space is the longest also makes sense, because the role of the personal space is to provide a safety zone that is large enough to ensure sufficient time to perceive upcoming hazards and to perform gait adaptations. This is why personal space is more than twice as long in the direction of travel to account for the movement of the body in space. The lateral axis of the personal space ensures that clearance is maintained at all times to allow the body to move through the environment while avoiding contacts with obstructions. The protocol used in this study only allowed for the quantification of personal space for the upper left quadrant since only right passes around the mannequin were analyzed. The same method, however, could be used to investigate whether both halves of the personal space maintained in front of pedestrians are symmetrical.

When navigating through an obstructed environment, the pedestrian must have a certain level of awareness of his or her environment. This is critical for the detection of potential hazards and for both monitoring the changing environment as well as processing other environmental stimuli. The results of Experiment 1 suggested that the gait adaptations (i.e., delayed deviations, a tendency for speed reduction and step shortening before circumventing the obstacle) when avoiding a moving obstacle reflected the increased information processing involved in this scenario. In Experiment 2, the increased attention allocated to the moving obstacle possibly allowed participants to tolerate greater, but controlled, intrusion of their personal space by the moving obstacle, most likely to gain time for collecting enough information before circumventing it.

A slightly compromised personal space was found during the most natural situation involving initial uncertainty. Again, this result might be indicative of the greater attentional resources allocated to the mannequin because of the uncertainty associated with its movement. On the other hand, when anticipation was facilitated by revealing the movement of the mannequin a priori, participants could plan for a larger personal space that would require less attention to the mannequin. This was especially the case when participants knew the mannequin was going to remain stationary in the pathway.

Paying attention to the simultaneous auditory message also had an effect on the personal space of young adults. A growing body of research demonstrates that attentional resources subserving audition, vision, and touch are shared and limited (Driver & Spence, 1998; Calvert, Brammer & Iversen, 1998; Just et al., 2001). Therefore, participants had less attentional resources available for the obstacle avoidance task while paying attention to the messages. In this situation, increasing the size of their preserved personal space might have allowed participants to diminish the relative importance of the visuospatial attentional demands related to obstacle circumvention versus the processing of the auditory message. Populations with a decreased ability to perform dual tasks, such as older adults (e.g., Chen et al., 1996; Lindenberger, Marsiske & Baltes, 2000), could be expected to choose even larger personal spaces to “free up” some attentional resources for the auditory messages while circumventing an obstacle. Preliminary results show that this is the case (Gérin-Lajoie, McFadyen & Richards, 2004).

In summary, even young, alert adults, adjusted their personal space in a systematic manner to navigate within the different realistic environmental contexts. The presence of effects related to the different environmental conditions suggests that more complex environments (e.g., with more, freely moving obstacles and more complicated messages) or diminished locomotor capacity could further impact the regulation of personal space or require greater gait adjustments to either preserve it to the same extent or to a higher, safer, level.

The systematic preservation of a personal space that is adjusted according to the different environmental contexts indicates that participants accounted for the dimensions of their protective space and suggests that it is used to regulate locomotor adaptations when avoiding obstructions. This implicit knowledge of their own personal space could have been used for anticipatory locomotor control such as in the planning of both the appropriate point of deviation from their travel path and the safe clearance to be used around the obstacle. Gait speed is also modulated according to the personal space maintained around the body. Although this relationship was not directly tested in this experiment by using different walking speeds as part of the protocol, we know that compromising the personal space in front of the mannequin (as in the MO condition) results in a speed reduction through a step shortening strategy (as it was observed in Experiment 1). The systematic preservation of personal space observed in the present study suggests that it is represented at some level in the brain. It is known that many brain sites are implicated in the interpretation of the body in space and the estimation of its relationship with surrounding physical constraints (Graziano et al., 1994). More research, however, is required to identify the specific brain areas involved in encoding the personal space that is used by the locomotor system to regulate obstacle circumvention.

## General Conclusions

This work provided the first description of the natural locomotor behavior for circumventing stationary and moving human-shaped obstructions with displacements that are not always initially predictable. It showed that different anticipatory locomotor adaptations (ALAs) are used to avoid stationary versus moving obstacles. Participants made specific modifications to the antero-posterior control of their center of mass that were aimed at gaining time for the avoidance of the obstacle moving in an uncertain manner, reflecting the increased cost of the anticipation process in a dynamically changing environment. When anticipation was facilitated by revealing the action and final position of the mannequin a priori, ALAs started earlier. This illustrated the impact on ALAs of the online acquisition and integration of information required for anticipation when navigating in uncertain, realistic obstructed environments. Even when the obstacle context was initially known, avoiding the moving obstacle was still different than avoiding the stationary one, most likely because of the increased information processing related to monitoring the moving obstacle. It was thus suggested that the differences in ALAs observed between the different obstruction contexts in the first experiment were due to the different mental processing entailed by those obstruction contexts.

To further our understanding of the adaptive avoidance behavior of pedestrians in ecological, obstructed environments, the preservation of a personal space during obstacle circumvention and its relationship with different attentional demands in different obstruction contexts were examined. This study was also the first to directly quantify personal space during locomotion (method introduced in Experiment 2). The shape and dimensions of a cross-section of this bubble of space were determined. Such quantification provides a window on this otherwise abstract concept related to the protective space maintained around the body when navigating through realistic, obstructed environments. Young adults appear to have at least implicit knowledge about their personal space since they preserve an elliptical protective zone around their body across different environmental contexts. Personal space is also adjusted to deal with environmental factors such as obstacle movement, certainty about obstacle movement, and auditory distractions. The preservation of personal space, therefore, appears to be a control criterion used by the locomotor system to plan gait adaptations in accordance with the environmental context.

The present methods and findings, although from a predominantly biomechanics approach, should have broad interest across different disciplines related to locomotor control and general human behavior. In the future, the cognitive and physiological processes underlying mobility control should be further investigated. In addition, the study of the avoidance of real pedestrians should account for more psychological and sociological issues such as personality and comfortable social distance. Measuring gaze directly or using virtual, but ecological, environments should also provide further insight into the type of visual information that is used in such an obstacle circumvention task. The effect of other aspects such as walking speed and different environmental constraints should be investigated to add to the personal space model that was introduced in this work. The study of other populations with challenges to locomotor capacity using this novel obstructed gait

paradigm will likely unveil different characteristics that will further our understanding of the regulation mechanisms used by the locomotor system for the control of both normal and pathological adaptive walking within realistic, obstructed environments.

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